Production of rice and associated crops in deeply flooded areas of the Chao Phraya delta

D. W. Puckridge[1], Tawee Kupkanchanul[2], Wilailak Palaklang[2] and Kalaya Kupkanchanakul[2]

ABSTRACT: *Thailand has approximately 500,000 ha of deepwater rice (OAE, 1991) in the Chao Phraya Delta. Most areas are rainfed with water levels uncontrolled by farmers. The average grain yield of deepwater rice (DWR) in the Central Plain is around 2.2 t/ha, similar to the average national rice yield. The main yield limiting factors are problem soils, drought in the pre-flood period part of the growing season, limited fertiliser use, and unpredictable depth and duration of flood. However, most farmers in DWR areas of Thailand want to continue growing DWR. It is the only crop that can survive in the flood period, and there is a lack of alternative off-farm occupations. The potential of dry season crops is limited due to lack of irrigation water. On less-acid soils, however, in the pre-flood period of 3-4 months from the beginning of the wet season there is good potential for non-rice crops with short growth duration and drought resistance. This paper reviews environment and production of DWR, the development of new varieties, response to fertiliser, and some alternative cropping possibilities.*

1 Introduction

> "*There is, moreover, a certain kind of land where the rice grows naturally, without sowing. When the water is up to one fathom* [1.8 m]*, the rice keeps pace with its growth. This I think, must be a special variety".* [Chou Ta-Kuan, reporting on his visit to Cambodia in 1296-1297] (Siam Society, 1987)

The history of Thailand is closely linked to the flood plains of the Chao Phraya Delta, where deepwater rice is widely distributed (Catling, 1985) and has been a main support of the people. Deepwater rice is defined as rice that is flooded deeper than 50 cm for one month or longer during the growing season (Catling *et al.*, 1988c), with the term floating rice used for that growing in the very deeply flooded areas. In recent years the DWR crop has declined from 800,000 ha to 500,000 ha due to changes in flooding patterns with building of roads and embankments, introduction of fish and shrimp farms, and the utilization of land for

---

[1] International Rice Research Institute (retired)

[2] Rice Research Institute, DOAC, Thailand.

industrialization, urban expansion and speculation. It is still providing around one million tons of rice each year in the low-lying areas that act as a safety escape for floodwaters near Bangkok. Studies of rice and other crops and alternative uses for these annually flooded fields are therefore topics of economic and social importance. As deepwater rice is the main crop, we will first discuss DWR and the conditions under which it is grown, then consider other crops which can fit into the system.

Flooding usually occurs in the later stages of plant growth and can last for several months (Figure 1) The stipulation that flooding must be sustained for at least one month is to distinguish deepwater rice areas from other flood-prone areas. These include the coastal wetlands, where water may rise more than 50 cm by tide action, and the flash-flood areas where rice may be temporarily submerged for only a few days. Most deepwater rice survives by elongation of stems, whereas other rice types lack this characteristic and are destroyed by deep water. Floating rices can survive and produce grain when floodwaters reach maximum depths of 4 metres or even more. In this paper deepwater rice (DWR) is used as a convenient inclusive term to include the floating rices grown in very deep water, the intermediate deepwater rices which elongate to a lesser extent than floating rices, and the tall non-elongating rices which are popular for water depths of 50-100 cm.

Deepwater rice is widely spread. It is grown on the flood plains and deltas of rivers such as the Ganges and Brahmaputra of India and Bangladesh, the Irrawaddy of Myanmar, the Mekong of Vietnam and Cambodia, the Chao Phraya of Thailand, and the Niger of West Africa. In Asia it is grown from latitude 27^{o} N in Assam and Uttar Pradesh, India, to latitude 3^{o} S in Indonesia. About 9% of the total area of about 11 million ha (IRRI 1997) is cultivated on the Chao Phraya basin of Thailand.

Farmers who live in areas subject to deep flooding are skilled at maintaining a livelihood in a high-risk environment. However, land and labour productivity remain at low levels due to low cropping intensity and lack of the associated agricultural growth induced by non-farm rural activities. Rice is the only food crop that can withstand deep flooding during the wet season, and in some seasons there is no harvest at all. The dry period is often too short or has insufficient water for production of other food crops. Farmers to date have benefited little from the ‘green revolution’ because of limited success in disseminating appropriate high-yielding varieties.

In more favourable areas households have increased food production and income through management interventions such as mixed cropping in the pre-flood period and fish production during the flood. For example, in Bangladesh and north-eastern India investment in shallow tube wells and low-lift pumps has resulted in a crop substitution program where much of the wet season DWR has been replaced by one crop of dry season irrigated rice. Over much of the Mekong Delta of Vietnam 2-3 irrigated rice crops have replaced the single crop of DWR. Short duration pre- or post-flood rice crops have also replaced DWR in some areas of the Chao Phraya Delta.

Not all the results associated with changes to intensive production have been positive, particularly with regard to environmental protection. Reduced fish habitat, increased soil salinity, and polluted drinking water for people and animals are some of the major problems associated with the departure from traditional rice cultivation practices. Converting low-lying coastal rice paddies into ponds for brackish water shrimp farming has no doubt increased the productivity of resources and farmers' incomes in many Asian countries, but is also causing severe environmental and social problems.

On the other hand, the productivity of deep-water lands can be by improved DWR varieties and resource management practices and alternative crops appropriate to this ecosystem. Varieties with high yield incorporated with the traditional capacity to elongate in deep water have become available.

2 Habitat and production environment

River water is the most important source of flooding in the lower basin of the Chao Phraya in Thailand, where the authorities dump surplus water at high river levels (Catling 1992). The Chao Phraya River rises in the northern mountains of Thailand. Its entire delta was once part of the Gulf of Thailand, which has been filled in by sediment carried down from the north. The floodplain is braided with numerous small channels and other rivers — notably the Pa Sak — join the Chao Phraya as it flows to the sea. Monsoon rains in the watersheds bring the river down in full flood. On reaching the flat topography, the flow rates slow and over-bank spills of turbid silty water begin to flood the land. The network of canals links rivers in the delta and helps to distribute the water. Around Bangkok the delta is seldom more than 2 m above sea level, and the flooded rivers cause a large part of the local rainfall to become ponded on the land. Drainage is further restricted by high tides, which often cause reverse flow of the Chao Phraya beyond Ayutthaya. The canals and sluices effectively control early flooding and can retain water on the land at the end of the wet season, but in high flood years peak flooding can not be effectively controlled. This occurs about 3 years out of every 10, and sudden flood surges of 50-100 cm may occur. The initial inundating surge of water commences June to August, reaches a peak in October or November, and recedes in December and early January (Catling, 1992).

Most deepwater rice grows under rainfed dryland conditions for 1-3 months before being inundated with floodwater, which coincides with the highest rainfall period. Flooding in the rice fields is thus accentuated by local or nearby rainfall in conjunction with the raised water levels from swollen rivers. For example, in 1990 heavy rains over most of the surrounding elevated areas of the Central Plain caused floodwater levels at HTA and surrounding areas to rise from 70 cm to 120 cm in three days and many DWR crops were destroyed.

The water regime has the most obvious effect on crop production in deepwater areas. The time of onset of flooding and the number of days the field is flooded during the crop growth period is very important (Puckridge et al 1988b). Classification of areas by time of arrival of floodwater, rate of rise of water level, range of maximum water depths and time of recession of the flood is essential for selection of DWR varieties.

Although precise data on flooding patterns are of fundamental value to targeting improved varieties and production practices, there is a paucity of long-term daily water records from actual DWR fields. The best records have been kept in Bangladesh and Thailand (Puckridge et al. 1988b). The onset of flooding can vary greatly between years. In Thailand it may be 50 to 120 days after emergence of direct sown crops, while in Bangladesh it can be from 20 to 60 days. Floodwaters commonly rise at a rate of about 2-3 cm/day in Thailand, but it can be over 10 cm/day for extended periods in Bangladesh. The most rapid increases in water depth tend to be early in the season, when the plants are most vulnerable. Maximum water depth differs with location, and at the same location may vary 50-100 cm between years. The date of flood recession at the end of the season is more regular than arrival of floodwaters in the field, and determines desired time of maturity of the crop. In most cases DWR is usually harvested after water drains from the fields, but in some slowly draining areas it must be harvested from boats or have very late maturity. Farmers use different types of DWR because water depth can change with topography in a short distance, particularly in areas with dish shaped depressions.

Some fields may temporarily flood from rainfall or river overflow, but after a few days the flash floods subside. Most rice varieties can survive only 3-4 days of submergence, but some have been identified that can persist under water for 10 days or more. Some varieties can survive both flash floods and stagnant floods of up to about 80 cm later in the season. Varieties of such type include Khao Tah Haeng 17 and Leuang Pratew 123. These varieties, though cultivated in low-lying areas, do not elongate. Important traits are height of 150-180 cm to withstand water depths to around 80 cm, photoperiod sensitivity for flexibility in planting time, tolerance to drought, submergence and soil-related stresses. Although elongation is essential for deep water that remains in the fields, it is a disadvantage for short term flooding. If plants elongate in response to flash floods they will lodge (fall down) after the flood subsides and yield will be reduced.

The first floodwater spreading from rivers is usually turbid, but most of the silt is deposited near the main channels. Contrary to earlier belief, sedimentation rates in DWR fields are variable and generally low, and silt is not a principal source of fertility (Catling 1992). Flooding from rain usually results in clear water that generally causes less damage than silted or turbid water. Physical and chemical properties of the floodwater have an important role in growth and nutrition of the rice crop. Marked diurnal cycles in oxygen, carbon dioxide and pH occur due to the activity of photosynthetic aquatic biomass; Highest CO2 concentrations in water occur in the afternoon, and the lowest at dawn (Setter et al. 1988a,b).

Soils. Deepwater rice soils are alluvial, ranging from sandy loam to heavy clay. Heavy silt deposition is usually associated with proximity to rivers, Many soils are fertile, but adverse acid sulphate soils are common. Soil pH ranges from 3.5 to 8.5 but is mostly acidic. Acid sulphate soils are a major problem in the south-eastern part of Thailand’s central plain.

Rainfall. Catling *et al.* (1988c) give details of climate in the major production areas. The mean annual rainfall of deepwater rice in Thailand ranges from about 1200 mm in the western part of the delta to 1700 mm in the east. About 60% of the rainfall occur during the flood period, and thus up to one meter of rain can be added to the floodwater originating from rivers. This is close to the average flood depth and helps to explain the general occurrence of clear water flooding. In Thailand DWR crops are sown in April-May and in the 2-4 months before floods arrive there can be periods of extreme drought stress. Severe drought in the northern delta damaged the rice crop in 1993, but in contrast the same area had disastrous floods in 1994 and 1995. Drought tolerance is an essential trait for DWR, and varieties from Thailand have been an important source of drought resistance for other rice types (DeDatta and Malabuyoc 1988).

Temperature. Day temperatures below 22^{o}C can cause sterility in rice, but in Thailand cool periods during flowering are rare and temperatures from October to December generally remain favourable for panicle initiation and flowering. Water temperatures near the surface range from 29^{O} to 35^{o}C from July to October. In deep water slightly lower water temperatures occur just above the soil. Water temperatures drop below 28^{o}C in November and below 25^{o}C in December (Catling et al 1988c).

Mineral toxicity. Mineral toxicity can occur in saline, sodic, acid sulphate, peat and dryland soils. They rarely occur in isolation. Some of the most common mineral toxicity problems limiting the growth and yield of rice are iron (Fe), manganese (Mn), aluminium (Al), boron (B), and hydrogen sulphide (H_2S). Aluminium toxicity occurs in most acid sulphate soils during the initial phase of flooding. The toxicity may persist for many weeks if soil reduction and rise in pH after submergence of acid sulphate soil is very slow. Soil pH of less than 4 and Al in soil solution of 1 ppm will indicate toxic levels of Al.

2.1 Deepwater rice cultural types

Despite the severe environment DWR has a long history of adaptation and provides a sustainable and environmentally friendly form of agriculture. It is over seven hundred years since Chou Ta-Kuan observed DWR in Cambodia (Siam Society, 1987), and although a significant change to irrigation has been occurred where water is available, conversion to irrigation in DWR areas is limited. In most of the current DWR areas rice is the only food crop possible during the wet season and farmers expect to continue growing it.

It was assumed that virtually all Asian deepwater and floating rices belonged to the *Indica* geographic race occurring in tropical monsoon climates from 0^{o} to 25^{o} North and that none could be classified with *Japonica*. However, Inouye and Hagiwara (1982) found that several showed distinct *japonica* characteristics. Other evidence points to the diversity of the DWR and its varied evolutionary background. It also helps to explain the extreme variability within indigenous areas and the difficulties sometimes encountered with hybridisation in variety improvement programmes (Catling 1992).

Many types of DWR can be found in a region. Different maximum water depths require distinct types of DWR and farmers may use several varieties of DWR where water depths change with topography in a short distance. For 50-80 cm water – flash flood tolerant, non-elongating varieties are usual; for 80-150 cm water – slow elongating (2-3 cm/day) varieties; and for deeper than 150 cm water – fast elongating (15-20 cm/day) varieties. The rices in the first two categories have the greatest potential for yield increase.

