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Review

Enhancing food security in semi-arid eastern Indonesia through permanent raised-bed cropping: a review

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Summary. Much of south-eastern Indonesia is mountainous and characterised by a semi-arid tropical environment. Soil erosion is a significant environmental problem facing the region, affecting both productivity of the land and water quality. The challenge for the region is to secure year-round food production in such a fragile environment. More than 90% of rain falls in a distinct wet season between November and April. Therefore, cropping in this region is dependent on matching crop growth with water supply. In particular, crop production depends on the efficient use of rainfall during the wet season, including avoidance of waterlogging, and efficient use of stored soil water during the dry season.

This paper summarises the results of a series of experiments undertaken in West Timor, Indonesia, between 1993 and 1999 aimed at developing a raised-bed cropping system. The objective of these studies was to better utilise the more fertile alluvial soils that are often susceptible to waterlogging during the wet season, allowing a range of crops to be grown in addition to rice.

Raised beds of height 0.2 m and width 1.5 m were constructed either manually or with an 8.5 hp two-wheeled hand tractor. A range of crops including soybeans, sorghum, maize, pigeon pea, yam bean and cassava were successfully grown on raised beds in the wet season in addition to rice, indicating that raised-bed technology overcomes the constraints of waterlogging in the wet season. Soybeans grew particularly well on raised beds, with December-sown crops producing almost twice the yield of January-sown crops (2.6 *v.* 1.4 t/ha). For rice and soybeans, early sown crops were better able to match growth with water supply, thereby avoiding end-of-season drought. Early sowing and harvesting of wet season crops enables a drought-resistant crop such as sorghum to be planted in late March or early April, utilising the stored soil moisture for grain production and also maintaining ground cover in the dry season.

It is argued that cropping systems based on permanent raised beds can reduce erosion in 2 ways. First, raised beds are a permanent structure and, with the inter-cropping and relay-cropping proposed, crops can provide all-year ground cover in lowland areas. Second, if sufficient food and cash crops are grown on raised beds to meet the basic needs of subsistence farmers, then upland cropping on steep slopes can be replaced by a variety of tree species, providing additional food, fodder, firewood and medicines. Together, these strategies have the capacity to enhance food production and security in the semi-arid areas of eastern Indonesia.

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Introduction and background

The region designated as south-eastern Indonesia includes the group of islands stretching from Bali in the west to Timor in the east, and straddles a dynamic crustal plate region. The islands of Bali, Lombok, Sumbawa and Flores through to Alor, which lie to the north of the crustal plate collision/subduction zone, are volcanic in origin. The islands of Sumba, Sabu, Rote and Timor are to the south of this zone and are marine in origin, the result of the Banda Arc System riding up onto the Australian crustal plate (Duggan 1991). Climatically, the further east and south one travels from Bali, the drier it becomes, with the wet season becoming shorter and more unpredictable (Ormeling 1957). The research outcomes presented in this paper are applicable to the drier regions of eastern Indonesia.

Stability of food supply is critical to the welfare of subsistence farmers in this semi-arid region where crop production is limited by poor soils (Pellokila *et al*. 1991) and water supply (Borrell *et al*. 1998). Most rain (>90%) falls in a distinct wet season between November and April, with little rain falling in the remaining months. To ensure food security, a cropping system is required that will enable subsistence farmers to produce sufficient nutritious food, despite negligible rain between May and October. Since cropping in this semi-arid region is dependent on matching crop growth with water supply, maximum production is reliant on the efficient use of rainfall during the wet season and of stored soil water during the dry season.

Soil erosion, an important environmental problem facing eastern Indonesia, reduces both the productivity of the land and water quality (Ormeling 1957; Duggan 1991). Geologically, the parental materials of Timor and the other uplifted islands are marine in origin or derived from marine sediment, including clay beds, coral and limestones, giving rise to specific soil types such as cracking clays, red earths and lithosols which are essentially calcareous. Soils derived from marine sediments have moderate to high erodibility, tend to be saline, and are readily dispersed in water. The uplifted islands are characterised by steep slopes, high wet season rainfall, erodible soils, and unstable junctions between sedimentary layers and seismic activity, all leading to natural instability.

