Cultivar Requirement for Sustainable Production of Rainfed Lowland Rice in SE Asia

Shu Fukai

(School of Land and Food Sciences, The University of Queensland, Brisbane, Australia)

Abstract

Rice is the main staple crop in many Asian countries and contributes greatly to the national economy. In some SE Asian countries, including Thailand, Cambodia and Laos, rainfed lowland rice occupies more than 60 % of the total rice growing areas, but grain yield is low due to drought and low inputs in general. An ACIAR (the Australian Centre for International Agricultural Research) project in 1992-2005 has examined cultivar requirement for rainfed lowland rice under different conditions. The project contributed to the development of plant breeding strategies such as, identification of plant characteristics associated with drought resistance, cultivar requirement for direct seeding, development of a new breeding program in Thailand, characterization of rice growing environments and the development of low temperature tolerant cultivars. This paper describes achievements of the ACIAR project, with particular emphasis on cultivar characteristics contributing to drought resistance and cultivar requirement for direct seeding in relation to sustainable agricultural development in SE Asia.

There has been a change in the socio-economic condition of rice cultivation in the region. A general shortage of labour has resulted in a recent shift in some regions from traditional transplanting to direct seeding. Major problems of direct seeded rice are poor crop establishment and presence of weeds. Cultivars required for direct seeding have high seedling vigour, competitive ability against weeds, lodging resistance and photoperiod insensitivity.

Drought is a major problem in rainfed lowland rice. Our recent work indicates that genotypes that can maintain higher leaf water potential produce higher yield than other genotypes under late season drought conditions, which are common in the region. In order to screen large numbers, the delay in flowering in response to water stress may be used. However, grain yield of a genotype under rainfed lowland rice is strongly affected by the potential yield of the genotype and the phenology, particularly flowering time in relation to drought timing. Therefore, cultivars widely adapted to the rainfed lowland environments should have high potential yield and the appropriate flowering time as well as drought resistance.

The importance of rice in SE Asia is such that improvement in rice production through development of adapted cultivars will have a large effect on the national economy. Another important area associated with sustainable agricultural production in SE Asia is human capacity development. Agricultural scientists in the region need to be well trained to ensure that the technologies they will develop are a component of sustainable agricultural production. The ACIAR project contributed to the training, particularly the postgraduate training of national scientists in Australia.

Corresponding author: s.fukai@mailbox.uq.edu.au

1. Rice production in SE Asia

In many SE Asian countries agriculture contributes greatly to the national economy. For example in 1998, agriculture's share of the total labour force was around 60-80 % in Thailand, Laos and Cambodia (the three countries in the Mekong region considered most in this paper), while that of gross domestic product (GDP) was around 10 % in Thailand and 50 % in Laos and Cambodia.

Rice is the main staple crop and is the backbone of the agriculture industry in many Asian countries. Rice consumption is still high in most SE Asian countries; per-capita consumption in 1999 exceeded 150 kg in Laos and Cambodia and 100 kg in Thailand. Rice is mostly consumed in the area of production and the proportion that enters into the market is rather small.

In some SE Asian countries, including Thailand, Cambodia and Laos, rainfed lowland rice ecosystem is the most common among the different rice ecosystems, occupying more than 60 % of total rice growing areas. In this ecosystem, irrigation water is not available for rice production. However, farmers grow rice in bunded lowland fields so that standing water can be maintained during crop growth in seasons of good rainfall. Most rainfed lowland areas practice subsistence agriculture with rather low input and low productivity. The farmers have limited resources and hence, the use of fertilisers and other chemicals are generally low, limiting rice production particularly in Laos and Cambodia. Therefore, grain yield is often limited by the lack of availability of water and soil nutrients. Drought is a common problem particularly in seasons of low rainfall. More than 50 % of the total rainfed lowlands in Asia are considered to be drought-prone according to Garrity et al. (1986). In some countries such as Laos, farmers consider drought as the most important constraint for high yield in rainfed lowland rice. Currently, yield is low in rainfed lowland rice; for example, 1.3 t/ha in Cambodia, but this can be increased with development and adoption of suitable technologies, including new cultivars that are widely adapted to the rainfed lowland area.

