Improving Water-Use Efficiency in Rice-Based Cropping Systems Using Permanent Raised Beds

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Abstract

A major challenge for the next 20 years is to develop genetic and agronomic solutions to combat water shortages for rice production and to develop ecosystems that better match crop growth with water supply. Experiments were conducted in northern Queensland, Australia (1989–1992) and eastern Indonesia (1993–1999) to develop a cropping system based on raised beds and saturated soil culture (SSC), whereby rice could successfully be grown in rotation with several field crops. Advantages of the SSC system include improved efficiencies of water use, energy savings, enhanced timeliness of field operations and reduced soil compaction. The northern Queensland studies indicated that double cropping rice and field crops on permanent raised beds provides additional synergistic and logistic benefits over those found in the traditional rice/fallow system. Subsequent experiments in West Timor found that various crops, as well as rice, can be grown on raised beds during the wet season, thus overcoming the problem of waterlogging. Moreover, if raised beds were constructed before the wet season in lowland areas, crops could be sown at the onset of the wet season, thus avoiding end-of-season drought and permitting significant increases in crop yields. Reforesting of eroded upland cropping areas with perennial tree species was also possible, provided the intensive lowland production met the subsistence farmers' basic food and/or cash crop requirements. By increasing the probability of year-round crop production, this system, overall, can help enhance food security for South-East Asian subsistence farmers.

GLOBALLY, water for irrigated rice (*Oryza sativa* L.) production is becoming increasingly scarce due to greater urban and industrial demand (DuPont 2000). Water, more than any other resource, also limits rainfed rice production throughout the world. The challenge is to develop rice ecosystems that use less water and improve water-use efficiency (WUE) by better matching crop growth to water supply. This paper summarizes a series of studies that were undertaken initially in northern Australia (1989–1992), then in West Timor (1993–1999), to develop a raised-bed cropping system in which rice could successfully be grown in rotation with a range of other field crops. These concepts are equally applicable to lowland rice production in South-East Asia.

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Options for decreasing water use and increasing WUE for irrigated rice were first investigated in north-eastern Queensland, Australia, because of the high costs of water in the Burdekin River Irrigation Area (BRIA). In addition to improving economic returns to growers, it was believed that increasing the WUE for irrigated rice production would have long-term environmental benefits by lowering water tables and reducing salinization in irrigation areas (Gardner and Coughlan 1982; Borrell et al. 1997).

In the northern Queensland studies, it was hypothesized that WUE (g m^{-2} mm^{-1}) of field-grown rice could be increased by implementing an agronomic system known as saturated soil culture (SSC). This system was initially developed for soybean production on raised beds in the greenhouse (Hunter et al. 1980; Nathanson et al. 1984) and later in the field (Wright et al. 1988; Troedson et al. 1989; Garside et al. 1992a). Plants were grown on raised beds that were 0.2 m high and 1.2 m wide, with water

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maintained in furrows, which were 0.3 m wide and about 0.1 m below the bed surface. Water-use efficiency (WUE) was increased by reducing water use without reducing dry matter production. The Queensland studies aimed to reach similar efficiencies for rice grown under SSC.

Both northern Queensland and eastern Indonesia are characterized by a typical monsoonal rainfall pattern with hot, humid, wet seasons from November to April and cooler dry seasons from May to October. Improved WUEs for rice production with SSC in tropical Australia indicated that similar benefits might be realized with this method of irrigation in West Timor. It was also thought that permanent raised beds would reduce the incidence of soil erosion, the most significant environmental problem facing Timor today (Duggan 1991).

To ensure food security in eastern Indonesia, a cropping system is required that will enable subsistence farmers to produce sufficient nutritious food, despite the lack of rainfall between May and October. Maximum crop production depends on efficient use of rainfall during the wet season and of stored soil water during the dry season, that is, on matching crop growth with water supply. The development of any new cropping system should be considered in the context of the region's existing agricultural production systems. Simpson (1995) highlighted five production systems that commonly exist side by side within a single farm in West Timor: (1) swidden (shifting/slash and burn) cultivation of rainfed crops, mainly maize (*Zea mays* L.); (2) the cultivation of rainfed or irrigated rice in lowland areas; (3) house gardens with rainfed maize, cassava (*Manihot esculenta* Crantz) and beans (*Phaseolus* spp.) intercropped with tree crops; (4) cattle production, including the use of the breeding herd for rencah system, in which cattle are herded into flooded rice fields to puddle the soil in preparation for rice planting); and (5) harvesting forest products such as tamarind (*Tamarindus indica* L.), candlenut (*Aleurites moluccana* (L.) Wild.), sandalwood (*Santalum album* L.) and fuel wood.