2.2 Special characters of deepwater rice

Deepwater and floating rices have three special adaptations; (1) elongation of stems and leaves; (2) kneeing which is the upward bending of the terminal parts of the plant and (3) the ability to develop nodal tillers and roots from upper nodes in the water. Kneeing keeps the reproductive parts above water as the floods subside. The first two traits are accentuated in floating rices such as Leb Mue Nahng 111, Pin Gaew 56, Plai Ngahm, Khao Luang and Tewada in Thailand. Nodal tillers arising during the flood period can sometimes compensate for sparse stands.

2.2.1 Elongation

Elongation ability is an escape mechanism for survival from partial or total submergence. Total plant elongation, including increase in lengths of leaf blades, leaf sheaths and stems may be as much as 20-25 cm in 24 h during initial flooding (Choudhary and Zaman, 1970). The stems produce new nodes where leaves are attached and the internode, which is the section of stem between the nodes, can increase in length when submerged. Elongation of leaf blades and leaf sheaths is important for survival of seedlings but internode elongation is the most important mechanism for increasing plant length in very deep water (Vergara et al 1975). Internode elongation commenced between 4 and 6 weeks of age for most of 100 lines of DWR plants growing in rising water (Puckridge *et al.* 1990a). The elongation induced after panicle initiation affects the final 4-5 internodes and is not influenced by water depth (Morishima 1975, Bekhasut *et al.* 1990). Elongation stops after flowering in all varieties

Catling (1992) concluded from review of the literature that there is general agreement that elongation and floating traits in cultivated rice of Asia are derived directly from a perennial *Oryza rufipogon* wild progenitor, or from an intermediate perennial-annual type in swampy lowlands. Floating rices of South Asia such as Jalmagna (India), Baisbish and Rayada 16-3 (Bangladesh) are faster elongators than the Thai rices Leb Mue Nahng 111, Pin Gaew 56 and Plai Ngham. Hence they are better adapted to rapidly rising water.

Total length of stems, comprising many internodes, is usually considerably more than the depth of water. Plants move by wind away from a vertical habit, thus having more stem sections under water and receiving more stimuli for elongation. Long internodes indicate rapid water rise. Bekhasut *et al.* (1990) reported for plants developing a total of 19 internodes that up to 14 showed marked elongation (5-30 cm) due to increase in water depth. The longest were the early-formed internodes at the base of the plants (numbered 2-5), produced when water was rising most rapidly. New nodes were produced at interval of 10-12 days, and only the most recently formed internodes elongated. Because of a period of stable water level, internodes 6-10 elongated less than internodes 11-14 which developed during a second rise in water level.

Elongation of internodes was considered by Sugawara and Horikawa (1971) to be due to increase in number of cells, while Nasiruddin *et al.* (1977) ascribed it to a lengthening of cells. Kende *et al.* (1984) reported that submergence or exposure to ethylene of whole plants led to as much as ten-fold increase in number of cells in the zones that elongated between 0 to 3 days after treatment. Their plants were at least 29 days old before internode elongation could be stimulated by ethylene treatment. Takahashi (1988) found that approximately half of the total cell population in the longitudinal direction of the internode was already formed when the internode reached 10% of its final length.

Both processes are involved. Partial submergence of DWR results in an increased rate of cell division and elongation in the intercalary meristem of the internode (Rose-John and Kende 1985, Bleecker *et al.* 1987, Kende and Raskin 1988). There appear to be four biochemical processes involved — submergence lowers the level of oxygen in rice internodes, low oxygen levels stimulate ethylene synthesis, ethylene accumulates in the submerged internodes; and finally ethylene concentration increases the sensitivity of the tissue to giberellic acid or increases the concentration of physiologically active giberellins. Production of ethylene by submerged plant parts in DWR fields near Ayutthaya was indicated by ethylene concentration of 1-2 ppm in the floodwater, compared with only 0.1-0.2 ppm in the plant canopy above the water surface (Setter et. al 1988b).

2.2.2 **Kneeing**

Kneeing is the bending upwards of the upper parts of the culms (stems) as water levels fall and rice plants lodge during the recession of floodwater. When culms lie on the water surface and the upper leaves are held vertical above the water, the plants appear to float even though the base of the plant is still attached to the soil, hence the common name floating rices. Kneeing keeps the canopy and panicles erect and above water level. It maintains grain quality by preventing submergence of the panicles in water, and protects the grain from damage by aquatic fauna (Vergara *et al.*, 1977; Vergara, 1985). Traditional deepwater rices have good kneeing ability but some modern varieties lack this trait. It should be considered as an objective of any DWR variety improvement program (Haloi, 1989).

2.2.3 Submergence tolerance

Submergence tolerance and elongation ability are essentially distinct plant traits that represent opposite mechanisms or strategies for flood adaptation, and attempts to combine them fully in a single rice variety have failed. Deepwater rice may be completely submerged if floodwaters rise rapidly, but elongation is usually sufficient to raise part of the foliage above the water level. Photosynthesis can then continue and starch and sugars in emergent leaves and in plant parts under the water are maintained (Setter *et al.*, 1987b) and further elongation can take place. Submergence tolerance is most useful for non-elongating rices that may be submerged for a few days by rapidly increasing and then decreasing water levels.

Submergence-tolerant rice may survive complete submersion by water for 10 days or more, depending on water conditions, and resume growth after the water has subsided. However, the effects are highly dependent on the growth stage. Young plants are least tolerant. Submergence at the seedling stage kills weak plants, drastically reduces growth and inhibits tiller formation.

Submerged rice has a limited supply of carbohydrates (energy) for survival and it rapidly declines (Setter *et al.* 1987b; Setter *et al.* 1988a). Recent research has focused on the way plants use this carbohydrate during submergence for growth and for maintenance processes essential to survival. These include water relations in the cell, the recycling of membranes and the expression of anaerobic genes. Since carbohydrates are limiting, it is considered likely that during submergence elongation growth competes with maintenance processes essential to survival (Setter and Laureles 1996). They used an inhibitor of GA biosynthesis (paclobutrazol) to reduce elongation growth during submergence. When this chemical was applied , either before submergence or in the floodwater, elongation was inhibited and survival of rice plants improved dramatically. For instance, an intolerant cultivar (Calrose) had 100% survival of after 10d submergence when sprayed with paclobutrazol before submergence, as opposed to no survival in the unsprayed control. They also found that a GA-deficient mutant, which did not elongate during submergence, had unexpectedly high tolerance to submergence. Conversely, when elongation was increased by giberellic acid application, submergence tolerance was reduced.

Waitruardrock et al. (1992) tested the extent to which different DWR varieties could sustain elongation. Twenty DWR entries were sown in a pond with controlled water level at Huntra Rice Experiment Station. At 6 weeks after emergence the water level was increased to 80 cm and all plant tops were cut off at the water surface. Plant were cut once only at 6 weeks, or at 2, 4 or 8 days intervals after the first cut. Heights of plants above water level were measured every 2 days after the first cutting. Plants cut once reached a height of 70-80 cm above water and were not adversely affected by cutting, whereas elongation of plants cut at intervals of 2-4 days declined rapidly, indicating depletion of reserves (Figure 2). After 18-20 days plants cut at 2 or 4 day interval ceased elongation and died. Stem glucose content was used as an estimate of the apparent energy resources of four of the rices tested. The varieties RD 19 & Huntra 60, which have medium elongation ability, had higher glucose contents than Pin Gaew 56 and Leb Mue Nahng 111, which elongate rapidly. Pin Gaew and Leb Mue Nahng appeared to be more efficient users of carbohydrate reserves, being able reduce glucose to levels lower than in RD19 and Huntra 60 and thus to elongate more.

2.3 Deepwater rice in the Chao Phraya Delta

Current production is approximately 500,000 ha of DWR (OAE, 1991) with a mean grain yield of 2.2 t/ha, similar to the national average yield for all rice types. Compared with other DWR countries, the average farm size of 4-7 ha and fields of >1.5 ha are large. Hundreds of local cultivars have been grown and until quite recently simple cultural methods and farming equipment were used. Farming systems dramatically changed in the 1960's and 1970's with introduction of tractors and flood control schemes. In the early 1990’s DWR in Thailand was still reaped by hand sickles, but most threshing was done by contractors using mobile threshing machines. Manual harvesting is now being replaced by field operation of locally produced combine harvesters; developed from axial flow threshers previously used as stationary machines.

Even though there are canals and some flood control, Thai DWR areas are rainfed with water levels uncontrolled by farmers (Puckridge et al. 1989). The climate has a harsh and pronounced dry season from December to March. Dry DWR stubble is burnt in February and March. Contractors with large 4-wheel tractors pulling 7-disc ploughs now do most of the ploughing, often before the opening rains of the season in April-May. There are one or two ploughings and occasionally the second ploughing covers the seed. Seed is usually broadcast on roughly ploughed dry soil to await rain. Early rainfall is sporadic, maximum temperature is 35-36^{O} C and evaporation rates are 6-8 mm/day. Early sown DWR is often exposed to severe drought stress before the flood arrives. In drought years farmers may be forced to sow more than once.. Santasumaron (unpublished) surveyed 110 farm fields and found seed rates up to 200 kg per hectare, sowing date was extremely variable and not closely related to rainfall pattern. The most common cultivars in her survey were Khao Puang (17 fields), Plai Ngahm (10), Kao Banna (5) and Nhang Kiew (5).

Puckridge et al. (1994) surveyed 87 farmer's fields in the Central Plain of Thailand in 1988-89. Flooding started from 22 to 122 days after seedling emergence, with a mean of 66 days Maximum water depths ranged from 30 to 210 cm. Thirty-seven DWR varieties were found. The mean farmer application of nitrogen (N) for 52 fields sampled in 1989 was 15.2 kg N ha^{-1}. Above-ground plant dry mass at maturity ranged from 2.7 t ha^{-1} to 20.5 t ha^{-1}, with a mean of 10 t ha^{-1}. Plant nitrogen content at maturity ranged from 23 to 115 kg ha^{-1}, with a mean of 66 kg. Eighty percent of plant N was accumulated during the flood, but pre-flood plant production had a significant correlation with above ground dry mass at maturity, indicating the importance of good early crop development. Yield ranged from 0.65 to 4.87 t ha^{-1}, with a mean of 2.13 t ha^{-1}. This compares with an earlier estimate of average yield of DWR of close to 2.0 t ha^{-1}, with yields ranging from zero to over 4.0 t ha^{-1} (Catling *et al.*, 1982b).

During the 1992-1993 cropping season a sample of 889 farmers were selected at random from 184 villages in 20 provinces with major DWR areas in the North, Central and Northeast of Thailand by Charoendham et al. (1995). The survey aimed to identify general conditions of DWR cultivation, technology used and general ideas on future situation of growing DWR. The results are summarised below.

1) The total cultivated areas for DWR were estimated at approximately 504, 000 ha, with a mean cultivated area per family of 5-7 ha. About 68% of the farmers owned the lands they were farming.
2) The mean maximum water depth during the growing season ranged from 86-192 cm. Water depths of 50-100 cm covered 263,000 ha. The rate of increase in water depth ranged from 3 to 13 cm/day. The duration of near maximum water depth was 29-46 days.
3) Land preparation — 94% of farmers burned stubble before ploughing, 74% ploughed twice without harrowing. The land usually dried before second ploughing (75%).
4) Planting method — 93% broadcast dry seeds, 6% broadcast pre-germinated seed and only 1% transplanted DWR.
5) Eighty-four varieties of DWR were recorded. Local varieties were grown by 75% of farmers. They considered the recommended varieties to be unsuited to their areas, to have uncertain or low yields, to be no better than the local varieties, or else they followed neighbours practice.

6) Fertiliser — 72% of farmers used chemical fertiliser. Ammophos (16-20-0) was the most popular (81%). Seventy percent applied fertiliser once, at the time of water arrival. For those who applied fertiliser twice (30%), the first application was at 20-30 days after seedling emergence or at water arrival, and the second about panicle initiation stage.

7) Farmers variety requirements were for maturity mid December - early January, desired height 150-200 cm with good elongating ability, drought & submergence tolerance, prolific tillering, non-lodging, long panicle, good kneeing, medium-non shattering panicles, and long slender grain with aroma and good cooking quality.

8) Yield constraints mentioned by farmers were weeds (90% of farmers), drought 55%, rats 54%, insects 25% (Brown Planthopper, Stemborer, Green Leaf Hopper And Thrips), flooding 22%, crabs 22%, birds 11%, and diseases 10% (Blast and Ragged Stunt virus).

9) The mean yield calculated from farmer's assessments was 2.2 t/ha.

10) The major weeds were *Melochia corchorifolia* L., *Ipomea aquatica* Forssk*,* *Aeschynomene* spp & *Sesbania* spp. Eighty six percent of farmers sprayed herbicides following the instructions. Most (92%) sprayed once only and 67% sprayed at beginning of flooding.

11) Cropping pattern: 93% of farmers left the fields fallow before and after DWR, the other 7% grew crops such as cucumber, watermelon, long bean, maize, chilli, tomato and mung bean.

12) On average farmers sold 83% of the DWR produced, kept 8% for seed and used 6% for family consumption.

13) Future trends: 89% of farmers want to continue growing DWR. It is the only crop that can survive in the wet season, and there is a lack of alternative work.