Human population density in the rainfed lowland areas in these countries is low compared with most other countries in Asia. This general lack of labour in the Mekong region for rice production means that labour saving technology is required for rainfed lowland rice (Pandey 1997). Thus for example, direct seeding technology, which requires much less labour inputs than transplanted rice, may be more appropriate in the Mekong region than other highly populated areas in Asia. However, current cultivars are developed for transplanted rice and the development of cultivars adapted to direct seeding will help increase the yield and stabilize rice production.

The development of cultivars adapted to rainfed lowlands, particularly drought resistant cultivars and those suitable for direct seeding, is required for sustainable agricultural development in the region.

2. The ACIAR rice improvement project

The Australian Centre for International Agricultural Research (ACIAR) provides funds for international agricultural research partnerships for the benefit of developing countries and Australia. There are more than 25 partner countries and more than 40 Australian R&D providers involved in ACIAR operations. Most projects are conducted in Asia, particularly in SE Asian countries. A larger proportion of ACIAR funds are spent on bilateral projects such as the rice improvement project described below, but there is also a multilateral program, which contributes to individual international agricultural research centres.

In a bilateral project, the common mode of operation is that Australian scientists visit the partner country often, and inspect research and discuss strategies with national scientists. After the research program is set up, national scientists conduct most experiments in their own countries. The national scientists may visit Australia to attend a short-term training course. For long-term training, postgraduate scholarships are available to participating scientists in most countries.

An ACIAR project in 1992-2005 (Plant breeding strategies for rainfed lowland rice in Thailand, Laos and Cambodia) has predominantly examined cultivar requirement for rainfed lowland rice under different conditions. The project aims to develop plant- breeding strategies for rainfed lowland rice in the Mekong region. This may be achieved by identifying plant characteristics associated with drought resistance and cultivar requirement for direct seeding, examining different genotype selection methods suitable for rainfed lowlands and characterizing rice-growing environment.

Major achievements of the project are as follows: 1) Identification of environmental constraints; 2) Identification of large genotype by environment interaction for grain yield; 3) Modification of the Thai rice breeding program; 4) Identification of drought resistant characteristics; 5) Identification of characters of cultivars widely adapted to rainfed lowlands; 6) Development of direct seeding technology; and 7) Identification of mechanisms of low temperature tolerance in rice.

Early work is described in Fukai et al. (1998) whereas some of the more recent achievements are described in our recent ACIAR proceedings (Fukai and Basnayake 2001). The issues of drought resistance characteristics and cultivars adapted to direct seeding (part of 6. Development of direct seeding technology) are detailed later in the paper under separate headings while the topic of identification of mechanisms of low temperature tolerance is done in Australia, and will not be discussed. Here the remaining issues are described briefly, particularly in relation to drought problems in the Mekong region.

1) Identification of environmental constraints

The major limitation for rainfed lowland rice is drought, and we have identified two major drought patterns, i.e. early season drought and late season drought. The early season drought is common in all three countries examined. Frequent problems are transplanting failure and the use of old seedlings for transplanting and subsequent reduction in yield, as a result of no standing water at the appropriate time of transplanting. Late season drought is also common particularly in Northeast Thailand, which, on average, causes yield loss of around 10-35 % each year (Jongdee et al 1997, Khunthasuvon et al 1998).

Soil fertility is also low in the rainfed lowland areas and the use of fertilizer is rather limited. Without severe drought, rice growth and yield can respond strongly to N and sometimes P fertilizer (Khunthasuvon et al 1998, Suriya-arunroj et al 2000). Drought reduces nutrient availability to rice, and this causes further yield reduction when standing water disappears before flowering. Detailed characterization of growing environments, particularly water environments, which are variable in space and time (Wade et al. 1999), is essential for the development of efficient rice breeding programs. To assist in the characterization of rice growing environments in Laos, we have developed GIS temperature and rainfall maps.

2) Large genotype by environment interaction for yield

A large genotype by environment (G x E) interaction component of variance for yield has been found consistently in our rainfed lowland rice experiments in Thailand, Laos and Cambodia. The interaction variance component could be as much as six times greater than the genotype variance. The G x E interaction for yield is often associated with genotypic variation in flowering, as drought affects genotypes differently when they are in different phenological development stages. The large G x E interaction for yield was due mostly to large genotype by location (L) by year (Y) interaction. This is partly associated with the irregular pattern of drought development in rainfed lowlands. The involvement of large G x L x Y interaction is also associated with variation in times of seeding and transplanting and occurrence of flash flood as well as drought and biotic stresses. Commencement of the wet season varies greatly from year to year, resulting in variation in time of sowing. Cultivars differ in their photoperiod sensitivity, and hence their flowering times vary greatly, depending on the time of sowing. This also contributes to the large G x E interaction for yield.