All these systems are constrained by drought and, at times, waterlogging. The incompatibility of upland crops such as maize and soybean with flooded rice culture hindered the development of rice-based cropping systems in both northern Queensland (Garside et al. 1992b) and West Timor (Van Cooten and Borrell 1999). The key to overcoming this inherent incompatibility was SSC on raised beds.

Northern Queensland

Garside et al. (1992b) report the development of a rice-based cropping system for tropical Australia that included the double cropping of rice, soybean and maize. They discuss a series of experiments conducted at Millaroo Research Station (20° 03′ south, 147° 16′ east) in the BRIA, between 1989 and 1992. Such a system, based on rice production under SSC on permanent raised beds, was shown to improve productivity and to have considerable advantages over the traditional rice/fallow system, such as greater WUEs, energy savings, improved timeliness of field operations and reduced soil compaction.

To develop a viable and practical rotation, Garside et al. (1992b) identified and examined in isolation those cultural and management components most likely to inhibit the system. Three key areas were identified:

1. Incompatibility of irrigation practices for flooded rice and furrow-irrigated upland crops (Borrell et al. 1991, 1993, 1997).
2. Impact of cultural changes on timeliness of operations (Braunack et al. 1995; McPhee et al. 1995a, b, c); and
3. Effects of crop and irrigation practice on soil chemistry and nutrient availability (Borrell 1993; Dowling 1995; Ockerby et al. 1999a, b).

Development of an irrigated rice-based cropping system for tropical Australia was driven by both economic and environmental imperatives. At the time of research, water and nitrogen fertilizer accounted for about 40% and 20%, respectively, of the variable costs of growing a rice crop (Bourne and Norman 1990), highlighting the need to improve the efficiencies with which these resources were used. Previous studies in the BRIA had also found that deep drainage losses from rice fields ranged from 50 to 240 mm per crop, depending on the permeability of the B horizon (Gardner and Coughlan 1982). Therefore, it was considered likely that increasing the area of flooded rice production would lift the regional water table, possibly leading to soil salinization in some areas. It was thought that SSC, an alternative irrigation strategy, may obviate this problem. In addition, there was increasing pressure for nitrogen fertilizer inputs to be reduced to prevent drainage of excess nitrate from agricultural enterprises into coastal rivers and, eventually, into the Great Barrier Reef (Prove et al. 1990).

Irrigation practices

Field crops such as maize and soybean are not suited to the anaerobic environment associated with flooded rice production. Therefore, rice would need to be grown under a different cultural system to improve compatibility between rice and field crops. Experiments were conducted to examine alternative methods of irrigating rice. The responses of biomass

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production and yield in rice (cv. Lemont) to five methods of irrigation were examined in a wet and dry season in northern Australia (Borrell et al. 1997). Permanent floods at sowing (PF-S), at the three-leaf stage (traditional, PF-3L) and before panicle initiation (PF-PI) were compared with two unflooded methods: SSC and intermittent irrigation at weekly intervals. The objective of these studies was to maximize grain yield by optimizing its functional components: water use, plant water-use efficiency for biomass production and harvest index.

These studies found that flooding rice is not necessary to obtain high grain yield and quality (Borrell et al. 1997). Although the trend across all water regimes was for yield to increase with water supply, no significant difference in yield and quality was found between SSC and traditional flooding (PF-3L), even though SSC used about 32% less water in both seasons (Table 1). Transpiration would have been small during the first 30 d of crop growth. Therefore, higher water losses during this period in flooded (290 mm) than unflooded (160 mm) treatments suggest that evaporation, seepage and percolation losses were higher with ponded water. These factors were not measured separately in this study, but their combined values support earlier findings that percolation increases with increasing depth of ponded water due to the imposition of a larger gradient in hydraulic head (Ferguson 1970; Sanchez 1973; Wickham and Singh 1978). Alternative irrigation strategies comprising lower depths of ponded water such as SSC, are likely to be most advantageous in relatively porous, non-swelling soils where flooding simply creates a greater hydraulic head which, in turn, increases percolation.

In the dry season, there was a trend for increased WUE for grain production (WUE_g) in SSC, compared with the other treatments (Table 1). In the wet season, WUE_g was higher in PF-S and SSC than in the other treatments. The Australian studies pointed out that the selection of an optimal irrigation method for rice production in tropical environments should not be based on the criterion of WUE, but rather on the dual criteria of WUE_g and total water use. Had selection been based on WUE_g alone, both SSC and PF-S would have been acceptable in the wet season, despite significantly higher water use in PF-S (about 35% more). With increasing water scarcity, the urgent issue is to select a system that encompasses both improved efficiency and lower water use. Based on these dual criteria, SSC was the optimal treatment in the Australian experiments.