2.4 Pests of deepwater rice

Catling and Islam (1999) recently reviewed the pests of DWR. This section on pests was summarised from information provided by Dr. Catling. Further details and full references are in the review.

Deepwater rice tends to share the same fauna as lowland rice, and pests such as yellow stem borer, and brown planthopper move between DWR and other rice crops (Catling et al, 1988a). The DWR pest complex is dynamic and changeable. Early damage caused by nematodes, rats, stunt viruses and some borers that weaken plant vigour and elongation capacity, may reduce plant stands. Although compensatory tillers (nodal tillers) replace some of the injured stems, the overall yield is decreased by a loss of bearing stems and the production of smaller panicles. On the other hand, injury caused by leafeaters and foliar diseases in the preflood and early elongation stages, unless severe, is probably offset by new leaves produced during elongation with little or no yield loss (Catling, 1992).

The preflood period of DWR is conducive to moderate build-ups of canopy-living insects whose numbers are limited by the synchronous planting of large areas, the sparse stands, and poor plant condition (Catling, 1992). During the main flooding period, however, the presence of succulent DWR stems and leaves, and milder weather extremes are favourable for several major pests that are able to deal with deeply flooded conditions. The abrupt change to deep flooding profoundly affects the composition, population structure and density of the flora and fauna. Species less affected by deep flooding are those living in the top canopy and those possessing definite aquatic adaptations. Rice insects either move to adjacent irrigated rice, other dry season crops and alternate host plants, or aestivate or enter diapause.

Major pests.

Yellow Stem Borer (YSB) is the major pest of DWR. Living exclusively on rice and Oryza wild rices, it has been associated with cultivated rice for thousands of years and may have originated in the DWR environment (Catling and Islam 1982). It is a terrestrial species that requires high levels of moisture and is uniquely adapted to the aquatic environment. During the elongation stage, larvae and pupae inside the stem are either below or near the water surface (Catling and Islam 1995; Islam, 1994). Larvae and pupae not only survive in totally submerged stems, but the stem lumen affords protection from parasites and predators (Islam, 1992). The sixth instar packs an exit hole with special membranes to keep out the water so that the adult can emerge from the submerged stem. The long vegetative stage of DWR enabling the progression of two or three field generations is a major reason for high levels of stem damage at the end of the season. Generally pre-flood infestations cause little if any yield loss (Catling et al. 1987). However, in most fields by flowering stage >20% and by late ripening stage 35-44% of the stems have been damaged by stem borers. Catling et al (1984-85, 1987) and Islam (1991) indicate that yield loss is caused by: (i) a loss of bearing stems due to the production of deadhearts (the outright death of stems), or from damaged but symptomless stems attacked in the vegetative stage and later covered by rising water; (ii) smaller panicles borne by compensatory nodal tillers, (iii) the production of whiteheads in the reproductive phase, and (iv) a decrease in filled grains and lowering of panicle weight from late damage. They concluded that yield losses of 15-20% are caused in many fields every year. Despite a large complex of natural enemies it is unlikely that parasitism rates can be easily improved (Catling, 1992). No strong source of varietal resistance was found after screening many hundreds of DWR genotypes and many advanced breeding lines and traditional cultivars are highly susceptible (Catling et al, 1988b). Attempts at chemical control (Islam et al, 1988) have not been promising. Thus YSB, the major pest, represents a major challenge in DWR.

Rats are significant pests of DWR throughout the region (Catling et al, 1988a). Two bandicoot species are important in Thailand. They are aggressive, opportunistic species having similar habits and characteristics. *B. bengalensis* is present throughout the DWR season, *Rattus losea* persists in a reproductive state in deeply flooded fields and increases in numbers at harvest time, while *Rattus argentiventer* is less active when the bunds are submerged (Somsook et al, 1986). Bandicoots bite open the leaf sheath to reach the tips of growing shoots causing the terminal leaves to die and produce a deadheart, cut off stems 2-4 cm above the water at an oblique angle, and cut panicles at ripening stage. In parts of the Central Plain, rat damage has been so heavy that farmers were obliged to cease growing

DWR for several years (Catling, 1992). The degree of damage varies between fields and years, and is most intense around burrows and along rat pathways (Ahmed et al, 1986). Fertilized plots having denser stands are damaged earlier and more severely than unfertilized plots, and panicles of late maturing cultivars are attacked more heavily. Varietal differences in susceptibility to rat damage were observed in Thailand, but no resistance was discovered. The variety LMN 111 is often the most severely damaged in DWR experimental plots. Baits mixed with brodifacuom, DRC-4575, difenacoum and zinc phosphide, can reduce rat field populations by 87-94% (Poche and Mian, 1986). Rats are more effectively controlled if farmers take concerted action and carry out standard control recommendations based on regular baiting.

Sporadic, Localised and Minor Pests.

Bacterial and fungal diseases generally occur either too early (before completion of tillering) or too late (after development of the panicle) to cause substantial yield loss. Vigorously elongating plants apparently outgrow many early infections (Catling, 1980). The major disease is probably bacterial leaf blight where wind and leaf cutting by farmers may increase damage. The brown spot diseases sometimes occur in drier areas of north India before flooding, especially in years of drought stress (Catling et al, 1988a). Farmers do not spray.

Virus diseases. Ragged stunt (RSV) and tungro are sporadic diseases causing stunting and loss of stems (Catling et al 1982a). An epidemic of RSV occurring in Thailand in 1981-82 was probably spread by brown planthopper vectors migrating from irrigated rice (Pattrasudhi and Catling, 1988; Disthaporn et al, 1985). Another epidemic in Thailand in 1990-91 caused severe damage to DWR stimulated the search for varietal resistance.

Leaffolder, grasshoppers and thrips are more abundant before flooding (Catling, 1980; Catling and Islam, 1999). One tettigoniid and the field cricket may continue at moderate levels during flooding but they do not cause serious outbreaks (Catling, 1992).

Farmers follow few of the cultural control measures recommended in the literature (Catling and Islam, 1999). Although most Thai farmers spray herbicides before flooding, pesticide use in DWR is problematic because of application difficulties, the danger of environmental contamination and cost-benefit considerations. Pesticides should not disturb natural enemies, be safe for edible fish, and not contaminate the open waters used by rural people (Catling, 1992).

2.5 Weeds

Although weeds compete with DWR, many are used for food or medicine and cannot be regarded just as weeds. For example, *Ipomea aquatica* Forssk. (water spinach) is an important vegetable in Thailand and other parts of Asia, and *Echinochloa colona* (L.) Link. is cut as fodder for milk cows.

Pre-flood weeds in DWR fields may be divided into groups (Catling 1992, Catling and Islam 1999)). The first are dryland species which either complete their growth cycle before deep flooding occurs, or are drowned when the water rises, such as short grasses like *E. colona* and *Digitaria spp*., and sedges like *C. iria*. A second group establishes in the pre-flood period but is adapted to rising water and prolonged flooding and thus continues to compete with DWR. During flooding a number of aquatic weeds quickly colonise the open spaces in DWR fields and the unplanted areas. The most notable is *Ipomea Aquatica* (a creeping vine) which grows vigorously in the pre-flood period and readily survives deep flooding by putting out long floating runners. Nantasomsaran (unpublished) conducted a systematic survey of weeds in DWR fields in Thailand over three years, 1988 to 1990. In the first two years the fields and sample areas were selected jointly with a related N-uptake study (Puckridge et al.1994). In 110 fields sampled pre-flood 78 species were found, and for 84 fields sampled at flood recession 81 species were found. Annual grasses dominated the pre-flood period, and *E. colona* was the most common weed. In most fields it occurred at mean densities of 25-100 plants/m2. Also important were four other annual grasses: *Leptochloa chinensis* (L.) Nees., *S. gracilis*, *Echinochloa crus-galli* (L.) P. Beauv., and *Ischaemum rugosum* Slisb., of which the last two are emergents that survive deep flooding. Next was the broad-leaved *I. aquatica*, the only weed classified as emergent and aquatic, followed two annual sedges, *C. iria* and *Fimbristylus miliacea* (L.) Vahl, and two broad-leaved annuals, *Melochia concatenata L.* and *Alternanthera philoxeroides* (Mart.) Griseb.

Wild rice, *Oryza rufipogon* Griff., is as an important weed of DWR, but was not common in Nantasomsaran's survey. It is locally important in some areas of Thailand (Puckridge *et al.*, 1988a), and some fields have been abandoned because of it (Hyakutake *et al.*, 1984). Water hyacinth, *E. crassipes*, the major flood weed in Bangladesh (Catling, 1992) was not recorded at all in the Thai fields, even though it is abundant in rivers and water channels. The flood control systems at the beginning of the season may effectively prevent the entry of this potentially serious weed.

Total weed numbers were more than double in fields ploughed two or three times than in those ploughed once only. The improved seedbed resulting from increased cultivation may favour germination and growth of grass weeds. Differences in rice seed rate had no significant effect on weed populations. Thai farmers apply 2,4-D as a spot spray against broad-leaved weeds such as *M. concatenata, I. aquatica* and *Aeschynomene spp*. but frequently the herbicide is applied too late to be very effective. Farmers do not consider grasses very important provided the fields flood deeper than 60 cm (Vongsaroj *et al.*, 1988). Despite the importance attached to weeds in DWR, very few weed loss assessments have in fact been carried out. In many experiments in Thailand, effective control of broad-leaved weeds before flood inundation with herbicides showed no yield benefit unless weed populations were very dense (Vongsaroj *et al.*, 1988).

3 Crop research

Prachinburi Rice Research Center (PCR) and its satellite Huntra Experiment Station are responsible for most aspects of deepwater and floating rice research in Thailand. The PCR was established in 1975 and laboratories and other facilities have been upgraded to regional research center status. It is 150 km east of Bangkok, approximately 3 m above sea level, flooded in the wet season with 1-2 m of water, and with average annual rainfall of about 1700 mm. Soil is moderate acid sulfate with a pH of about 4.5. It has a total area of 120 ha; 20 ha are used for research and 67 ha for seed multiplication. PCR has well qualified staff, good equipment and excellent facilities for training researchers and farmers.

Huntra Experiment Station (HTA) is 75 km north of Bangkok near Ayutthaya and was founded in 1941. It has less acidic soil than PCR, and a different flooding pattern It is used primarily for deepwater and floating rice and cropping systems research. Huntra has 28 deep rectangular ponds of varying sizes with full water control where rice can be subjected to water depths to 2m. There are also 55 ha of rice fields subject to natural flooding, where maximum water levels vary from 50 to 150 cm between years. About 20 ha is normally used for variety improvement, agronomic and other experiments, the remainder for seed multiplication. Annual rainfall is around 1,300 mm.

Research at PCR and HTA is divided into 5 units:

- Plant Science:- rice breeding to improve production, grain quality, resistance and/or tolerance to some insects and diseases, and adaptability to adverse environments; and studies of genetics, and physiology
- Plant Production and Technology: - agronomic management, soil science, weed science and cropping systems.
- Plant Protection: - research on insect pest and disease management.
- Seed Technology and Production: - germination testing, seed dormancy characteristics, maintenance of genetic purity and seed multiplication of recommended varieties and promising lines.
- Post-Harvest Technology: assessment of grain quality, grain storage, cooking and consumption quality and transformation of products.

Research policies reflect the following development objectives;

- Increasing profit margins through decreasing unit input costs.
- Improving quality of products in response to local and export market requirements.
- Increasing agricultural production through improved soil and water management.
- Identification of appropriate production technology related to specific farmer's needs.
- Solving assigned problems of national or regional priority.

3.1 Variety improvement

Breeding new varieties of DWR for the extremely diverse environment is a great challenge to rice breeders. It is difficult to attain the genetic potential of a DWR variety because of the range of constraints that occur during the season. A theoretical example is given in Figure 3. Under ideal conditions a variety may be genetically capable of yielding 6.5 t/h. The series of favourable and unfavourable events during the season, however, can affect the number and size of stems produced per unit area and determine the eventual number and size of grain bearing panicles. Consequently the achieved yield may be less than a third of the potential.

It is obviously not feasible to select a single genotype for all or even most of the traits needed for the different environments. Each trait for which selection is practised reduces the effective size of the breeding population. Inclusion of non-essential traits therefore needlessly loads the breeding program and reduces the output of superior types. Then there are ‘competing’ characters involved in the different strategies of flood adaptation. For example, submergence tolerance and elongation ability represent opposite mechanisms for flood adaptation. Many attempts to combine them fully in a single plant have failed.

On the other hand, breeding appropriate high-yielding rice varieties is considered the most favourable, effective, and efficient means to increase rice production under adverse environmental conditions. Most rice producers have limited resources and inputs such as fertilisers and chemicals are expensive. In contrast, seeds of new cultivars can be readily distributed among growers who seek crop improvement. Furthermore, rice cultivation that is less dependent on chemical inputs ensures an ecosystem that is potentially more sustainable (Senadhira, unpublished).

Good understanding of the target environment is important. Environmental characterisation will indicate whether there is potential for increasing production by improved varieties and/or management. Farmers grow only the varieties with highest adaptability and stability. If their varieties have defects that constrain yield, e.g. susceptibility to pests and diseases, or that do not allow high production (poor plant type), the potential for improvement is high. However, farmers often do not accept new varieties if they require different or improved management practices. Each replacement should possess the ability to produce higher yields than presently grown types, under the same management practices, but should also be responsive to introduction of improved management.