3) Modification of rice breeding program in Thailand

The current breeding program conducts mostly intra-station trials with early generation materials, and inter-station yield trials are conducted only later with advanced generation materials. This approach is not effective in the rainfed lowland conditions where G x E interaction for yield is large. Here a large number of yield trials across locations and years are required for identifying widely adapted lines that produce high yield in the region.

The emphasis in the suggested new breeding program is on increased early yield testing at a large number of sites in the selection program, use of a drought resistance screening technique, use of a rapid generation advance technique, and increased on-farm testing. Some of these points have already been incorporated into the breeding program, and it is gradually evolving into a new system in Thailand. The outcome would be the development of new cultivars in a shorter period of time and hence, the breeding program is more efficient in terms of financial return (Pandey and Rajatasereekul 1999).

4) Characterization of cultivars widely adapted to rainfed lowlands

Using the drought tolerance screening method that we have developed recently in Thailand, we hope to produce cultivars that are drought resistant. Grain yield of a genotype under rainfed lowland rice is, however, also affected strongly by the potential yield of the genotype and the phenology, particularly flowering time in relation to drought timing.

Our experience indicates the importance of high potential yield (that is obtained under well fertilized and irrigated conditions) in determining yield under many conditions in rainfed lowlands, particularly under conditions where yield reduction is not large. Where yield reduction was less than about 50 % of the potential yield, genotypes with high potential yield produced higher yield. Examination of performances of cultivars in Thailand indicates increase in potential yield by about 1 t/ha from traditional cultivar to advanced elite line (Fukai and Basnayake 2002). The genotypes suitable for drought conditions in rainfed lowland rice depend on drought severity, and also whether the timing of drought is predictable. In cases where the timing of drought is predictable, phenology is important in escaping the drought, whereas for unpredictable and severe drought conditions, genotypes that possess appropriate drought resistant traits would produce higher yield than genotypes without them.

5) Cultivars for direct seeding

Direct seeded area increased rapidly with shortage of labour for transplanting in the late 1980s in Northeast Thailand. By 1992, rice areas established from transplanted and dry-seed broadcast were 73.6 % and 25.5 %, respectively (Naklang 1997). Direct seeding is a common practice in Northwest Cambodia; however, it is rarely practiced in Laos. This situation may change with the decline in labour availability for transplanting.

For the whole area of Northeast Thailand, mean yield in 1989-92 was 1.80 and 1.37 t/ha respectively, for transplanted and dry-seeded, broadcast rice (Naklang 1997). Thus, one of the reasons for the lack of yield improvement in recent years in Northeast Thailand was the expansion of areas under direct seeding, which produced lower yields compared with transplanting. Existing cultivars were developed under transplanted conditions and may not be most suitable for direct seeding.

The effects of the change from transplanting to direct seeding on agronomy of rice are as follows:

- *Early seeding*. With direct seeding, wetland cultivation operation is reduced compared with transplanting, and this makes early seeding possible. Early seeding will allow the direct seeded crop to often escape from late season drought, if photoperiod insensitive or mildly sensitive cultivars are used.
- *Crop establishment difficulty*. Compared with the growing environment of a seedling nursery, which is generally located at a favourable and protected position within the farm, direct seeding of a crop in the main fields takes place under more difficult crop establishment conditions. Direct seeding in rainfed lowlands often requires more precise soil moisture conditions for good crop establishment. Thus, there is a higher risk of poor establishment under direct seeding.
- *High plant density*. Compared with transplanting, direct seeding particularly broadcasting, will result in a higher established plant density under favourable growing conditions. This is related to the larger amount of seeds used for direct seeding, and the high plant density may result in a larger number of panicles and hence higher grain yield.
- *Weed problems*. The problem of weeds in direct seeded rice paddies is greater than in transplanted paddies. This is associated with poor land preparation often due to seeding early in the wet season. Poor rice establishment due to direct seeding results in poor competition against weeds. Lack of standing water during early stages of growth causes difficulty in controlling weeds.