The predominant agricultural production systems in this region (Simpson 1995) are (i) swidden (shifting/slash and burn) cultivation of rainfed crops, mainly maize; (ii) the cultivation of rainfed or irrigated rice (*Oryza sativa*) in lowland areas; (iii) house gardens with rainfed maize (*Zea mays*), cassava (*Manihot esculenta*) and beans intercropped with tree crops; (iv) cattle production in which the breeding herd is also used for *rencah* (a system of herding cattle in flooded rice fields to puddle the soil in preparation for rice planting) and; (v) harvesting of forest products such as tamarind (*Tamarindus indica* L.), candlenut (*Aleurites moluccana* (L.) Wild), sandalwood (*Santalum album* L.) and fuel wood. These production systems overlap one another and commonly exist side by side within a single family farm.

Of these systems, shifting (slash and burn) agriculture is experiencing yield decline due to eroded upland soils and a reduction in the fallow period (Pellokila *et al*. 1991), while rice production is limited by late sowing (Borrell *et al*. 1998) and nutrient deficiencies (Pellokila *et al*. 1991). All systems are constrained by drought. In the upland system, farmers grow maize, sorghum (*Sorghum* spp.), upland rice, pumpkins (*Cucurbita* ssp.), cassava and a mixture of legume species in the wet season. These crops are not grown on the more fertile valley soils because of their susceptibility to waterlogging. In contrast, rice grows well under waterlogged conditions, making it more suited to the alluvial soils. However, rice yields remain low on the alluvial soils (about 1.5 t/ha), although yields can be improved by sowing early into raised beds, thereby escaping end-of-season drought (Borrell *et al*. 1998).

Crops may fail in south-eastern Indonesia because of a sudden end to the wet season (Pellokila *et al*. 1991), highlighting the need to sow at the beginning of this season to better match crop growth with water supply (Borrell *et al*. 1998). With the present level of technology in this region, land cannot be prepared for rice until well into the wet season when enough rain has fallen to enable puddling of the soil. Delayed preparation of the soil results in late planting which increases the probability of water deficit during the grain filling period.

A number of methods have been developed in eastern Indonesia which allow the farmer to plant early and therefore avoid end-of-season drought (Prasetyo 1996; Utomo and Nazaruddin 1996). In one method, farmers till in the dry season and, if large tractors are not available, it can take more than 200 man-days with crowbars to prepare one hectare. Another method involves no tillage where farmers clear their land by either burning or using a herbicide (e.g. glyphosate). Following land preparation, farmers then have the option of direct seeding or transplanting. With the latter option, farmers plant seedlings in areas that are near reliable water sources, and by the time the seedlings are ready for transplanting, the soil is wet enough for cultivation (Pellokila *et al*. 1991). Advantages of this system are reduced labour inputs for land preparation and higher yields due to early harvesting. The success of this system is dependent on rice seedlings being transplanted on time. It will fail if transplanting is delayed. However, all of these options are still limited by the availability of labour because farmers are dividing their time between planting upland gardens and preparing lowland cropping areas.

Hence, there is a need to develop alternative cropping systems in south-eastern Indonesia which better utilise the more fertile lowland soils compared with the less fertile upland soils. In particular, a system is required which allows a range of crops in addition to rice to be planted early in the wet season in lowland areas. Similarities between the environments of northern Australia and eastern Indonesia suggest that common methods of crop improvement could be used in both regions. Studies in northern Australia (Garside *et al*. 1992*a*; Borrell 1993) have found that rice can successfully be rotated with upland crops such as soybeans (*Glycine max*) and maize using saturated soil culture on permanent raised beds. Saturated soil culture (SSC) is a method developed in northern Australia for soybeans (Troedson *et al*. 1989; Garside *et al*. 1992*b*) and rice (Borrell *et al*. 1991, 1997) in which plants are grown on raised beds with water maintained in the furrows below the bed surface. This permanent raised bed cropping system displayed considerable advantages over the traditional rice/fallow system, including improved water, nitrogen and phosphorus economies, energy savings, greater timeliness of operations and reductions in soil compaction (Garside *et al*. 1992*a*). These experiments suggested that similar benefits may be realised with permanent raised bed cropping in eastern Indonesia. Indeed, recent experiments in West Timor have highlighted the advantages of rice (Borrell *et al*. 1998) and soybeans (R. M. Kelly pers. comm.) grown on raised beds compared with traditional practices.