Improving existing varieties is a logical approach, but there are constraints. Floating rice varieties in very deep flood areas do not show much potential for improvement. Transferring their good traits to other varieties could be more promising. For intermediate depths a new deepwater rice plant type has been developed where need-based elongation (only elongate if water is deep) and erect leaves are the main features. The new plant type has the appearance of a semi-dwarf high yielding variety in shallow water and is expected to perform better than present varieties up to maximum water depth of about one meter.

Prototypes of this new type have been developed in Thailand and at IRRI. Huntra 60, IR11141-6-1-4, and RD19 are close to this plant type except for their leaf characteristics, and have good yield. In an experiment designed to reduce the effect of environmental differences, the DWR variety Huntra 60 and the irrigated variety IR72 were grown in adjacent ponds. Huntra 60 (maximum water depth 80 cm) yielded 5.3 t ha-1, not significantly different from the 5.8 t/ha of IR 72 in 10 cm water (Mazaredo et al. 1996). This experiment established that a DWR variety could produce comparable yields to a high yielding irrigated variety despite growing in deep water.

The demand for new varieties is a continual process because of need for increased productivity, quality, and more resistance to pests and diseases. In the DWR ecosystem many factors influence variety improvement, but because of its relatively small extent, policy makers often consider DWR as a low priority crop. Furthermore, harsh soils, floods and climatic stresses make many people think that rice in this ecosystem is impossible to improve.

Success in developing better varieties through hybridisation depends entirely upon the efficiency of evaluating segregating populations. Traits most important are elongation, survival of temporary submergence, and resistance to drought, salinity, P deficiency, Zn deficiency, Fe toxicity, and Al toxicity. Traits common to all rices such as resistance to major pests and diseases, and grain quality are also important. Relative importance of these traits differs from one target environment to another, and essential traits must be prioritised for selection purposes.

Because DWR is grown only during the wet season the breeding cycle is very long. Natural field conditions must be used for selection and the degree of stress; for example depth and duration of floodwater, is always a major problem. Under such conditions, effective selection can be done only when the stress level is appropriate, and development of new varieties takes many years. Irrigated rices such as IR8 and IR36 were released after 4-5 years, but a DWR variety such as HTA 60 has seldom been released in less than 10 -15 years. The extreme is the variety ”Prachinburi 1” which was tested in Thailand for 22 years before its official release as a recommended variety in September 1998. It started as a composite cross from F2 seed of 29 crosses of DWR+FR with RLR+IR lines at Suphanburi Rice Experiment Station in 1976 and became the fixed line SPR76 com3-5-2 in 1979. Research station trials were followed by farmer field trials in 1986, after which there was extensive testing for N response and pest resistance (Blast, BPH, GLH + SB) before the production of Breeder Seed and Foundation Seed. This is an extreme example, partly determined by over-strict requirements by official release committees.

3.1.1 Selection methods

Pure line selection has been the start of many breeding programs in Asia, and can give rapid payoff for the breeder. Pure line selections are usually made directly in farmer’s fields from materials already well adapted to local conditions, but which are genetically variable. It is a rapid, straightforward method giving uniformity and yield increase of up to 10-15 percent, but larger gains are unlikely. Varieties such as Pin Gaew 56 (released in 1956) and Leb Mue Nahng 111 (released 1959) were developed through this procedure.

The pedigree method is most effective when there are clear breeding objectives and adequate resources. This method has been followed at IRRI and in Thailand and other research centres in Asia. As for other cultural types of rice, DWR pedigree lines are tested concurrently for resistance to diseases and insect pests, and for tolerance to appropriate deepwater stresses. Selection and screening for essential characters like submergence tolerance and elongation ability should be conducted under both natural and controlled conditions. RD 19 was developed through this method.

Bulk breeding is a reliable, time-honoured method that is simple and labour saving. Formerly it was less commonly used in the tropics but effective new techniques and better facilities, especially controlled water tanks, have made it a standard method for working with large numbers of rice progenies when breeding for submergence tolerance and elongation ability. Bulk populations can be grown under stress conditions and the surviving plants bulk harvested. The advantage of this method is that it is easy to manage and requires few resources. It is particularly effective when selection pressure is high, as undesirable genotypes are naturally removed from the population. Surviving plants are transplanted into regular shallow-water fields for further evaluation or, in the case of early maturing elongating deepwater populations, are harvested direct from standing water. The bulk and modified bulk selection procedures can be extended to the F3 generation, increasing the capacity to handle and select from large populations.

Re-selection was used in Thailand to improve grain quality of RD19, which was derived from a cross between IR262-43-8-11 (a semi-dwarf high yielding line) and Pin Gaew 56 (traditional floating rice of Thailand). Under shallow water conditions RD19 appears similar to a modern semi-dwarf but can elongate in water rising up to about 1-m depth. But despite good yield, farmer acceptance of RD19 has been extremely poor because of its high grain chalkiness. Re-selection begun in 1987 using 1,400 individual plants resulted in four new lines with yield comparable to the original RD19 but with chalkiness reduced to about one fifth (Kupkanchanakul, unpublished).

3.1.2 Photoperiod sensitivity.

Deepwater rice is grown from the equator to 29^{o} N and daylight ranges from 10 to 14. Most varieties are photoperiod sensitive, meaning that date of flowering is affected by day length. Varieties have a minimum photoperiod (day length) for inducing reproduction and a longest photoperiod beyond which they cannot produce panicles (Vergara and Chang, 1976). For example, the time to flowering of Leb Mue Nahng 111 from initiation of treatment was 60 days with 10 hours light each day, but 126 days with 12-hour light. The advantage of photoperiod sensitivity is that it determines flowering date in relation to day length and not length of the growing season. It is one of the most important traits determining the adaptability of deepwater rice to different areas because it induces properly selected varieties to flower after the flood water level reaches its peak. Unfortunately photoperiod sensitivity is also a barrier to transfer of productive deepwater rices between countries. When introduced varieties have different maturity than local varieties it is very difficult to make crosses between the introduced varieties and local rices to produce improved types. If Thai varieties are planted in India they flower too late, after mid December, when low temperatures cause sterility and reduce yield. Conversely, varieties from India and Bangladesh introduced into Thailand are induced by daylength to flower much earlier than normal, as early as September when the water is still rising. The panicle may be submerged and the grain spoiled or eaten by fish.

3.1.3 Breeding for improved elongation ability

Differences between varieties in elongation ability usually become noticeable at about 80-100 cm water depth, and there has been no easily identifiable indicator other than plant length (stem and leaves). Prechachart *et al.* (1975) developed a pond method for screening large numbers of lines under controlled conditions, in which plants were scored on ability to maintain foliage above the water level. Most screening is now done with large plant populations in ponds. However, scoring is a subjective method, and Waitruardrok et al. (1992) proposed direct measurement 2-4 days after cutting at the water surface. This can be done in shallow water, for example 60 cm, and give a rapid and measurable result which can be analysed.

Elongation ability is a stable and heritable trait. The number of internodes and length of culm elongation in DWR appear to be controlled by different genes (Morishima 1975). Supapoj *et al.* (1977) reported that populations from crosses between floating and non-floating varieties segregated with only a small portion of true floating type and more of intermediate types. Hamamura and Kupkanchanakul (1979) identified partial dominance and multigenic nature of floating ability. Nasiruddin *et al.* (1982b) suggested multigenic control but were not certain of its degree of dominance. In some crosses, partial dominance was indicated, but there were cases where dominance was found. They also suggested that hybrid populations should be flooded for a short period only and that the parents, F1 and F2 be grown in the same environment to avoid variation. Tripathi and Balakrishna Rao (1985) reported that a single dominant gene controlled early nodal differentiation.

Suge (1988) examined the genetic behaviour of internode elongation in relation to ethylene and giberellic acid. F_1 plants of a cross between elongating and non-elongating types showed intermediate values for internode elongation and for ethylene concentration. Suge considered that there are two complementary major genes, one controlling GA3 production and another controlling responsiveness to ethylene.

Thakur and HilleRisLambers (1989) studied two F2's involving floating rice and non-elongating semi-dwarf, four F2's involving floating rice and an elongating semi-dwarf, and two F2's involving elongating and non-elongating semi-dwarf parents with 20 day-old seedlings. They reported that floating rice combinations with non-floating semi-dwarf parents segregated into a ratio of 9 elongating and 7 non-elongating.

Dwivedi and Senadhira (1993) reported estimates of genetic parameter by diallel and generation mean analysis revealed the importance of additive and non-additive gene action with preponderance of additive gene action. Involvement of at least one group of genes for plant elongation was detected. However, positive and significant dominant and dominant x dominant effects indicated the presence of complementary type of epistasis. It implied that genetic control of this trait could be affected by different gene action in different crosses, depending upon the genetic background of the parental lines.

3.1.4 Breeding for submergence tolerance

Although submergence tolerance and elongation now appear to be partly exclusive traits, there has been much screening for submergence tolerance of DWR lines. It is particularly important for tall non-elongating DWR varieties exposed to flash floods in early growth. A simple mass screening method for submergence tolerance using controlled water level in ponds was developed in Thailand (Boonwite *et al.*, 1977; Supapoj *et al.*, 1979). Mass screening in ponds is now the most common method for testing submergence tolerance. Seedlings 30 days old are transplanted in the pond and 30 days after transplanting, the pond is filled to 150-cm water depth for 10 days or until the death of a susceptible check. Submergence tolerance scoring is done immediately after draining water and 14 days later.

Existence of genetic differences for submergence tolerance in rice germplasm has been reported by many (e.g. Ramiah and Rao, 1953). A systematic screening of the world rice collection at IRRI and elsewhere has resulted in identification of some traditional submergence tolerant rice cultivars. Segregation analysis indicated that at least three dominant genes are involved for controlling submergence tolerance; two with duplicate gene action, while the third is complementary to either of the first two. At least one major gene, a closely allied group of genes, or at least two dominant genes was involved. All of the investigations found highly significant additive and non-additive gene effects (Senadhira, unpublished)

3.1.5 New techniques and novel germplasm

Since DWR cultivars are usually subject to flood and complex abiotic stresses associated with acid sulphate soils, salinity, iron and aluminium toxicity, and zinc and phosphorus deficiency, the traditional varieties grown under these conditions possess tolerance for many of the stresses. However, most lack high-yielding traits such as broad, erect, dark leaves or many productive tillers with heavy panicles. Transfer of appropriate traits from high-yielding genotypes to traditional cultivars and the incorporation of stress tolerance would increase the yield potential. Hybridisation between two types can develop desired types, but the efficiency of selection of segregating populations for tolerance for abiotic stresses is so slow that there has been little progress in variety improvement.

The rapid development of DNA marker technology provides great opportunities to use the new tools and minimise screening problems. Some agriculturally important genes for photoperiod sensitivity and resistance to blast, bacterial blight, and tungro have been mapped. However, actual application of marker-aided gene transfer is yet very limited. In the next decade or so, it is expected that DNA markers will be available for major abiotic stresses and also less expensive procedures.

Marker-aided selection (MAS) techniques can increase selection efficiency to as high as 100% and permit simultaneous selection for a number of traits. They offer great opportunities for dealing with abiotic stresses. Cultivars needed for developing the techniques have been identified, but the DNA-level polymorphism between traditional cultivars and other yield-improving types will determine the rate of progress. For example, the mechanisms of tolerance to flood, zinc deficiency, and iron toxicity must be determined to accelerate the development of MAS for those stresses. Advances could lead to enhanced tolerance levels by pyramiding different mechanisms to produce novel genotypes.

Even in a small-scale breeding program, there are thousands of plants to evaluate. Evaluations under controlled conditions done at later breeding stages are very expensive and MAS can reduce costs to less than one tenth. Furthermore, the technique requires less capital expenditure, is very rapid (2-3 days compared with many seasons by field technique), highly reliable, and can be used simultaneously for other traits (Senadhira, unpublished).

Improved rice varieties with high available nutrients for human consumption such as iron and zinc could also provide better nutrition to even the poorest people. One recently developed rice variety has good yield and shown high bioavailability of the iron in feeding trials with rats (Graham et al. 1998). This must now be confirmed for humans. However, more adapted high micronutrient varieties must be proven in order to fit the many different environments in rice producing areas, with careful trials to measure the extent to which iron-rich rice can reduce iron malnutrition in rural communities. Deepwater rices from coastal areas of Bangladesh are a source of iron and zinc efficiency.

3.1.6 Collaborative plant breeding

Collaboration between researchers in Asia has been valuable in developing techniques and genotypes for improving the yield, yield stability and nutritive value of deepwater rice. Potential outputs include marker aided selection techniques (MAS) for genotypes for excess water- and soil-related stresses, novel genotypes for increasing yield and improving yield stability, and rices with high available iron and zinc content in the grain to help combat iron and zinc malnutrition in humans.

But plant breeding is but one input into a complex system that includes a wide range of socio-economic conditions. There are very limited resources available for research on the DWR ecosystem in any one country, hence international co-operation and appropriate funding can make a major difference to the rate of progress and impact.