A review of the cultivar requirement for direct seeding in rainfed lowland rice by Fukai (2002) is summarized here. Characters required for direct seeded rice are associated with the agronomy of direct seeding mentioned above, and they include photoperiod insensitivity, good competitive ability against weeds, seedling vigour including submergence tolerance and lodging resistance.

- *Photoperiod insensitivity*

The requirement for photoperiod sensitive cultivars for drought-prone areas may not be strong under the direct seeding system, because with early seeding, photoperiod insensitive cultivars would mature early and escape the late season drought. Compared with photoperiod sensitive genotypes, the use of photoperiod insensitive genotypes would provide a better opportunity to develop high yielding cultivars (Mackill et al. 1996).

- *Competitive ability against weeds*

With rather limited resources available for hand weeding or purchase of herbicides, rainfed lowland rice farmers in the Mekong region need competitive cultivars to suppress weed growth. Several plant characters have been identified for strong competitiveness. They are tall plants with good tillering ability and canopy development. Since tall plants are often low yielding and tend to lodge, shorter intermediate height (eg, between tall traditional plants and semi dwarf plants) would be desirable. Rapid tillering in the seedling stage will contribute to rapid canopy development. The ideal plant type for strong competition against weeds will have shoots that spread and cover the ground rapidly during the vegetative stage but with the onset of panicle initiation they will not dominate over reproductive organ development. Another character associated with competitiveness is the long growth duration of rice genotypes. Long duration genotypes have more time to recover from weed competition that may have taken place during early growth stages.

- *Seedling vigour*

Seedling vigour is required for direct seeded rice, particularly for rainfed lowlands where water control is limited and crop establishment conditions are not favourable. Semi dwarf cultivars have shorter mesocotyl and total seedling length, and this is disadvantageous for good crop establishment particularly when seeded deep in the soil or in standing water. Submergence of young seedlings is a common problem with direct seeded rice, and hence submergence tolerance is required.

• *Lodging resistance*

Lodging is another common problem in rainfed lowland rice, particularly under direct seeding in high soil fertility areas. This is associated with the use of high plant density and resultant tall plants with thin stems, and shallow planting in direct seeding. Tall traditional cultivars tend to lodge, and intermediate height cultivars are generally more suitable to direct seeding. Large stem diameter, thick stem walls and higher lignin content would also reduce lodging (Mackill et al. 1996).

6) Drought resistant cultivars

Environment characterization has been made to identify drought types. While early season drought is a common problem in Thailand, Laos and Cambodia, development of cultivars adapted to this type of drought is considered more difficult than for cultivars resistant to late season drought. Thus, we have concentrated on identifying plant characteristics that convey resistance to late season drought, which is often severe particularly in Northeast Thailand.

Our research results have shown that rainfed lowland rice may be considered as conservative drought avoider. Rice is very sensitive to water stress, and leaf elongation stops, stomata close and leaves roll under mild soil water deficit. The root system is always shallow, and extraction of water from deep soils is limited. Late season drought develops earlier if plant size is large and hence, soil water extraction is fast and water demand is high. Thus, ideal rice plants will use the limited amount of available water slowly so that soil water will last till well beyond flowering stage. Once standing water disappears from the field before flowering, and no substantial rain falls during the flowering to grain filling stage, yield is reduced severely. The pattern of water use and subsequent development of water stress is schematically shown in Figure 1 (from Pantuwan et al. 2002a).

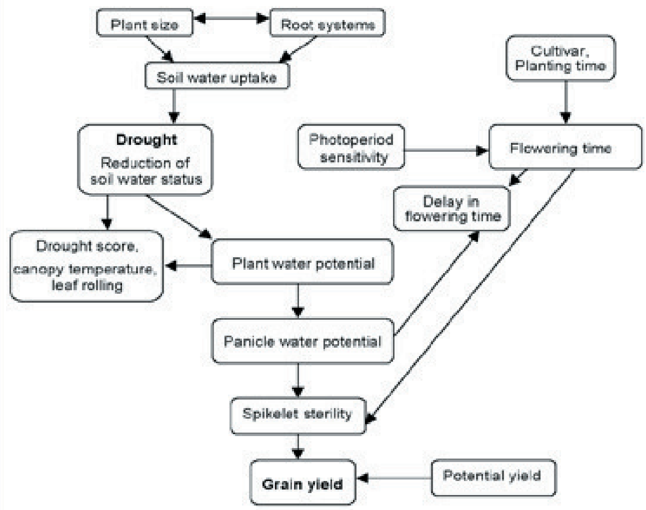

Fig 1. Schematic diagram illustrating the effects of drought stress on grain yield when drought develops at around flowering time.