This paper summarises the results of a series of experiments conducted in West Timor between 1993 and 1999 aimed at developing a cropping system based on permanent raised beds. The key objective of these studies was to develop appropriate technologies to better utilise the more fertile alluvial soils that are often prone to waterlogging in the wet season, enabling a range of crops to be grown in addition to rice. We discuss the rationale behind, and our approach to, developing this system.

Components of the system

It was considered necessary to identify and examine in isolation, those cultural and management components likely to inhibit the development of a viable and practical system based on permanent raised beds. We have attempted to integrate these components in the discussion section. The following components are considered: (i) compatibility of raised beds for rice and upland cropping; (ii) timeliness of operations; (iii) water harvesting and drainage; (iv) utilising stored soil water; (v) mechanisation; (vi) weed control; (vii) erosion control; (viii) an integrated approach to food and cash cropping; (ix) living fences; and (x) availability of labour.

Compatibility of raised beds for rice and upland cropping

Upland crops such as maize, sorghum and soybean are not compatible with the flooded culture used for rice production. Therefore, in order to improve compatibility between rice and upland crops, rice needs to be grown under a different system. 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*. 1992*a*; Borrell 1993). This concept has been extended to eastern Indonesia where soybean (R. M. Kelly pers. comm.), maize, sorghum, garlic (*Allium sativum* L.), mungbeans (*Vigna radiata*) and cassava have been grown on raised beds in rotation with rice near Kupang in West Timor.

Timeliness of operations

Timeliness is an indicator of the ability to perform operations such as planting and harvesting at the optimum time (McPhee *et al*. 1995*c*). Timeliness can be improved by working faster, starting operations earlier, or by reducing the number of operations required.

The single largest constraint to cropping in eastern Indonesia is late planting of the wet season crop. Delayed sowing reduces yield because growth is poorly aligned with water availability, resulting in the crop experiencing end-of-season drought. All crops in a particular region may fail due to a sudden end of the wet season (Pellokila *et al*. 1991) and total crop failure may be as high as 1 year in 5 (McWilliam 1986). A related factor is the staggered plantings because farmers need to wait for cattle or tractors in order to cultivate. 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 the pest population from earlier plantings (Pellokila *et al*. 1991). Rice yields have been shown to be significantly less from plantings in March compared with January due to higher populations of *Nymphula depunctalis* in the later sown crop (Sama *et al*. 1989).

Recent experiments in eastern Indonesia (Borrell *et al*. 1998) have found that 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. Comparing the early and late sowing of an improved rice genotype on raised beds in West Timor, Borrell *et al*. (1998) found dry matter production was significantly higher for the crop sown in mid December compared with that sown in mid January. They concluded that 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. Similarly, it has been observed that December-sown soybeans spaced at 20 plants/m^2 yielded almost twice that of January-sown soybeans at 50 plants/m^2, due to more pods per plant and larger seed size (R. M. Kelly pers. comm.). These responses are consistent with other soybean studies that show a delay in sowing date, under conditions of declining photoperiod, reduces dry matter yield (Johnson and Major 1979; Beech *et al*. 1988; Mayers *et al*. 1991). Therefore, permanent raised beds enable farmers to sow at the optimum time, providing a means of better matching crop growth to water supply and phenology.

Water harvesting and drainage

Water shortage is a major constraint to agricultural production in eastern Indonesia. Duggan (1991) defines the problem as the underexploitation of available water resources and continued dependence on rainfall with all of its uncertainty. She suggests that key areas for further attention in development and aid projects are the harvesting and storage of the wet-season surplus water through collection of rainfall, retention and storage of runoff, and more efficient use of natural reserves on flood plains and in aquifers. Pellokila *et al*. (1991) further examine water harvesting by defining the ideal cropping area as one that has sufficient drainage to prevent waterlogging but is capable of storing sufficient moisture to ensure that the crop is not stressed during periods of drought. Although drought is normal in south-eastern Indonesia, excess rainfall is common during January and February when the north-west monsoons are at their peak. Waterlogging can occur for a number of weeks following cyclonic activity, particularly if drainage is poor. In fact, cropping areas can be inundated with 250 mm of rainfall in 3 days following a cyclone. The natural occurrence of ideal cropping areas as suggested by Pellokila *et al*. (1991) is 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 in the furrows during periods of low rainfall (Borrell *et al*. 1998).