For rice grown as a row crop on permanent raised beds, irrigation water can be supplied to the furrows at a constant rate, maintaining the water level at about 0.1 m below the bed surface. Alternatively, water can be supplied at regular intervals (e.g. twice weekly) to rice grown on raised beds within bunded fields, maintaining the water at an average level of 0.1 m below the bed surface. While SSC was initially developed for irrigated crop production, the principles still apply to rainfed rice production within bunded fields during the wet season, although water levels cannot be controlled to the same extent as for irrigated production.

Table 1. Water use (mm), grain dry mass (g m^{-2}) and efficiency of water use for grain production (WUEg, g m^{-2} mm^{-1}) for two seasons and five methods of irrigation.

Irrigation method[b]	Water use	Grain dry mass	WUE_g
Dry season			
PF-S	1351 d	875 b	0.65
PF-3L	1320 d	822 b	0.63
PF-PI	1170 c	789 b	0.67
SSC	904 b	734 b	0.82
II	764 a	507 a	0.66
Mean	1102	746	0.69
$LSD_{0.05}$	94	177	ns
Wet season			
PF-S	1286 d	612 c	0.48 b
PF-3L	1228 c	456 b	0.37 a
PF-PI	1075 b	421 ab	0.39 a
SSC	833 a	402 ab	0.48 b
II	873 a	363 a	0.41 ab
Mean	1059	451	0.43
$LSD_{0.05}$	49	64	0.07

[a] Means within a column and season followed by differing letters are significantly different ($P < 0.05$). ns = not significant at $P < 0.05$, F-test.
[b] PF-S = permanent floods at sowing; PF-3L = at three-leaf stage; PF-PI = before panicle initiation; SSC = saturated soil culture; II = intermittent irrigation.
Source: Adapted from Borrell et al. (1997).

Controlled traffic

At the same experiment site (Millaroo Research Station, BRIA), but separately from the irrigation studies, timeliness and trafficability were studied. The potential of controlled traffic was assessed for irrigated double cropping of soybean and maize in northern Australia (McPhee et al. 1995c). Timeliness measures the ability to perform operations such as planting and harvesting at optimal time. Two controlled traffic treatments, using direct drilling and conventional tillage between the traffic lanes, were compared with a conventional tillage system. (Controlled traffic is defined as the separation of the traffic zone from the crop growth zone.) Controlled traffic with direct drilling improved timeliness, creating earlier planting opportunities in all seasons examined, compared with controlled traffic for both cultivation

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and conventional tillage. Raised beds under SSC in the irrigation studies were observed not to degrade, suggesting that no obvious limitation was present to prevent the combination of SSC, permanent beds and controlled traffic.

Eastern Indonesia

Van Cooten and Borrell (1999) discussed the development of a rice-based cropping system for eastern Indonesia, arguing that crop production on permanent raised beds enables growth to be better matched to water supply. To develop a viable and practical system based on permanent raised beds, Van Cooten and Borrell (1999) first identified, then examined, the following components: (1) compatibility of raised beds for rice and upland cropping; (2) timeliness of operations; (3) water harvesting and drainage; (4) using stored soil water; (5) mechanization; (6) weed control; (7) erosion control; (8) an integrated approach to food and cash cropping; (9) living fences; and (10) availability of labour. Those components directly related to improved WUE in rice-based cropping systems are discussed later in this paper (see 'Developing Rice-Based Cropping Systems for South-East Asia').

Improving rice management

Three field experiments were conducted at Batu Plat, Kupang, West Timor (10.2° south, 123.9° east), between 1993 and 1995 to improve rice production in this region (Borrell et al. 1998). The primary objectives of these studies were to examine the effects of irrigation method (raised beds under SSC v. flooded system), irrigation frequency (daily v. twice weekly) and rice genotype (traditional v. improved) on crop yield and yield components. Secondary objectives were to examine the response of rice grown on raised beds to sowing time and nitrogen fertilization. Higher WUEs for rice grown under SSC in tropical Australia suggested that similar benefits might be realized with this irrigation method in West Timor. The West Timor experiments were conducted within a low-external-input system, and all experiments were affected by drought. The key issue was to match crop growth with water supply to ensure adequate quantity and quality of grain production at the end of the season.

Time of sowing

An improved lowland rice cultivar (cv. Lemont) was sown early (15 December) and late (15 January) to examine the impact of sowing time on grain yield in the wet season. Crop growth was better aligned with the available water resources in the early sowing, since yield potential (indicated by grains m^{-2}) was similar for both sowings, yet more water was available to complete grain filling in the early sowing, resulting in higher grain quality (indicated by grain size) for this sowing time (Borrell et al. 1998). Permanent raised beds, such as those used in SSC, provide a mechanism for sowing crops immediately after the onset of wet-season rains, thereby minimizing the risk of drought late in the grain-filling period. The SSC therefore provides a means of better matching crop growth with water supply by enabling farmers to sow at optimal time.