The plant breeding process for drought adaptation can be made more efficient when traits other than yield are added to the selection process. In rice, various workers have identified putative traits for drought resistance. Our recent work (Jongdee, 1998; Pantuwan et al. 2002b) indicates that genotypes that can maintain higher leaf water potential (LWP) produce higher yield than other genotypes under late season drought conditions, which are common in the region. Leaf water potential integrates a number of mechanisms that contribute to the water status of the plant, but it appears stable under different environmental conditions. The mechanisms of maintaining high LWP under water stress appear to be related to water transport systems within the plant, and large xylem size was found to be associated with high LWP among six genotypes examined (Sibournheung et al. 2001). In order to screen a large number of genotypes, the delay in flowering in response to water stress may be used. One of the consequences of the loss of plant water potential is a delay in flowering of the stressed plants relative to those that are well watered (Pantuwan et al. 2002b). Other characters that have been examined as putative drought resistant traits include deep root system and osmotic adjustment, but they were not found to be effective in minimizing the adverse effect of late season drought.

A new project has just commenced with funding from the Rockefeller Foundation. The objective of the project is to select drought resistant lines in rainfed lowland rice for the Mekong region. Table 1 lists selection criteria for development of adapted cultivars for rainfed lowland rice in the Mekong region.

Table 1. Suggested selection criteria within a maturity group for developmentof adapted cultivars for rainfed lowland rice (Irrigated and rainfed conditions with drained water) in the Mekong region.

Irrigated conditions	Rainfed conditions with drained water prior to anthesis
• High potential yield with • High harvest index • Intermediate height • Small dry matter at anthesis	• High potential grain yield • Minimal delay in flowering • Maintenance of favourable plant water status

For this project we will be utilising the screening method we developed in Thailand, whereby we select a site with low rainfall and where drainage of standing water is possible. We screen genotypes mostly in the wet season, as rice growth in the dry season is quite different from that in the wet season. In these screens, the planting will be 2-3 weeks later than the commercial crops to increase the chance of late season drought, particularly with photoperiod insensitive materials. In addition, standing water from 10 days before flowering onward will be drained from the field, to increase the likelihood of drought stress. There will be a well-watered control trial. Grain yield under the drought trial will be adjusted for flowering date and yield potentials using the concept of drought response index (DRI) (Bidinger et al., 1987). The DRI will be used for identification of drought resistant genotypes.

3. Sustainable agricultural production

Sustainable agricultural production is discussed here in relation to increased rice production as a result of development of improved rice cultivars, international research projects and human resource development.

1. Increased rice production

Once improved cultivars are found to be well adapted to a rainfed lowland region, they are generally well adopted by farmers. An example of this is shown in Laos, where recently released improved cultivars such as TDK1 have been widely adopted in different parts of the Mekong river plains. The improved cultivars are high yielding, and often are photoperiod insensitive with shorter growth duration than traditional cultivars. Thus, they can be more flexible in terms of planting windows. Unlike most other technologies where cultural practices are altered or additional resources are required, farmers can use new cultivars without any modification in their cultural practices. However, it should be stated that the advantage of new improved cultivars is often increased with addition of appropriate inputs, such as fertiliser application.

Another point to note is that adapted cultivars such as those with drought resistance should reduce yield losses, and this contributes to reduced fluctuation of rice production; reduced crop failure and yield loss contribute directly to sustainable agricultural production.

Introduction of cultivars may contribute to the development of a new cropping system. This may be the case with the introduction of IR66 to rainfed lowlands in Cambodia. This cultivar is quick maturing and photoperiod insensitive, and could be planted early in the wet season, followed by traditional photoperiod sensitive cultivars late in the season. This has contributed to increased rice production in the country.