Rainfall within the wet season can also be highly variable, resulting in patches of intermittent water deficit between periods of intense rainfall. A dry period of 2 weeks during anthesis can greatly reduce yields of a determinant crop such as maize, although drought during the vegetative period has less effect on yield (Pellokila *et al*. 1991). These intermittent droughts occur every wet season and since it is not yet possible to predict when they will occur, farmers are vulnerable to this risk. However, the effect of intermittent drought can be minimised by harvesting and storing more water during intense rainfall periods, thereby increasing the availability of water to the crop during subsequent dry periods. Within bunded fields, furrows between raised beds have the capacity to capture water during high rainfall events without causing waterlogging, providing more water for crops if dry spells do occur.

There is some evidence that it is not necessary to flood rice to obtain high grain yield and quality. Studies in northern Australia found no significant difference in yield and quality of rice grown on raised beds under saturated soil culture compared with flooded culture, yet plants grown on raised beds used about 32% less water in the wet and dry seasons (Borrell *et al*. 1997). It was concluded that the lower water table and hydraulic conductivity associated with saturated soil culture are likely to be most beneficial in relatively porous, non-swelling soils where flooding provides a greater head for increased percolation.

Utilising stored soil water

For the 10-year period between 1985 and 1995, only 3% of the annual rainfall in Kupang, West Timor, fell

Table 1. Total monthly rainfall (mm) from January to December recorded at Kupang, West Timor, 1985–95

Year	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	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

during the 6 months to October (Table 1). Therefore in rainfed systems, crops sown at the end of the wet season will need to rely almost exclusively on stored soil water for growth. 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), harvesting of these crops can occur by the end of March. This opens the way for drought-resistant crops such as sorghum to be sown into the beds in late March or early April. Rainfall data for the 10 years preceding 1995 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 (Table 1). This suggests that, on average, sorghum can be planted into a near-full soil water profile at the start of the dry season. If, for example, 150 mm of soil water was available to the crop at the beginning of the dry season, and the crop produced dry matter at an efficiency of 4 $g/m^2.mm$ (Peng and Krieg 1992), then 6 t/ha of dry matter could be produced. Assuming a harvest index of 0.4, the sorghum crop could yield 2.4 t/ha of grain. Experiments have shown that drought-resistant sorghum lines can yield over 2 t/ha in southern India (Borrell *et al*. 1999) and that hybrids can yield over 5 t/ha in northern Australia (Borrell and Douglas 1996) when grown on stored soil water under a terminal deficit. An alternative opportunity crop for the dry season is quick-maturing mungbeans. Therefore, relay cropping of sorghum or mungbeans immediately after wet-season rice or soybeans is an effective means of utilising stored soil water.

Mechanisation

Permanent cropping areas need to be established, yet on the heavy clay soils draught animals are not appropriate, and hand cultivation is time consuming. Duggan (1991) suggests that production from the land must be sustainable within the given technological circumstances, and for eastern Indonesia this means an agricultural production system without sophisticated mechanisation in the foreseeable future.

What then is an appropriate level of mechanisation for a low-external-input cropping system for subsistence farmers in south-eastern Indonesia? In order to plant early in the wet season, raised beds need to be constructed prior to the commencement of monsoonal rains (Borrell *et al*. 1998). When a raised bed cropping area is being established for the first time, beds will need to be carefully formed. However, if the raised beds are to be permanent structures, they will require only maintenance in subsequent years. Raised beds can be constructed manually or mechanically. It is estimated that the manual construction of raised beds on clay soils will take more than 200 man-days/ha. Considering the weakened state of the labour force at the end of the dry season due to malnutrition, combined with time constraints, manual construction is not a practical option for larger areas (i.e. >5 ha). A viable alternative is to use two-wheeled hand tractors with 8.5 hp capacity diesel engines. Hand-tractors can be bought or leased by village communities, enabling villagers to construct or maintain raised beds, thereby taking advantage of the benefits of early planting.