Water management

Irrigation method (SSC v. flooded rice) was split for irrigation frequency (daily v. twice weekly applications), which was again split for genotype (traditional upland v. improved lowland). No difference in grain yield between rice grown on raised beds and rice grown in flooded bays was found, suggesting that yield can be maintained in an unflooded system, using SSC (Table 2; Borrell et al. 1998). Nor did irrigation frequency have impact on grain yield, highlighting the advantage of irrigating twice weekly rather than irrigating daily or flooding. Although water use was not monitored in these studies, reductions under SSC compared with traditional flooded production may have occurred, as for the northern Australian studies (Borrell et al. 1997).

Other benefits of raised beds are enhanced drainage, particularly in the wet season. Although drought is the main limitation to crop yield in eastern Indonesia, excess rainfall is common between January and February when the north-west monsoons peak. Poor drainage can result in crops being waterlogged for several weeks, following cyclonic activity. Pellokila et al. (1991) define the ideal cropping area as one that has sufficient drainage to prevent waterlogging but is capable of storing adequate moisture to minimize water stress during drought. Ideal cropping areas are rare, however such areas can be created by constructing fields of permanent raised beds, which provide excellent drainage during periods of intense rainfall in the wet season, yet capture and store water during periods of low rainfall.

The growth of rice on raised beds also opens the way for other crops to be grown in rotation with rice. Field crops such as maize and soybean are not suited to the flooded soil conditions used for rice production, but these crops do grow well on raised beds in rotation with rice (Garside et al. 1992b). The development of a rice-based cropping system on permanent raised beds would enable farmers to produce food and cash crops, thereby meeting the criteria of food security and income generation highlighted by Pellokila et al. (1991).

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Table 2. Grain dry mass, above-ground dry mass, harvest index, grain number per m^2, mass per grain, panicle number per m^2, grain number per panicle, plant number per m^2 and panicle number per plant for two irrigation methods, two irrigation frequencies and two rice genotypes.

Treatment	Grain dry mass ($g\ m^{-2}$)	Above-ground dry mass ($g\ m^{-2}$)	Harvest index	Grain number per m^2	Mass per grain (mg)	Panicle number per m^2	Grain number per panicle	Plant number per m^2	Panicle number per plant
Irrigation method									
Raised beds	150	487	0.28	6374	21.8	228	29	119	2.3
Flooded	154	353	0.44	6180	24.9	210	32	84	2.0
$LSD_{0.05}$	ns	ns	ns	ns	ns	ns	ns	ns	ns
Irrigation frequency									
Daily	163	465	0.36	6696	24.1	224	32	104	2.2
Twice weekly	140	375	0.35	5858	22.6	214	29	98	2.1
$LSD_{0.05}$	ns	ns	ns	ns	ns	ns	ns	ns	ns
Rice genotype									
Traditional	127	371	0.34	5546	21.9	163	35	102	1.6
Improved	176	469	0.37	7008	24.8	275	26	101	2.8
$LSD_{0.05}$	ns	ns	ns	ns	1.5	50	ns	ns	0.2

Source: Adapted from Borrell et al. (1998).

Traditional versus improved genotypes

The performance of an improved short genotype (cv. Lemont) was compared with that of a taller traditional rice from the neighbouring island of Alor in a dry and wet season (Borrell et al. 1998). The traditional genotype appeared to have an advantage over the improved genotype when growth was limited by water during grain filling. The choice of traditional versus improved genotypes, and their associated 'input' packages, requires careful consideration. Experience from other parts of Indonesia has shown that rice production can be significantly increased with improved resources. However, the cost is high and the appropriateness of these high-input systems needs to be fully examined (Pellokila et al. 1991). There is a need to better examine the world's genetic stocks of crops and forages that are well suited to eastern Indonesia (Barlow and Gondowarsito 1991). Pellokila et al. (1991) are now identifying early maturing rice varieties that are disease resistant, adapted to the environment and able to flower during the wet season, thus avoiding a potential end-of-season drought.

Developing Rice-Based Cropping Systems for South-East Asia

Below we briefly discuss some of the cropping system components identified by Van Cooten and Borrell (1999) in terms of their applicability to the development of rice-based cropping systems for South-East Asia.