3.1.7 Grain quality

In Thailand traditional DWR is considered of poor grain quality owing chalkiness which lowers milling recovery. The Thai DWR breeding program has concentrated on improving grain quality, aiming for translucent grains with a minimum length of 7.0 mm. Nearly all new lines in the Thai breeding program have good grain quality. One promising line with good grain quality, good cooking, tall stature, and photo-period sensitive flowering time about end October ~ 10 days after KDML105 at PCR is suitable for both rainfed lowland and deepwater areas of 50-100 cm where fields are dry by the end of November. Other promising lines from mutation breeding using Gamma rays have clear grain, better milling characteristics, more resistance to blast disease, and have essential DWR traits. Examples are HTA60'93 G1-66-10, HTA60'93 G1-67, and PNG'93 G1-73-18.

3.2 Crop nutrition

The deepwater areas act as a natural release for floodwaters from the rivers, and retain many of the natural nutrients that would otherwise be washed into the sea. Adapted DWR varieties, which have been used for centuries and produce around 2 t/ha of rice without added fertilisers, reduce the level of nutrients in floodwater spreading out from rivers to almost negligible levels (Setter *et al.* (1987a).

Roy (1975), in a review of several hundred trials in Bangladesh, concluded that traditional DWR varieties generally do respond to fertiliser, but that the degree of yield response varies with soil conditions, the extent of flooding and rainfall in the pre-flood period. In some DWR areas fertiliser application tends to increase dry matter production but not grain yield (Francis, 1983; Jugsujinda *et al.* 1982; Puckridge and Thongbai, 1988). In other areas there can be good response, but generally DWR farmers apply little fertiliser. In a survey of 52 Thai DWR farms Puckridge et al. (1994) found that fertiliser applications were mostly small amounts of N and P, with the highest rates used on acid sulphate soils. Only three farmers used more than 40 kg N ha^{-1}, 35 averaged 23 kg ha^{-1} each of N and P, and seventeen did not apply fertiliser at all. Fields with fertiliser, usually a combination of N and P, averaged about 30 % higher yield than unfertilised fields on the eastern plain, but effects of fertiliser could not be separated from effects of cultural practices and environment.). Plant analysis showed that most of the N was accumulated during flooding, and that nitrogen uptake before flooding averaged only 15 kg ha^{-1}, and was not directly correlated with grain yield. Rainfall, soil type, drought, and variety affect crop production in DWR and understanding nutrient balances in these ecosystems is difficult.

On-station experiments with different N rates in two DWR areas in Thailand indicated a marked reduction in yield if plant N before flooding was less than 20 kg N ha^{-1} (Puckridge *et al.* 1991). On acid sulphate soils at Prachinburi Rice Research Centre Wiengweera *et al.* (1988) showed that yields of DWR increased about 80% with 75 kg N ha^{-1}. A problem for such experiments is the extreme variability brought about by the long growing season, soil variability, water depth changing with date and season, and genetic differences in height of plants that makes it difficult to obtain consistent statistically significant effects. An example is given in Figure 4. Despite careful maintenance the experiment had high variation (C.V. = 29%). Maximum water depth was around 100 cm. The interaction (entry x treatment) plot yields, means of three replications, ranged from zero to 401 g/m^2 ($P < 0.01$). The treatment means of 141 to 251 g/m^2 ($P < 0.01$) indicate the effectiveness of nitrogen application, but even though the acid soils are generally responsive to phosphorus it did not show much effect in this trial, probably due to residual effects of previous application. Average effects over seasons determine the economic effectiveness of fertiliser applications.

In the western delta, where DWR farmers generally do not apply fertiliser, dry matter production (biomass) and yields are relatively high and fertiliser responses often small and unpredictable (Puckridge and Thongbai, 1988). To produce high yields in unfertilised fields that have been continuously cropped for centuries there must be alternative sources of nitrogen. Vacharotayan and Takai (1983) analysed river water and calculations from their data indicate that one meter depth of river water entering the fields in Thailand would provide around 13 kg N, 1.6 kg P, and 42.9 kg K ha $^{-1}$. Another source could be biological fixation. A large part of the DWR plant is under water, offering a larger biomass for colonisation by aquatic microorganisms than rice in shallow water. Kulasooriya *et al.* (1981) estimated by extrapolation from pot studies that organisms such as blue-green algae living on DWR could fix about 10-20 kg N ha^{-1} crop^{-1}. Algal populations tend to be higher in less acid floodwater (Whitton and Catling, 1986). Puckridge et al. (1994) found a trend for increased N uptake during flooding as the pH increased from 5.8 to 7.5, but further information is needed on these topics.

The introduction of the new plant type is expected to result in higher yields, and to be more efficient in utilisation of both natural and applied sources of nutrients. But fertiliser response will still be difficult to predict. How is plant N uptake related to soil type, high or low producing fields, and the pre-flood and flood periods? When farmers do not apply nitrogen to DWR is it an economic decision, a yield limitation or an indication of natural sustainability?

3.3 Multiple cropping

Although crops such as mungbean, corn and sesame are commonly grown after DWR in Bangladesh, this practice is limited in Thailand due to lack of irrigation or appropriate soils with stored water. However, in the western plain the pre-flood period of 3-4 months from the beginning of wet season to the time of arrival of flood has good potential for non-rice crops with short growth duration and drought resistance. Kupkanchanakul *et al.* (1988) reported promising yields of sunflower, mungbean, sesame, and cowpea and baby corn, with DWR broadcast into the field crop before maturity. The crop characteristics for pre-flood production in intercrops with deepwater rice are short growth duration of less than three months, tolerance for drought and water logging, vigorous seedling growth and development, and high local market demand. Both field mungbean and sesame crops have good local markets. Although sunflower can give good yields, the low price of the harvested product in Thailand compared with the high cost of hybrid seed and cultural practices makes it less attractive. The strong sunflower stems also need to be removed from the field otherwise they are a problem in harvest of the rice crop.

The cropping system experiments reported below were conducted for four years, 1988-1991, at the Huntra Rice Experiment Station near Ayutthaya, Thailand (Puckridge et al 1990b, Sattarasart et al. unpublished). The soil at Huntra is a Thio-gypsic Tropaquept of Ayutthaya series (Motomura et al., 1979), a silty clay moderately high in organic matter and with moderate fertility. The soil is acid with pH 5.0 to 5.5. The topography is flat and drainage is poor, typical of much of the delta.

Deepwater rice, mungbeans (*Vigna radiata*), sesame (*Sesamum indicum*) and sunflowers (*Helianthus annuus*) were sown in randomized complete block experiments with four replicates. Details of sowing and emergence dates, flood arrival and harvest dates are given in Table 1. Deepwater rice was sown as a sole crop or mixed with a field corp. There were two times of sowing of DWR, either broadcast at the same time as the field crops (initial sowing) or broadcast onto the soil surface in standing field crops near their harvest (delayed sowing). The date of the second sowing of DWR depended on the stage of development and density of the canopy of the field crop and the rainfall. This date determined the stage of growth of the DWR for survival when the flood arrived. Soil preparation consisted of one ploughing with a 7-disk plow followed by two or three passes of a spring-tine harrow to level the soil and provide an even seed bed. There was no additional tillage for the second sowing of deepwater rice into the field crops, but manual hoeing roughened the soil surface of the bare plots of the deepwater monoculture.

The DWR cultivar was Huntra 60; sesame was a local variety of red sesame; and sunflower the hybrid Hysun 33. The mungbean cultivar Uthong 1 was used in 1988, and Kampangsaen 1 in 1989-1991. The seed rate was 125 kg ha^{-1} for broadcast DWR and 19 kg ha^{-1} for broadcast sesame. For broadcast munbeans the rate was the recommended rate of 19 kg ha^{-1} in 1988, but establishment was poor. The rate was increased to 31 kg ha^{-1} in 1989 and 1990, but dense foliage of the mungbean depressed the DWR plant population and the rate was reduced to 19 kg ha^{-1} in 1991. Mung beans and sesame in rows were sown to give approximately 2 cm between plants. Sunflowers were 50 cm between plants within rows 75 cm apart. Fertilizer rates followed local extension department recommendations for crop production, using 69-87-0 N-P-K kg ha^{-1} applied to DWR monoculture and 52-23-43 to the field crops. Monocrotophos 0.1%, was applied for control of insects each week between 30 and 75 days after emergence. Weeds were removed by hand from the field crop plots, and 2,4-D was applied in DWR before flooding for control of broad leaf weeds. Plot size was 8m x 8m. The harvested area was 6m x 6m for mungbeans, sesame and deepwater rice, and 6m x 6.75m. for sunflower. Treatments are listed in Table 2. The “paired rows” indicate two rows of field crop alternating with two rows deepwater rice, or two rows of a field crop alternated with a two-row space for treatments in which deepwater rice was broadcast. “One row” indicates single rows spaced 50 cm apart for mungbeans and sesame, or 75 cm apart for sunflowers. In the first year water-logging on the heavy soils affected plant growth. In the third and fourth years drains 20-30cm deep and 9 m apart excavated between plots to remove surface water after heavy rains prevented the problem

Over the four years of trials competition from DWR in mixed crops reduced the yield of mungbean by 27% or the yield of sesame by 43% compared with a crop without DWR (Table 2). Competition in mixed crops is for water, light and nutrients, and the small sesame seedlings may be less competitive in the early stages than mungbean. Sunflower, with wide spacing between rows and tall vigorous plant habit, is a strong competitor and its yield was reduced only 13% by DWR competition. The main constraint to production of sunflower was low percentage establishment. Over three years competition from field crops sown with the rice reduced DWR yield by 5% to 14%. The highest DWR yields were when mixed with mungbean, even though mungbean appeared to be more competitive than sesame. With delayed sowing of DWR into the standing field crop, poor establishment of DWR due to competition for light and water reduced DWR yields by as much as 40%. The complete loss of DWR due to the sudden rise of floodwaters in 1990 emphasised the value of including the field crops in the cropping system. Risk of failure of the DWR was higher with delayed sowing, and is not recommended despite the higher yield of field crops. Sowing both crops together gave good establishment and is best for areas where floods come early. Although establishment of field crops was better in rows, broadcast yields were equivalent and used less labour.

Although the area of Thailand reported here has favourable conditions, to date little use has been made of the obvious potential. Near urban areas there are alternative work opportunities, and little economic pressure for increased input. However, as mechanisation increases this situation may change. In NE India, the economic situation is different, and farmers are adding other crops to their deepwater rice. In Bihar over the four years 1986-89 the net return after expenses for rice with mungbean was 2.17 times that of rice alone, and sesame with rice gave 3.83 times the return of rice alone (Thakur et al 1994). The return was even better with sesame, where the rice equivalent yield of rice with sesame was 3.65 t ha^{-1}, compared with 1.98 t ha^{-1} for rice alone.

Although field crops under natural rainfall can be successfully grown in the western delta, in the south-eastern delta many farmers grow short duration rice before or after flooding. Depending on the flooding pattern they are grown March-April to July-August or November to March, leaving the fields fallow during the flood. Some farmers follow the off-season rice crop with DWR. Unfortunately, in this year 2000, flooding caused severe damage to the early rice.

4 Future prospects

The major reductions in deepwater rice appear to have already taken place. Farmers are still growing DWR rice in their fields and anything that can be done to increase crop production will be of great social and economic benefit. Increased production will not come solely from improved DWR varieties. There is a complex interaction between all facets of production which affect realisation of the potential of each component of the system (Figure 5). The achieved production and community welfare will depend on how these components are integrated. Socio-economic analyses can be of great value in establishing priorities. Such analyses should determine biophysical and socio-economic constraints to productivity, priority research, and the social benefit costs of alternate land use practices. The effect of different land use patterns on productivity, employment and sustainability in flood-prone ecosystems is an important policy question. Infrastructure developments – communications, roads and electricity – provide alternative occupation possibilities which generate cash for improved crop management. Enhancing the sustainability of deepwater ricelands and developing appropriate soil and water management techniques will increase productivity, sustain natural resource quality and reduce poverty

In DWR areas the water regime – flood and rain – will continue to be the dominant factors. Conventional breeding and selection activities have difficulty in differentiating between flod, nutrient imbalance effects and other yield limiting factors, so it has been difficult and meet the objectives of breeding programs. However, based on successful research to date it is expected that yield potential of DWR areas for rice and other crops can be raised. A main objective of breeding research is to develop molecular marker aided selection procedures and protocols for mass screening for tolerance to flooding and adverse soils. Improved nutritional quality of grain is desirable by-product with great potential. Improved varieties such as Prachinburi 1 and Plai Ngham Prachinburi should be promoted and spread widely. They are not spreading because of the high price of seed and a preference of farmers to exchange rather than to purchase foundation seed. Such exchange is not provided for in official regulations.

Acknowledgements

Grateful acknowledgement is made for contributions of R. Thakur, J. L. Dwivedi, S. K. Bardan Roy, S. B. Mishra, and the late D. Senadhira for information originally submitted for the monograph “Breeding Flood-prone Rice” (Puckridge and. Senadhira 1995). Special thanks also to H. D. Catling for providing information for the section on pests and diseases and writing the book “Rice in Deepwater” which is an inspiration to all workers in flood-prone ricelands.

References

Ahmed, M.S., Mian, Y, Haque, E. and J.E. Brooks. 1986. Rat damage characteristics and assessment methods in deep water *rice. Bangladesh J. Sci. Res.* 4(2), 131-46.