The improvement in rice production through development of adapted cultivars that will eventually have a large effect on the national economy highlights the importance of rice in agricultural production in SE Asian countries. With the higher yield of rice, as a result of adoption of new cultivars, the area required for rice production may be reduced particularly in areas where marketing of rice is limited. This allows other crops to be grown, and this contributes to diversification of cropping, and may result in reduced fluctuation of food production. The area, which is not suitable for rice production but may be suitable for other crops, such as that of sandy soils with high percolation rate, may be converted to production of other crops, contributing to the development of sustainable production systems. Alternatively if a rice market is available, then excess rice can be sold, contributing to the development of a cash economy. Once self-sufficiency in rice is achieved, rice production may be aimed at quality.

Rice cultivar development research is required for changing socio-economic environments to maintain and further develop sustainable agricultural systems.

2. International research projects

International projects in rainfed lowland rice are an important component of the rainfed lowland research in these countries. In most cases international projects work together with national scientists to improve rice production and/or develop sustainable agricultural production system. It is thus, important to understand the current problems of rice production and develop research projects addressing such problems together with national scientists. In the case of our ACIAR rice improvement project, we have worked on development of strategies for improvement of rainfed lowland rice. This has required the continual modification of objectives within the project framework as identification of limitations evolved. International projects need to be dynamic, and as the results are produced, research emphasis needs to be redirected to maximise the benefit to the project and more importantly, the region. Often, it is not until the project is well under way that the true limitations (to production) can be identified. This identification of the problem and modification of project activities cannot be achieved by conducting isolated short-term experiments. Results and their interpretation rely heavily on the establishment of good communication and understanding between national and international scientists and the development of this report alone requires a long-term project approach. New ideas and areas of research can then be incorporated relatively easily into existing projects. An example of a shift in emphasis in our ACIAR project was the identification of the need for characterization of the environment from a minor component to a major sub-project of Agro-ecological characterization in Laos.

International cooperation may be further promoted by conducting research in more than one country in SE Asia. For example, in our ACIAR project, there were always two neighbouring countries working together. Often the problem is similar; for example, drought and flood problems in rainfed lowland rice in Thailand, Laos and Cambodia. Technology transfer may be possible among areas of similar growth and social environments. For example, rice genotypes found to be high yielding in Thailand did well in Laos and Cambodia. Thus, adapted cultivars can be readily transferred from one country to another.

3. Human resource development

Another important area associated with sustainable agricultural production in SE Asia is human capacity development. The ACIAR project, like many other overseas projects from Australia contributed to the training of national scientists in Australia. This appears particularly successful in postgraduate training. A large number of scientists have successfully completed higher degrees at the University of Queensland in association with our ACIAR rice improvement project. The staff members who are associated with the ACIAR rice improvement project have supervised (including those currently enrolled) seven PhD students (including 3 from Thailand, 1 from Cambodia) and ten Masters degree students (including 2 from Laos and 1 each from Thailand and Cambodia). Four of these postgraduate students have conducted their research in the Mekong region. These former students have strong impact on research and development in the national breeding program of their home countries. For example, postgraduate students from Thailand contributed greatly to the development of the new rice-breeding program in the country.

In the medium to long term this improved research and human resource capability would flow on to the development of new rice cultivars and cropping systems in the region, again contributing to sustainable agricultural production.

Universities in Australia, as in Japan, have taken in a number of undergraduate and postgraduate students from SE Asia. One possibility for the further development of international cooperation would be to enable postgraduate research to be conducted in the student’s home country. The advantages of this are that the 1) research topic is more relevant to the student; 2) research findings are often directly applicable to the country of concern; 3) the supervising University staff will have the opportunity to gain greater awareness and understanding of research needs in the student’s home country; and; 4) the exposure of University staff to the country where the research is conducted would help in identifying future overseas research projects.

Acknowledgment

The author wishes to thank the Australian Centre for International Agricultural Research for financial support to the project.

References

Bidinger, F.R., Mahalakshmi, and V. Rao, G.D.P. 1987. Assessment of drought resistance in pearl millet [Pennisetum americanum (L.) Leeke]. II Estimation of genotypes response to stress. Aus. J. Agric. Res. 38: 49-59.

Fukai, S. 2002. Rice cultivar requirements for direct seeding in rainfed lowlands cultivar for direct seeding. Proceedings of International workshop on direct seeding. Bangkok, January 2000.

Fukai, S. and J. Basnayake. 2001. (eds). Increasing productivity of lowland rice in Southeast Asia. ACIAR Proceedings 101, Australian Centre for International Agricultural Research, GPO Box 1571, Canberra, ACT 2601, Australia. 327

Fukai, S. and J. Basnayake. 2002. Development of drought resistant cultivars for rainfed lowland rice. Proceedings of International Symposium on Biotechnology Application. Coimbatore, Tamil Nadu, May 2002.