Compatibility of raised beds for rice and upland cropping

The successful growth of rice on raised beds in northern Australia (Borrell et al. 1997) and in eastern Indonesia (Borrell et al. 1998) opens the way for upland crops to be grown in rotation with rice. In northern Australia, wet-season soybean was grown on raised beds in rotation with dry-season rice, and dry-season maize was grown in rotation with wet-season rice (Garside et al. 1992b; Borrell 1993). This concept has been extended to eastern Indonesia where soybean, maize, sorghum (*Sorghum* spp.), garlic (*Allium sativum* L.), mung bean (*Vigna radiata* L.) and cassava have been grown on raised beds in rotation with rice in West Timor (Van Cooten and Borrell 1999). Similarly, a range of crops could be grown in rotation with rice on raised beds in Cambodia and Laos.

Timeliness of operations

The single largest constraint to cropping in eastern Indonesia is late planting of the wet-season crop (Borrell et al. 1998; Van Cooten and Borrell 1999). Delayed sowing reduces yield because growth is poorly aligned with water availability, resulting in the crop experiencing end-of-season drought. A related factor is staggered plantings as farmers wait for cattle or tractors to become available for cultivation. Late-planted crops are more likely to run into moisture stress and, in addition, they are more likely to suffer yield reduction due to the build-up of pests

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from earlier crops (Pellokila et al. 1991). Raised beds provide a mechanism for sowing crops immediately after the onset of wet-season rains, thereby reducing the risk of drought during grain filling. Crops of rice (Borrell et al. 1998) and soybean (R.M. Kelly, pers. comm., 2000) sown in December yielded more than comparable crops sown in January. Therefore permanent raised beds enable farmers to sow at optimal times, providing a means of better matching crop growth with water supply and phenology.

Water harvesting and drainage

Water shortage, a major constraint to agricultural production in eastern Indonesia and throughout South-East Asia, can be defined as the under-exploitation of available water resources and continued dependence on rainfall with all of its uncertainties (Duggan 1991). Waterlogging can also occur for a number of weeks following cyclonic activity, particularly if drainage is poor. Further, rainfall within the wet season can be highly variable, resulting in patches of intermittent water deficit between periods of intense rainfall. However, the effects of intermittent drought can be minimized by harvesting and storing more water from the intense rainfall periods. Thus, during subsequent dry periods, the crop will have increased availability of water. Within bunded fields, furrows between raised beds can capture water during high rainfall events without causing waterlogging, while providing extra water for the crops in dry spells.

Using stored soil water

Capturing, storing and using soil water is one key to successful dry-season cropping. In eastern Indonesia, rainfed crops sown at the end of the wet season will need to rely almost exclusively on stored soil water for growth since, on average, less than 5% of rainfall occurs during the dry season. Potential still exists for dry-season cropping via improved agronomy (raised beds) and plant selection (drought-resistant species). If wet-season crops are sown on raised beds before mid-December as proposed by Borrell et al. (1998), they can be harvested at the end of March. This opens the way for drought-resistant crops such as sorghum [*Sorghum bicolor* (L.) Moench] to be sown into the beds in late March or early April. Rainfall data for the 10 years preceding 1995 (Table 3) shows that, on average, 214 and 72 mm of rain fell in the months of March and April, respectively, although only 42 mm fell during the following 6 months. This suggests that, on average, sorghum can be planted into a near-full soil water profile at the start of the dry season. Experiments have shown that drought-resistant sorghum lines can yield over 2 t ha^{-1} in southern India (Borrell et al. 1999) when grown on stored soil water under severe water deficit. Relay cropping of sorghum or mung bean immediately after wet-season rice or soybean is an effective means of using stored soil water (Van Cooten and Borrell 1999).

Weed control

Another critical issue for raised-bed cropping is the extent to which weeds will colonize this system, compared with a flooded rice-based system. Weed growth in unflooded systems is usually higher than in flooded systems (De Datta et al. 1973; Borrell et al. 1997), although this is not always the case (Tabbal et al. 1992). Rotational cropping systems have the potential to reduce weed growth since the environment for the survival of any particular weed species is constantly being changed, preventing the build-up of any one species. We have observed that,

Table 3. Total monthly rainfall (mm) from January to December recorded at Kupang, West Timor, between 1985 and 1995.

Year	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
1985	203	163	196	49	0	8	0	0	4	92	101	57	873
1986	640	299	129	45	5	0	95	0	0	0	47	1075	2335
1987	1075	416	52	0	0	0	0	0	0	0	250	375	2168
1988	544	122	243	12	0	0	0	0	0	0	378	321	1620
1989	272	202	264	0	9	20	21	0	0	0	26	114	928
1990	187	386	337	55	29	0	0	0	0	0	113	252	1359
1991	554	456	50	274	0	0	5	0	0	0	180	95	1614
1992	314	395	200	154	0	0	0	2	9	16	42	58	1190
1993	453	250	189	0	14	5	0	0	43	13	30	150	1147
1994	265	318	236	66	0	0	0	0	0	0	7	82	974
1995	427	569	460	141	59	2	0	0	0	20	179	266	2123
Mean	449	325	214	72	10	3	11	0	5	13	123	259	1485

Source: Adapted from Van Cooten and Borrell (1999).