Bekhasut, P., Puckridge, D.W., Wiengweera, A., and T. Kupkanchanakul. 1990. Sequential elongation of internodes of Deepwater Rice at different water depths. *Field Crops Res.*, 24:195-209.

Bleecker, A.B., Rose John, S. and Kende. 1987. An evaluation of 2,5-norbornadiene as a reversible inhibitor of ethylene action in deepwater rice. *Plant Physiol.* 84:395-98.

Boonwite, C., Setabutara, C., Jackson, B.R., Prechachart, C. and P. Anugul. 1977. Screening for submergence tolerance using a deepwater pond. In *Proceedings of the 1976 Deepwater Rice Workshop, Bangkok, Thailand.* International Rice Research Institute, Manila. pp. 101-108

Catling, H.D. 1980. *Deepwater Rice in Bangladesh: a Survey of its Fauna with Special Reference to Insect Pests.* Deepwater Rice Pest Management Project, Bangladesh Rice Research Institute and Overseas Development Administration of the UK, pp. 100 (mimeo).

Catling, H.D. 1985. *An agro-ecological characterisation of the deepwater areas in the Chao Phaya Basin of Thailand with a subdivision into five regions.* International Rice Research Institute, Manila. Mimeo, 27 pp.

Catling, H.D. 1992. *Rice in Deep Water.* London: International Rice Research Institute and Macmillan Press. 542 pp.

Catling, H.D. and Z. Islam. 1982. The problem of yellow rice borer in Asian deepwater rice. In: *Proceedings of the 1981 International Deepwater Rice Workshop, Bangkok, Thailand* pp. 451-8. International Rice Research Institute, Manila.

Catling, H.D. and Z. Islam. I995. Studies on the ecology of the yellow stem borer, *Scirpophaga incertulas* (Walker) (Pyralidae), in deepwater rice in Bangladesh. *Crop Prot.* 14(l), 57-67.

Catling, H.D. and Z. Islam. I999. Pests of deepwater rice and their management. *Integrated Pest Management Reviews* 4: 193-229.

Catling, H.D., Boonyaviwatana, S. and R. Pattrasudhi. 1982a. Incidence of ragged stunt in floating rice in Thailand. *International Rice Research Newsletter 7(3),* 11.

Catling, H.D., Puckridge, D.W., Boonyaviwatana, S., Pattrasudhi, R., Kupkanchanakul, T., Tanasate, M. and P. Supapornhaemin. 1982b. Deepwater Rice crop-cuts for 1981. In: *Report of Deepwater Rice Planning Meeting, March 1982.* Department of Agriculture, Bangkok, pp 39-40.

Catling, H.D., Islam, Z. and R. Pattrasudhi. 1984-85. Seasonal occurrence of the yellow stem borer *Scirpophaga incertulas* (Walker) on deepwater rice in Bangladesh and Thailand. Agriculture, *Ecosystems and Environment* 12, 47-71.

Catling, H.D., Islam, Z. and R. Pattrasudhi. 1987. Assessing yield losses in deepwater rice due to yellow stem borer, *Scirphophaga incertulas (Walker)* in Bangladesh and Thailand. *Crop Prot.* 6 (1), 20-27.

Catling, H.D., Islam, Z., and L. Rahman. 1988a. Status of pests and diseases in Asian deepwater rice. In *Proceedings of the 1987 International Deepwater Rice Workshop*, Bangkok, Thailand. International Rice Research Institute, Manila. pp. 525-537

Catling, H.D., Islam, Z. and R. Pattrasudhi. 1988b. New methods of screening deepwater rice for yellow stem borer resistance. In: *Proceedings of the 1987 International Deepwater Rice Workshop, Bangkok, Thailand* pp. 539-49. International Rice Research Institute, Manila.

Catling, H.D., Puckridge, D.W., and D. HilleRisLambers. 1988c. The environment of Asian deepwater rice. In *Proceedings of the 1987 Deepwater Rice Workshop*, Bangkok, Thailand. International Rice Research Institute, Manila. pp. 11-34

Charoendham, P., Palaklang, W., Niyomvit, L., Prommanart, P. and N. Charoensilp. 1995. *Survey of Deepwater Rice Cultivation in Thailand 1992/1993.* Prachinburi Rice Research Center. Mimeo.

Choudhary, M. A. and S.M.H. Zaman. 1970. Deepwater rice of East Pakistan. Paper presented at the *International Rice Commission Working Party on Rice Production and Protection.*13th Session, Teheran, Iran. (1970). 19 pp. (mimeo).

DeDatta, S.K. and J.A. Malabuyoc.1988. Drought tolerance screening for deepwater rice. In *Proceedings of the 1987 International Deepwater Rice Workshop*, Bangkok, Thailand. International Rice Research Institute, Manila. pp. 199-208

Disthaporn, S., Catling, H.D., Chettanchit, D. and M. Putta. 1985. Effect of time of infection of rice ragged stunt virus on deepwater rice. Int. J. Tropical Plant Diseases, 3, 19-25

Dwivedi, J.L. and D. Senadhira. 1993. Inheritance of internode elongation in deepwater rice induced by treating seedlings with gibberellic acid. *Oryza* 30 (1):41-45.

Francis, P. 1983. Note on fertiliser responses in Bangladesh. *Deepwater Rice Newsletter*, International Rice Research Institute, Bangkok. 5 (2/83): pp.1-2.

Graham,R., Senadhira,D., Beebe,B., Iglesia,C., and I. Monasterio. 1998. Breeding for micronutrient density in edible portion of staple food crops: conventional approaches. *Field Crops Research* 60, 57-80.

Haloi, B. 1989. Physiological characters associated with deepwater rices. *Oryza* 26:168-172.

Hamamura, K. and T. Kupkanchanakul . 1979. Inheritance of floating ability in rice. *Japan. J. Breeding.* 29 (3):211-216.

Hyakutake, H., Zungsontiporn, S., Wanichananantakull, P., Supatankul, C., Vongsaroj, P. and O. Wonkasem. 1984. Distribution, habitats, seed germination and ecological characteristics of wild rice *Oryza perennis* and its response to herbicides. Report No. 2. National Weed Science Research Institute and Department of Agriculture, Thailand. 105 pp. (mimeo)

Inouye , J. and T. Hagiwara. 1982. Character association among isozymic genotype, grain type and phenol reaction of grains in Bangladesh floating rice varieties. *Japan J. Trop. Agric.*, **26**, 68-73

IRRI 1997. *Rice Almanac.* Second edition. International Rice Research Institute, Manila. 181 pp.

Islam, Z. 1992. Mortality of yellow stem borer, *Scirpophaga incertulas* (Walker), larvae and pupae in deepwater rice stem. *Bangladesh J. ZooL* **20**(2), 367-9.

Islam, Z. 1994. Key factors responsible for fluctuations in rice stem borer populations in deepwater rice ecosystems. *Insect Science and Its Application* **15**(4), 461-8.

Islam, Z., Catling, H.D. and Pojananuwong, S.. 1988. Attempts to control stem borer in deepwater rice with insecticides. In: *Proceedings of the 1987 International Deepwater Rice Workshop*, Bangkok, Thailand. International Rice Research Institute, Manila, pp. 551-8.

Jugsujinda, A., Satawathananont, S., Hirunyupakorn, W., Charoendham, P. and N. Kroppetch. 1982. Fertiliser management for deepwater rice soils. In: *Proceedings of the 1981 International Deepwater Rice Workshop*, Bangkok, Thailand. International Rice Research Institute, Manila, pp 365-372.

Kende, H. and I. Raskin. 1988. Growth and aeration in deepwater rice. In *Proceedings of the 1987 International Deepwater Rice Workshop*, Bangkok, Thailand. International Rice Research Institute, Manila, pp. 287-300.

Kende, H., Metraux, J.-P. and I. Raskin. 1984. Ethylene –induced growth response in submerged deep-water rice. In Fuchs, Y. and Chalutz, E. (Eds). *Ethylene: Biochemical, Physiological and Applied Aspects*. Martinus Nijhoff/Junk, The Hague, pp. 121-128.

Kulasooriya, S.A., Roger, P.A., Barraquio, W.L. and I. Watanabe. 1981. Ephiphytic nitrogen fixation on deepwater rice. *Soil Sci. Plant Nutr.*, **27**:19-27.

Kupkanchanakul, T., Puckridge, D.W., Thongbai, P., Petchrit, K., Kupkanchanakul, K., and A. Sattarasart. 1988. Pre-flood crop production in deepwater areas. In *Proceedings of the 1987 International Deepwater Rice Workshop*, Bangkok, Thailand. International Rice Research Institute, Manila, pp. 469-479.

Mazeredo, A.M., Laureles, E.V. and T.L. Setter. 1996. Growth and yield of modern deepwater rice: comparisons with modern irrigated rice. *Field Crops Research* **46**: 105-116.

Morishima, H. 1975. Floating ability as an adaptive character of the rice and its measuring method. In: Proceedings of the International Seminar on Deepwater Rice, August 1974. Bangladesh Rice Research Institute, Joydebpur, Dacca, pp. 109-114

Motomura, S., Seirayosakol, A., Piyapongse, P. and W. Cholitkul. 1979. Field observations and laboratory analyses of paddy soils in Thailand. Ministry of Agriculture, Forestry and Fisheries, Iabaraki, Japan, 363 pp

Nantasomsaran, P. 1995. Weeds in deepwater rice. Unpublished report. Department of Agriculture and Cooperatives, Bangkok, Thailand.

Nasiruddin, M., Ahmed, M.S., Zaman, S.M.H. and E. Haq. 1977. Effects of flooding on morphological characteristics of floating rice varieties of Bangladesh. In Proceedings of the 1976 Deepwater Rice Workshop, Bangkok, Thailand. International Rice Research Institute, Manila. pp.67-74.

Nasiruddin, M., Waheb, A. and B.A. Dewan. 1982. Genetics of plant and internode elongation in rice. In: *Proceedings of the 1981 International Deepwater Rice Workshop,* Bangkok, Thailand. International Rice Research Institute, Manila, pp.113-120

OAE 1991. Report on Survey of Major Rice Crop Year 1990/91. Office of Agricultural Economics, Ministry of Agriculture & Co-operatives, Bangkok, Thailand 1991.

Pattrasudhi R. and H.D. Catling. 1988. An epidemic of rice ragged stunt virus in deepwater rice in Thailand. In *Proceedings of the 1987 Deepwater Rice Workshop*, Bangkok, Thailand. International Rice Research Institute, Manila. pp. 563-567

Poche, R.M. and M.Y. Mian. 1986. Effectiveness of four rodenticides in deepwater rice. *Zeitschrift fur Angewandte Zoologie* **73**, 37-48.

Prechachat C, Sariqbutr A, Jackson B R (1975) Breeding improved rice for deepwater condition in Thailand. SABRAO 7(2):131-136.

Puckridge, D.W. and P. Thongbai. 1988. Fertilizer management in deepwater rice. In *Proceedings of the 1987 Deepwater Rice Workshop*, Bangkok, Thailand. International Rice Research Institute, Manila. pp. 387-406.

Puckridge, D.W., Chankasem, L., Vongsaroj, P., Thongbai, P. and S. Chinawong. 1988a. Effects of tillage and sowing methods on control of wild rice *Oryza rufipogon* in deepwater rice. In *Proceedings of the 1987 Deepwater Rice Workshop*, Bangkok, Thailand. International Rice Research Institute, Manila. pp. 593-598.

Puckridge, D.W., Panichagoon, P. and P. Thongbai. 1988b. Analysis of floodwater patterns. In *Proceedings of the 1987 Deepwater Rice Workshop*, Bangkok, Thailand. International Rice Research Institute, Manila. pp. 35-46.

Puckridge, D.W., Catling, H.D., Vonsaroj, P., Boonyawivatana, S., Niyomwit, L., and P. Thongbai. 1989. Factors affecting deepwater rice in the Central Plain of Thailand. *Field Crops Research*. **19**:263-283.

Puckridge, D.W., Kupkanchanakul, K., Peasaschar, K., Sripongpankul, S. and S. Runtan , 1990a. Influence of time of flooding on development of basal internodes. In: *Report of Deepwater Rice Planning Meeting 1990*, Department of Agriculture, Bangkok.

Puckridge, D.W., Sattarasart, A., Kupkanchanakul, T. and S. Runtan 1990b. Production of upland crop-deepwater rice intercrops with concurrent or delayed sowing of deepwater rice. In: *Report of Deepwater Rice Planning Meeting*, March 1990. Department of Agriculture, Bangkok, pp:9-12.

Puckridge, D.W., Wiengweera, A., Thongbai, P., Sangthong, P., Sattarasart, A., Kongchum, M. and S. Runtan. 1991. Nitrogen uptake by deepwater rice during the pre-flood and flooded phases, in relation to dry-matter and grain production. *Field Crops Research* ***27***:315-336.

Puckridge, D.W., Kongchum, M., Thongbai, P, Sattarasart, A., and S. Sinoupakarn. 1994. Nitrogen uptake and yield of deepwater rice in the Central Plain of Thailand. *Field Crops Research* **37**: 193-204.

Puckridge, D.W. and D. Senadhira (Eds). 1995. *Breeding flood-prone rice*. International Rice Research Institute, Manila. (mimeo 115 pp.).