Fukai, S., P. Sittisuang, and M. Chanphengsay. 1998. Increasing production of rainfed lowland rice in drought prone environments - a case study in Thailand and Laos. Plant Production Science 1(1):75-82.

Fukai, S. and M. Cooper. 1999. Plant breeding strategies for rainfed lowland rice in Northeast Thailand. In Horie, T., Geng, S., Amano, T., Inamura, T., Shiraiwa, T. Editors. Proceedings of the Kyoto International Symposium on World Food Security and Crop Production for Tomorrow. 8-9 October 1998, Kyoto, Japan, 153-156.

Garrity, DP., L.R. Oldeman, and R.A. Morris. 1986. Rainfed lowland rice ecosystems: characterisation and distribution. In Progress in Rainfed Lowland Rice. Manila (Philippines): International Rice Research Institute, 3-23.

Jongdee, S., JH. Mitchell, and S. Fukai. 1997. Modelling approach for estimation of rice yield reduction due to drought in Thailand. Proceedings of an International Workshop, Ubon Ratchathani, Thailand, 1996,Australian Centre for International Agricultural Research, Canberra, ACT, 65-73.

Jongdee, B. 1998. The importance of leaf water potential and osmotic adjustment on growth and grain yield of rice genotypes under water deficit conditions. PhD thesis. The University of Queensland.

Khunthasuvon, S., S. Rajatasereekul, P. Hanviriyapant, P. Romyen, S. Fukai, J. Basnayake, and E. Skulkhu. 1998. Lowland rice improvement in northern and northeast Thailand. 1. Effects of fertiliser application and irrigation, Field Crops Res. 59: 99 – 108.

Mackill, DJ., WR. Coffman, and D.P. Garrity. 1996. Rainfed Lowland Rice Improvement. International Rice Research Institute, P.O. Box 933, Manila, Philippines, 242p.

Naklang, K. 1997. Direct seeding for lowland rainfed rice in Thailand. In Fukai, S., Cooper, M. and Salisbury, J., (eds). Breeding strategies for rainfed lowland rice in drought prone environments. Proceedings of an International Workshop, Ubon Ratchathani, Thailand, 1996, Australian Centre for International Agricultural Research, Canberra, ACT, 126-36.

Pandey, S. 1997. Rainfed lowland rice research: challenges and priorities for the 21st century. Proceedings of an International Workshop, Ubon Ratchathani, Thailand, 1996, ACIAR Proceedings 77, Australian Centre for International Agricultural Research, Canberra, ACT, 1-12.

Pandey, S.and S. Rajatasereekul. 1999. Economics of plant breeding: The value of shorter breeding cycles for rice in northeast Thailand. Field Crops Res. 64: 187-197.

Pantuwan, G., S. Fukai, M. Cooper, S. Rajatasereekul, and JC. O'Toole. 2002a. Yield response of rice (Oryza sativa L.) genotypes to drought under rainfed lowlands. 1. Grain yield and yield components. Field Crops Res. 73: 153-168.

Pantuwan, G., S. Fukai, M. Cooper, S. Rajatasereekul, and JC. O'Toole. 2002b. Yield response of rice (Oryza sativa L.) genotypes to drought under rainfed lowlands. 3. Plant factors contributing to drought resistance. Field Crops Res. 73:181-200.

Sibournheung, V., J. Basnayake, S. Fukai, and M. Cooper. 2001. Leaf water potential as a drought resistance character in rice. In: Fukai, S. and Basnayake J (editors). Increased lowland rice production in the Mekong region. Proceedings of International Workshop. Vientiane, 30 October-1 November 2000. ACIAR Proceedings 101, 86-95.

Suriya-arunroj, D., P. Chaiyawat, S. Fukai, and P. Blamey. 2000. Identification of nutrients limiting rice growth in soils of Northeast Thailand under water-limiting and non-limiting conditions. Plant Production Science. 3: 417-421.

Wade, LJ., S. Fukai, B.K. Samson, A. Ali, and M.A. Mazid. 1999. Rainfed lowland rice – physical environment and cultivar requirements. Field Crops Res. 64:3-12.