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in West Timor, wet-season soybean, when well established, quickly reach full canopy, choking out competing weeds. The subsequent dry-season sorghum crop is drought-resistant, competing well with weeds in this arid environment. Combining stringent herbicide use, mechanical cultivation, manual weeding and rotational cropping systems should adequately control weeds on permanent raised beds in South-East Asia.

Erosion control

Using permanent raised beds can reduce erosion in two ways. First, raised beds on clay soils in the lowlands increases the stability of the system because the beds are permanent and can provide all-year ground cover. Hence bare soil is not exposed to high rainfall at the beginning of the wet season. Second, upland cropping on steep slopes can be replaced by a variety of tree species, providing additional food, fodder, firewood and medicines while reducing erosion. This is possible because the crops currently grown in upland fields (e.g. maize) can instead be grown on raised beds in the lowlands since waterlogging is not a problem on the raised beds. Replacement of upland cropping areas with forests, however, assumes that all the farmers' basic food and cash crop requirements can be met by growing a diverse intercrop on large raised beds, interspersed by smaller raised beds planted to monocultures of rice or soybean in the wet seasons and sorghum or mung bean in the dry season (see below 'An Integrated Approach …').

Availability of labour

To reduce the risk of crop failure, farmers may cultivate three or four swidden gardens, 5 to 10 km apart, as well as cultivate rice. Widely dispersed fields increase the chance that at least one field receives enough rain at the right time for a successful harvest (Simpson 1995), but they also increase the labour and time required for walking to and fro. The availability of labour, especially for land preparation, weeding and guarding of gardens from livestock intrusion, bird damage and stealing, is a major factor affecting crop production in eastern Indonesia (Pellokila et al. 1991). The permanent raised bed system proposed by Van Cooten and Borrell (1999) combines both upland swidden gardening with rice cultivation in the one field, thus reducing the labour and time involved in walking between widely dispersed fields and therefore increasing the farmers' opportunities for protecting their crops from livestock, birds and thieves. The higher water-holding capacity of the lowland soils and the ability to store excess water in the furrows better uses rainfall, reducing the need for widely dispersed gardens. Intercropping and crop rotation can also reduce the labour requirements for weeding. However, the initial establishment of raised beds and furrows requires considerable labour, that is, farmers adopting this system will need to work together or be helped with a revolving credit scheme that will enable them to hire additional labour or use machines.

An Integrated Approach to Food and Cash Cropping

Subsistence farmers' most important concern is to provide sufficient nutritious food for their families. Only after household needs are met can farmers consider the feasibility of entering the cash economy. Income generated from cash cropping is required for housing, health care and education. Food security is paramount in regions such as West Timor, and the cropping systems evolved in these areas aim to reduce total crop failure through drought or flooding (Pellokila et al. 1991). Cropping systems in South-East Asia must therefore meet the criteria of food production (food crops) and income generation (cash crops).

Recent experiments in West Timor have shown that rice (Borrell et al. 1998) and soybean (Van Cooten and Borrell 1999; R.M. Kelly pers. comm., 2000) can be grown successfully on raised beds in the wet season. Rice is an important food crop, supplying energy in the form of complex carbohydrates (Eggum 1979). However, rice production in eastern Indonesia is severely limited by drought (Borrell et al. 1998), and N and P deficiencies in the soil also limit yield (Pellokila et al. 1991). In contrast, soybean yields particularly well on soils depleted in both N and P, indicating the suitability of this grain legume to the harsh environment and poor soils of eastern Indonesia (R.M. Kelly pers. comm., 2000). Soybean is also an excellent source of protein, complementing the carbohydrates supplied by various cereals.

Garlic, an important cash crop, is grown mainly in the highlands of West Timor during the south-east monsoons (Pellokila et al. 1991; Simpson 1995). Garlic can be grown on raised beds in rotation with other crops (Simpson 1995). We also found that, when planted between April and June, garlic grew well on raised beds in the lowlands near Kupang. We observed that sequential cropping on raised beds of wet-season rice, soybean or cassava followed by dry-season sorghum, garlic, cassava or mung bean was a viable system that provided a balance of food (carbohydrates and protein) and cash income. Peanut (*Arachis hypogaea* L.) comprises another important cash crop in West Timor, being grown mainly as a monocrop in small areas (Pellokila et al. 1991).