Ramiah, K. and M.B.V.N. Rao. 1953. Rice Breeding and Genetics. *Indian Council Agri. Research Monograph 19*.

Rose-John, S. and H. Kende. 1985. Short-term growth response of deepwater rice to submergence and ethylene. *Plant Sci.,* **38**:129-134.

Roy, A.C., 1975. Soil characteristics and fertiliser response in the cultivation of Deepwater Rice in Bangladesh. In: *Proceedings of the International Seminar on Deepwater Rice, August 1974.* Bangladesh Rice Research Institute, Joydebpur, Bangladesh, pp 148-162.

Setter, T.L., Kupkanchanakul, T., Pakinnaka, L., Aguru, Y. and H. Greenway. 1987a. Mineral nutrients in floodwater and floating rice at water depths up to 2 meters. *Plant Soil* **104**:147-150.

Setter, T.L., Waters, I., Greenway, H., Atwell, B. J. and T. Kupkanchanakul. 1987b. Carbohydrate status of terrestrial plants during flooding. *In*: Crawford, R. M. M.. Ed.), *Plant Life in Aquatic and Amphibious Habitats*. British Ecological Society Symposium No. 5. Blackwell Scientific Publications, Oxford. pp. 411-433

Setter, T.L., Jackson, M.B., Waters, I., Wallace, I. and H. Greenway. 1988a. Floodwater carbon dioxide and ethylene concentrations as factors in chlorosis development and reduced growth of completely submerged rice. In *Proceedings of the 1987 Deepwater Rice Workshop*, Bangkok, Thailand. International Rice Research Institute, Manila. pp. 301-310

Setter, T.L., Kupkanchanakul, T., Kupkanchanakul, K., Bhekasut, P., Wiengweera, A. and H. Greeway. 1988b. Environmental factors in deepwater rice areas in Thailand: oxygen, carbon dioxide and ethylene. In *Proceedings of the 1987 Deepwater Rice Workshop*, Bangkok, Thailand. International Rice Research Institute, Manila. pp. 55-66.

Setter, T.L. and E.V. Laureles. 1996. The beneficial effects of reduced elongation growth on submergence tolerance of rice. *Journal of Experimental Botany* **47**(303), 1551-1559.

Siam Society. 1987. *The Customs of Cambodia*. A book translated into English by J. Gilman d'Arcy Paul from the French version by Paul Pelliot of Chou's Chinese original. Siam Society, Bangkok.

Somsook, S., Tongtavee, K., Catling, H.D., Keawta, T. and S. Hongnag. 1986. Survey of rodents and damage assessment in deepwater rice. Thai J. Agric. Sci. 19: 299-306.

Sugawara, T. and T. Horikawa. 1971. Studies on elongation of internodes in floating rice plants — morphological and histological observation [in Japanese, with English summary] *Bull. Coll. Agric Utsumomiya Uni.* **8**(1):25-46.

Suge, J. 1988. Physiological genetics of internode elongation in submerged deepwater rice. In *Proceedings of the 1987 Deepwater Rice Workshop*, Bangkok, Thailand. International Rice Research Institute, Manila. pp. 275-286

Supapoj, N., Setabutara, C., Kupkanchanakul, K. and E. Shuwisiku. 1977. Segregation for elongation ability in two crosses of floating rice with ordinary low land rice: 1. Estimation of heritability and implication of selection efficiency. In *Proceedings of the 1976 Deepwater Rice Workshop, Bangkok, Thailand*. International Rice Research Institute, Manila. pp. 29-36

Supapoj, N., Prechachat, C. and K. Kupkanchanakul. 1979. Screening for flood tolerance in the field. In *Proceedings of the 1978 International Deepwater Rice Workshop,* Calcutta, India. International Rice Research Institute, Manila. pp. 135-138

Takahashi, K. 1988. Hormonal regulation of internode elongation in rice shoots. In *Proceedings of the 1987 Deepwater Rice Workshop*, Bangkok, Thailand. International Rice Research Institute, Manila. pp. 245-255

Thakur, R. and D. HilleRisLambers. 1989. Inheritance of plant elongation ability at seedling stage in rice. *Euphytica* 41:227-233.

Thakur R, Singh A.K., Singh R S, Singh S S (1994) Development of sustainable deepwater rice farming systems in Bihar, India. Technical Exchange 3(2):7-9.

Tripathi, R.S. and M.J. Balakrishna Rao. 1985. Inheritance studies of characters associated with floating habit and their linkage relationship in rice. *Euphytica* **34**:875-881.

Vacharotayan, S. and Y. Takai. 1983. *Paddy nitrogen economy*. NODAI Research Institute, Tokyo University of Agriculture, Tokyo, Japan. 199 pp.

Vergara, B.S. 1985. Growth and development of the deepwater rice plant. *IRRI Research Paper Series*, Number 103, International Rice Research Institute, Manila. 30 pp.

Vergara, B.S., Mazaredo, A., De Datta, S.K. and W. Abilay 1975. Plant age and internode elongation in floating rice varieties. In: *Proceedings of the International Seminar on Deepwater Rice, August 1974.* Bangladesh Rice Research Institute, Dacca. . pp. 178-183

Vergara, B.S. and T.T. Chang. 1976. *The flowering response of the rice plant to photoperiod: a review of the literature*. Fourth Edition. International Rice Research Institute, Manila, 61 pp.

Vergara, B.S., Visperas, R., Peralta, J., Shuwisitkul, E., Karin, S., and S. Sophonsakulkaew. 1977. Screening for kneeing ability. In *Proceedings of the 1976 Deepwater Rice Workshop, Bangkok, Thailand*. International Rice Research Institute, Manila. pp. 123-124

Vongsaroj, P., Puckridge, D.W., Chinawong, S., and S. Chomvilai. 1988. Assessment of some weed control methods for deepwater rice. In *Proceedings of the 1987 Deepwater Rice Workshop*, Bangkok, Thailand. International Rice Research Institute, Manila, pp. 583-591.

Waitruardrok, T., Kupkanchanakul, K. and D. W. Puckridge. 1992. Influence of frequency of cutting on plant reserves and rate of elongation of deepwater rice. In: *Report of Deepwater Rice Planning Meeting 1992.* Department of Agriculture, Bangkok, pp 39-40.

Whitton, B. A. and H.D. Catling 1986. Algal ecology of deepwater rice-fields in Thailand. Arch. Hydrobiol., **105**:289-297.

Wiengweera, A., Puckridge, D.W., and P. Bhekasut. 1988. Testing Deepwater Rice for response to nitrogen and phosphorus. In *Proceedings of the 1987 Deepwater Rice Workshop*, Bangkok, Thailand. International Rice Research Institute, Manila, pp. 413-421

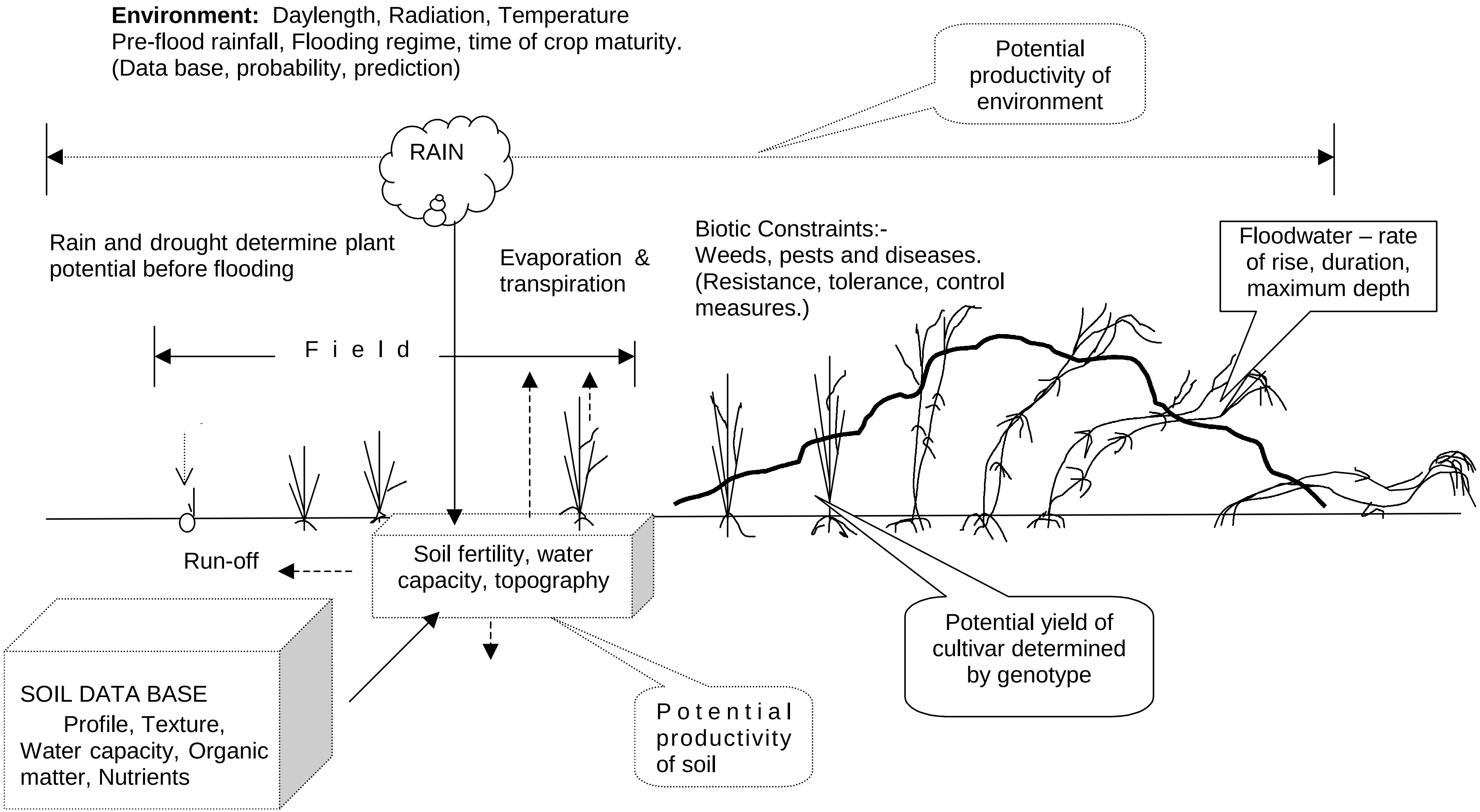

Figure1. Concepts of growth and production for a deepwater rice crop during the pre-flood and flooded phases indicating determination of eventual yield by environmental and biotic factors and genetic adaptability of the variety, with examples of data required to analyze the ecosystem

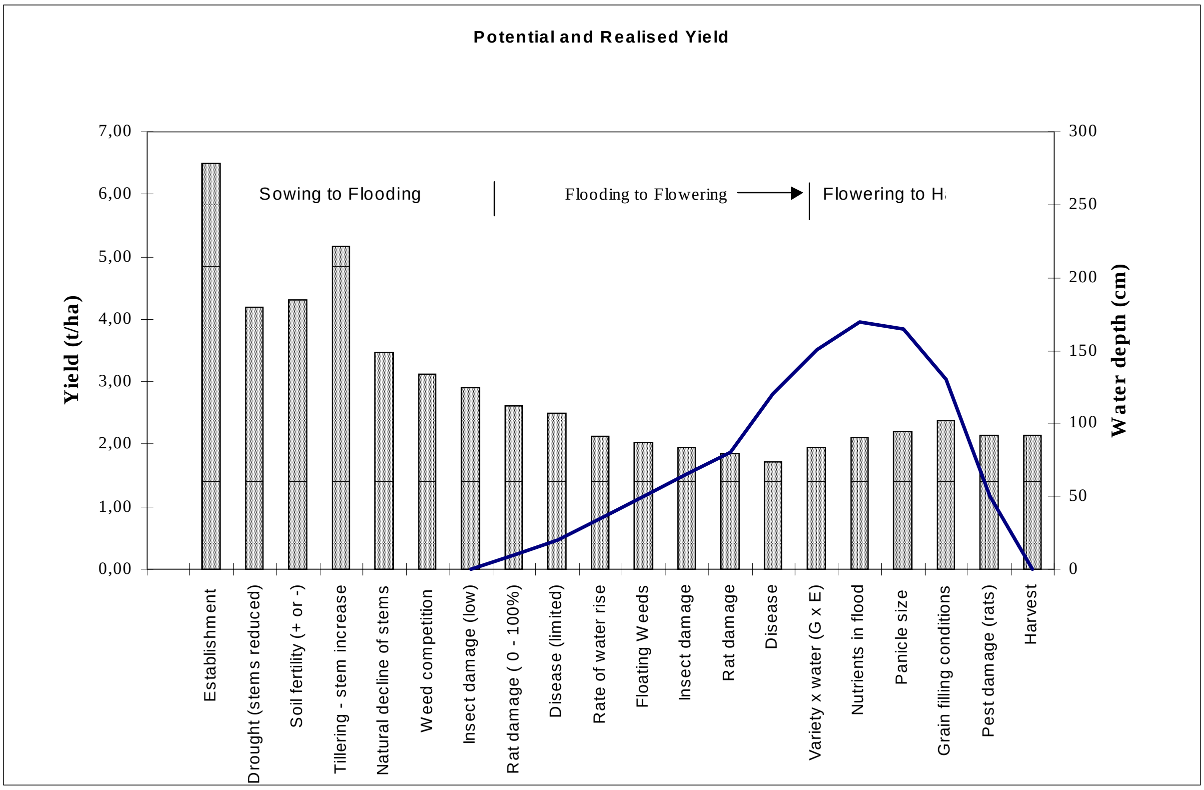

FIGURE 2. EFFECT OF FREQUENCY OF CUTTING ON MEAN ELONGATION (RATE OF INCREASE IN HEIGHT) OF 15 DWR ENTRIES AFTER REMOVING TOPS OF PLANTS LEVEL WITH THE WATER SURFACE AT 80 CM (MAXIMUM ELONGATION RATE WAS 16.8 CM PER DAY FOR LMN 111.) HUNTRA RICE EXP. STATION, THAILAND 1992.

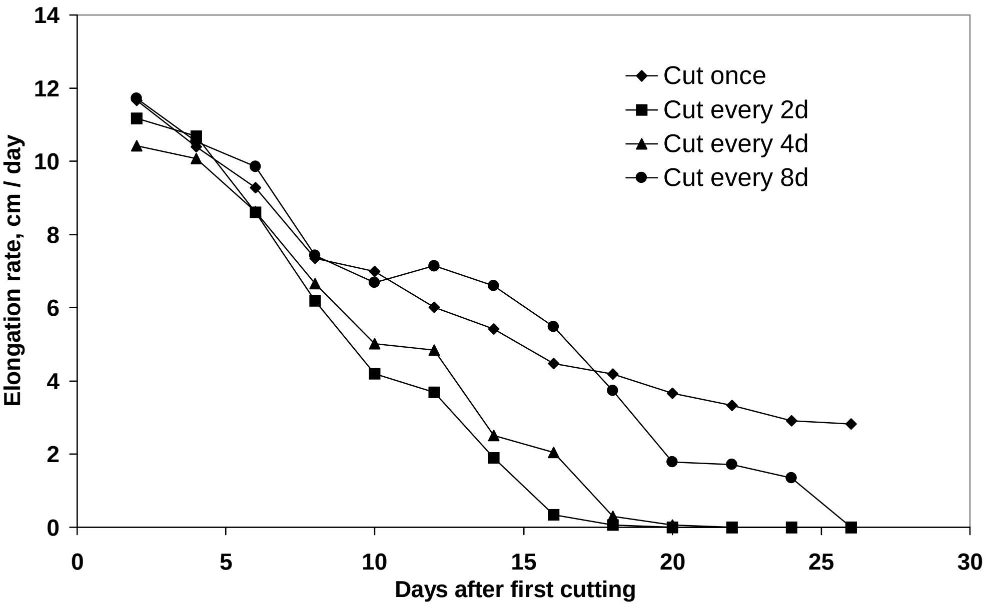

FIGURE 3. Illustration of the cumulative effect of a sequence of events on the eventual yield of a variety of deepwater rice which has a potential yield under ideal conditions of around 6.5 tons per hectare. The potential is shown by the bar at "establishment". Some events have a negative effect on yield, a

few have a positive effect, but all affect the final yield of the crop. The sequence changes from season to season. Minimisation of the negative factors (constraints) allows the crop to approach its potential..

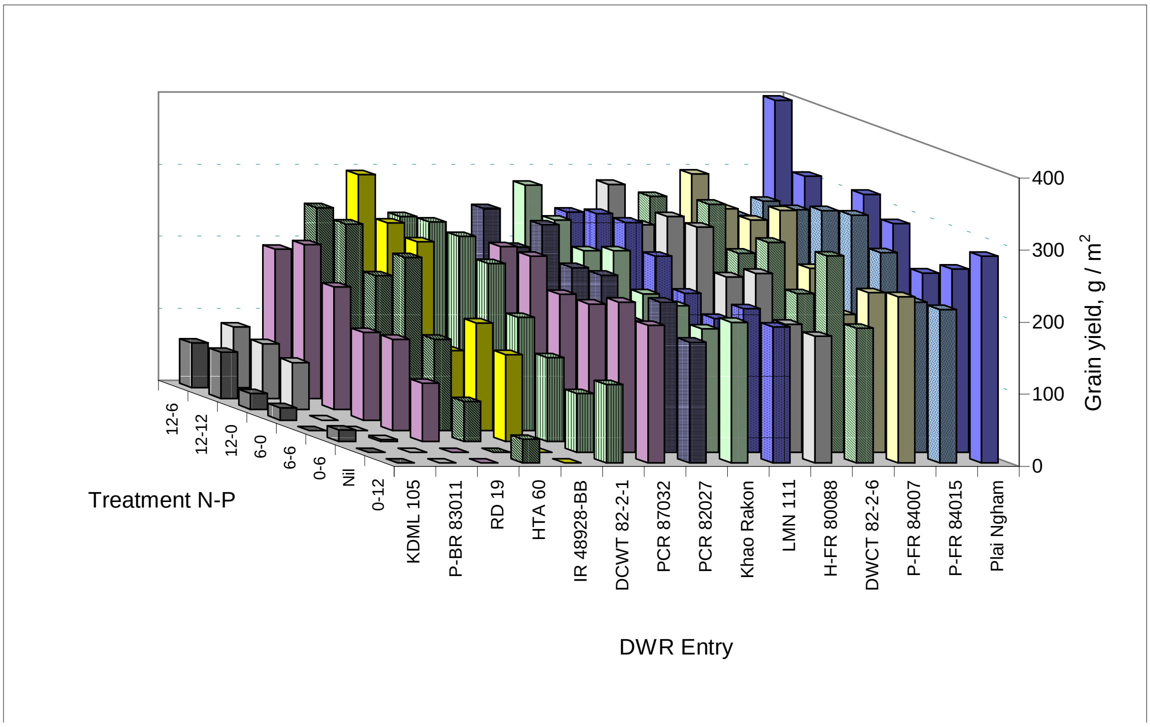

Figure 4. Yields of 15 DWR rice entries (mean of three replications) tested with eight nitrogen and phosphorus combination (N-P) showing their response to N and P and the extent of interaction. Plai Ngham was later released as a variety. Prachinburi Rice Research Center, wet season 1995.

Figure 5. The ultimate productivity of a system depends on the potential of each of the components and none can be viewed in isolation.

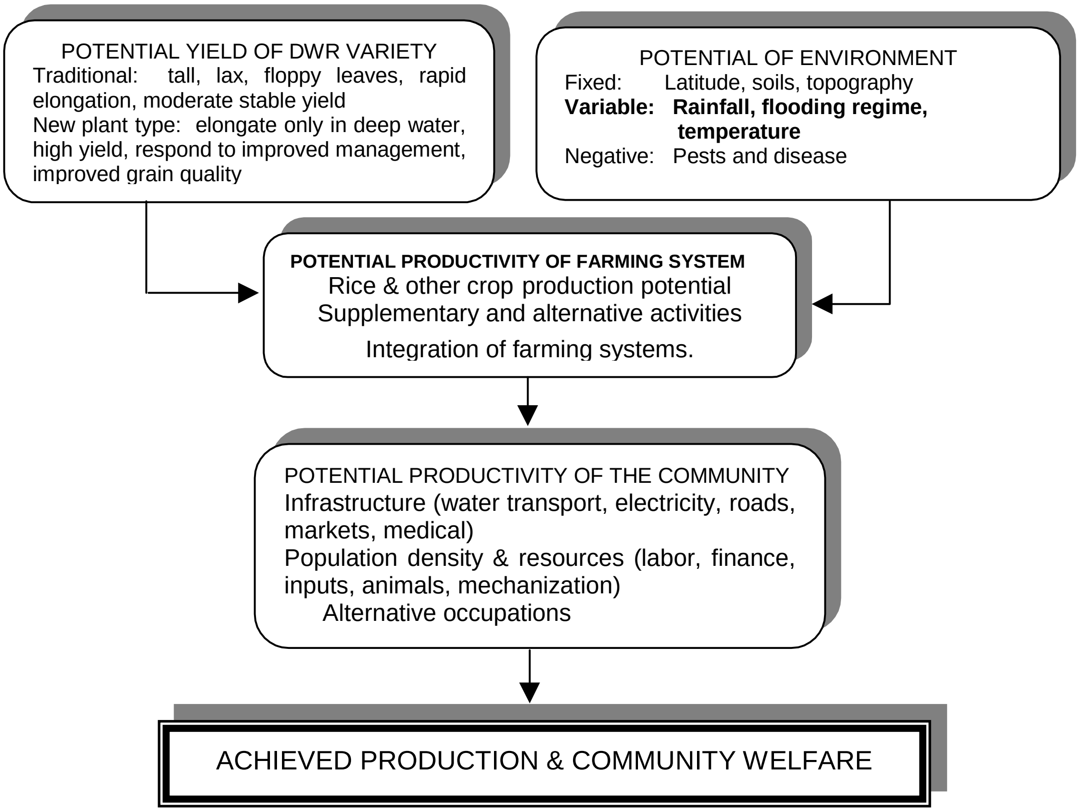

Table 1 Sowing and emergence dates, flood arrival and other cultural details for deepwater rice and field crops in inter-cropping experiments at Huntra Rice Experiment Station, Thailand, Wet seasons 1988-91.

	1988	1989	1990	1991
Date of first sowing (S1)	28-Apr	3-May	9-May	14-May
S1 plants emerged	7-May	15-May	15-May	27-May
Delayed DWR broadcast (S2)	11-Jul	30-Jun	18-Jul	8-Jul
Flood arrival date	27-Aug	28-Aug	7-Sep	9-Sep
Days after S1	121	117	121	105
Days after S2	47	59	51	63
Harvesting date				
Mungbean (3-4 times)	2-10 Jul	29 Jun-22 Jul	9-31 Jul	20 Jul-13 Aug
Sesame	16-Jul	31-Jul	4-Aug	13-Aug
Sunflower	2-Aug	3-Aug	10-Aug	23-Aug
Deepwater rice	3-Jan-89	2-Jan-90	Dec	28-Dec

Crop problems

1988 Insect damage and water logging of non-rice crops

1989 Drought, water-logging of non-rice crops, poor germination of DWR

1990 Poor germination of sunflower, DWR destroyed by sudden high flood.

1991 Poor establishment of sunflower, rapidly rising floodwater.

Table 2. Yield of field crops (kg ha-1) when grown as inter-crop rows or mixtures with DWR, or followed by delayed broadcast DWR, and subsequent yield of DWR (t ha-1). Huntra Rice Experiment Station, Thailand, Wet seasons 1988-91.

Treat.	Field crop	DWR	1988		1989		1990		1991	
	Type and Row spacing	Method, time sown	Field crop	DWR	Field crop	DWR	Field crop	DWR	Field crop	DWR
Rice alone										
1	None (check)	B'cast, 1	-	3.14 a-d	-	3.69 a	-	0	-	3.55 cd
2	None (delay check)	B'cast, 2	-	2.82 def	-	2.97 bcd	-	0	-	4.61 ab
Mungbean										
3	Pair 25 cm	Rows, 1	288 b	2.85 c-f	-	-	-	-	-	-
4	Pair 25 cm	B'cast, 1	299 b	2.86 c-f	894 d	3.40 ab	1,685 a	0	-	-
5	B'cast	B'cast, 1	173 b	3.41 a	1,214 bc	3.23 abc	1,279 c	0	286 c	4.12 abc
6	B'cast	B'cast, 1	-	-	1,299 ab	2.98 bcd	-	-	-	-
7	One 50 cm	B'cast, 1	-	-	991 cd	2.94 bcd	1,426 bc	0	736 b	4.68 a
8	Pair 25 cm	B'cast, 2	543 a	3.21 abc	1,503 a	0.72 f	1,491 ab	0	-	-
9	One 50 cm	B'cast, 2	-	-	1,400 ab	0.64 f	-	-	1,103 a	3.74 cd
Sesame										
10	Pair 25 cm	Rows, 1	383 b	2.57 f	-	-	-	-	-	-
11	Pair 25 cm	B'cast, 1	365 b	2.94 b-f	800 b	2.64 cde	631 b	0	-	-
12	One 50 cm	B'cast, 1	-	-	916 b	2.35 de	569 b	0	605 b	3.83 c
13	B'cast	B'cast, 1	-	-	-	-	809 ab	0	745 b	4.00 bc
14	Pair 25 cm	B'cast, 2	644 a	3.03 b-e	1,355 a	0.37 f	1,005 a	0	-	-
15	One 50 cm	B'cast, 2	-	-	1,528 a	0.46 f	-	-	1,185 a	3.13 d
Sunflower										
16	One 75 cm	Rows, 1	846 a	2.91 b-f	1,259 a	2.17 e	-	-	-	-
17	One 75 cm	B'cast, 1	729 a	3.27 ab	1,253 a	3.06 a-d	422 a	0	707 a	4.03 bc
18	One 75 cm	B'cast, 2	1,221 a	2.74 ef	1,464 a	0.49 f	621 a	0	670 a	3.54 cd

Notes : Yields in a field crop group in a column with the same letter are not significantly different by DMRT. DWR comparisons are between all treatments. B'cast = Broadcasting method. Time of sowing: 1=Sowing at start of experiment, 2 = Delayed sowing of DWR.