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Intercropping is an example of risk-aversion management used by subsistence farmers to maximize rainfall use, and is an important part of existing cropping systems in south-eastern Indonesia (Simpson 1995). Although yields may be lower for individual crops within this system, total crop production is optimized, regardless of the type of wet season (Pellokila et al. 1991). Intercropping in Timor usually involves crops that mature after the maize harvest and can grow on residual soil moisture (Pellokila et al. 1991), that is, cassava, sorghum and pigeon pea (*Cajanus cajan* (L.) Millsp.). The effects of intercropping peanut and maize on maize yields have been studied in some detail by Bahtier et al. (1989), Salam Wahid et al. (1989a, b) and Zubachtirodin (1989). They conclude that crops such as peanut with similar growing seasons to that of maize should not be intercropped because they compete for available resources, reducing the potential maize yield and therefore the amount of food available to the household.

Intercropping on large raised beds was evaluated in the village of Oenesu, West Timor, during the 1997/98 wet season (Van Cooten and Borrell 1999). Maize, yam bean (*Pachyrrhizus erosus* (L.) Urban), cassava, traditional sorghum and pigeon pea were intercropped on raised beds that were 0.5 m high and 4 m wide. Between the large beds, rice and soybean were grown on smaller beds, 0.2 m high and 1.3 m wide. The surface of the large beds was flat (3 m), with sloping edges (0.5 m) into which yam bean was planted. Sorghum was planted along the edge of the beds with maize, pigeon pea and cassava intercropped in the centre of the beds. Maize, pigeon pea and cassava were sown in the first week of December at the start of the wet season (Figure 1). Sorghum was planted in the third week in December, followed by yam bean in the first week in January. The crops were harvested sequentially as they matured, beginning with maize at the end of March (2.6 t ha^{-1}). Yam bean (0.8 t ha^{-1}), sorghum (1.8 t ha^{-1}) and cassava (2.3 t ha^{-1}) were harvested in June, and pigeon pea (0.3 t ha^{-1}) in the second week of July.

The yields quoted were fresh weights, as the village had no drying facilities. These experiments highlighted the fact that it is possible to grow crops other than rice on the lowland clay soils in the wet season and, more importantly, that the total yield of this system per unit land area (7.8 t ha^{-1} fresh weight) is far greater than that achieved with rice monoculture (about 1.5 t ha^{-1} dry weight, Borrell et al. 1998). Moreover, crops could be harvested from late March to early July, guaranteeing continuity of food supply over this time. Periods of intermittent drought affected some crops more than others, but all crops yielded something at the end of the season.

Raised-bed cropping in Timor would also provide a mechanism for farmers to plant a traditional mixture of crop species on the more fertile alluvial soils, thus improving the output of the traditional system and ensuring the survival of species diversity. In a survey on the ethnobotany of Alor, eastern Indonesia, Van Cooten (1999) reported 57 plant species of importance to the Abui people. These species are used for food, medicines, poisons and dyes (Kelly and Van Cooten 1997).

Conclusions

The permanent raised bed system proposed in the northern Australian (Garside et al. 1992b; Borrell et al. 1997) and Indonesian (Borrell et al. 1998; Van Cooten and Borrell 1999) studies recommends modifications to the current agricultural systems in these regions, to obtain a more sustainable system with higher annual production.

Collectively, the complementary studies conducted in northern Queensland between 1989 and 1992 indicate that the double cropping of rice and field crops in rotation is feasible and may provide additional synergistic and logistic benefits over those found in the traditional rice/fallow system (Garside et al. 1992b). The key to integrating the various system components seems to depend on developing SSC technology for rice production. Regardless of where this technology is adopted in the tropics, acceptance of SSC by rice growers would lead to decreased water use and more efficient use of water. In addition, adoption of permanent raised bed concepts and controlled traffic would improve the timeliness of farm operations, facilitate the change from one crop to the next, and greatly improve the reliability of achieving multiple crops per year. This would lessen the probability of unproductive fallow periods. Incorporation of a grain legume such as soybean would improve the N economy of the system, and P requirements for field crops following rice may be reduced by growing rice under SSC.

Experiments undertaken in West Timor between 1993 and 1999 have shown that a range of crops, in addition to rice, can be grown on raised beds during the wet season, overcoming the previous limitation of waterlogging to crop growth. Initial construction of raised beds before the wet season in lowland areas, and maintenance of permanent structures thereafter, enables crops to be sown at the onset of the wet season, thereby avoiding end-of-season drought and significantly increasing crop yields. Appropriate mechanization in the form of a two-wheeled hand-tractor and associated bed-maker can be used to construct and maintain the beds. Early sowing and harvesting of the wet-season crop opens the way to plant a drought-resistant species such as

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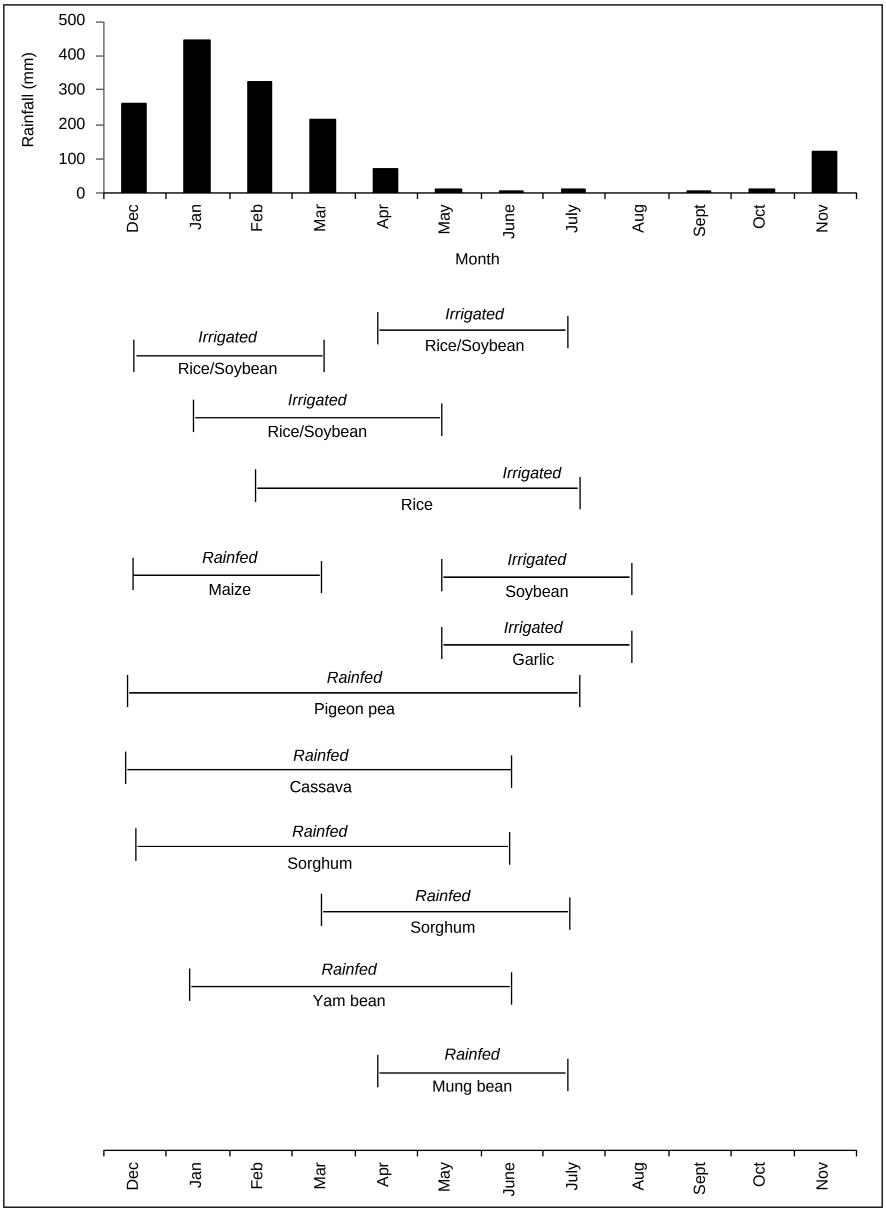

Figure 1. Cropping calendar for a raised-bed farming system in West Timor. Horizontal bars denote the length of the growing season for various crops. Each crop is also classified as either *irrigated* or *rainfed*. The total monthly rainfall was recorded at Kupang, West Timor, and is the mean of a 10-year period from 1985 to 1995.

sorghum in late March or early April, better using stored soil water from the end of the wet season. This system greatly increases the probability of attaining both wet- and dry-season crops each year, thus enhancing food security for subsistence farmers in eastern Indonesia. It also opens up the possibility of reforesting eroded upland cropping areas with a range of perennial species that would provide food, fodder, firewood, building materials and medicines, assuming that the subsistence farmers' basic food and/or cash crop requirements can be met by intensive lowland production.

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Together, the studies conducted in northern Queensland and eastern Indonesia provide a framework for using less water and increasing the WUE in rice-based cropping systems throughout South-East Asia. Saturated soil culture on permanent raised beds is the key technology underpinning these improved efficiencies.

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