There are additional benefits of mechanisation in a permanent raised bed system compared with a conventional tillage system. The firm soil conditions which are optimal for traction and traffic during field operations are quite different to the friable conditions required for plant growth and crop production, resulting in a conflict between the requirements for traffic and crop growth (Braunack *et al*. 1995). Permanent separation of the traffic zone from the crop growth zone, known as 'controlled traffic', has been examined in Australia (Murray and Tullberg 1986; Tisdall and Adem 1986; Braunack *et al*. 1995; McPhee *et al*. 1995*a*, 1995*b*, 1995*c*), the United States (Taylor 1983), the Netherlands (Perdok and Lamers 1985) and the United Kingdom (Campbell *et al*. 1986). Of particular relevance to subsistence farming is the fact that smaller tractors can be used in controlled traffic systems due to reduced draught, improved traction and vehicle support. Hence, the operation of hand-tractors would be maximised in a controlled traffic system.

The use of hand-tractors to build raised beds is being tested in the village of Oenesu, about 12 km south of Kupang in West Timor. This village lies on a plain of black clay soil and the potential exists to crop about 200 ha of land. A series of springs supply water at the interface of a coral ridge and black clay. An area of 2 ha was cropped in the 1997–98 wet season and 5 ha in the 1998–99 wet season to evaluate the permanent raised bed system. As part of this evaluation, ploughing, bed-making and seeding implements were developed for use with the hand-tractor. While a larger tractor (e.g. 65 hp) may initially assist in ploughing undeveloped land, its cost is about 10 times that of a hand tractor to purchase. Furthermore, maintenance and repairs are more difficult and costly at the village level for large tractors, which are also more prone to bogging in the wet season. Therefore, the use of hand-tractors at the village level appears to be appropriate for low-external-input cropping systems because the benefits (food security and cash) derived from the additional food produced exceed the costs (purchase/lease and maintenance) of using this level of mechanisation. Another advantage of hand-tractors is their ability to power other implements such as water pumps, threshers, corn mills and trailers. Training in tractor operation and maintenance should be provided at the village level.

Weed control

Farmers in eastern Indonesia need to weed their crops at least twice during the wet season, the most critical period being the first 3 weeks after planting (Metzner 1980; Field 1986*b*). Delaying weeding by more than 25 days after planting can result in yield reductions of 25%. Weeding can take more than 40 man-days/ha on heavy soils because farmers have to use machetes or iron rods to pull out weeds. Weeding is faster on more friable soils where the Dutch hoe is commonly used.

The critical issue for raised bed cropping is the extent to which weeds will colonise this system compared with a flooded rice-based system. Weed growth in unflooded systems is generally 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). A negative correlation was observed between weed growth and water use in rice by De Datta *et al*. (1973). They found the number of weeds declined with increasing depth of floodwater. Similarly, method of irrigation greatly affected weed growth in raised-bed rice culture in northern Australia such that weed dry mass at maturity was negatively correlated with total water use in the wet (r^2 = 0.82; P<0.05) and dry (r^2 = 0.80; P<0.05) seasons (Borrell *et al*. 1997). Weed growth in unflooded conditions appears to be higher for a number of reasons (De Datta 1981). Grass growth is favoured by moist but unflooded soil, warm temperatures and adequate light. In addition, lack of floodwater prevents the effective spread of granular herbicides, and higher temperatures and light may cause rapid breakdown of herbicidal components of some compounds.

On the other hand, experiments in the Philippines on rice grown under a saturated-soil regime found that no additional weed control measure, manual or chemical, was necessary to achieve water savings compared with flooded transplanted rice (Tabbal *et al*. 1992). In this system when weed pressures were high, shallow flooding during the first 45 days after transplanting followed by maintenance of a saturated-soil regime for the rest of the season achieved the same yield as conventional transplanted rice, but used 30% less water.

To successfully grow rice on raised beds in northern Australia, Borrell *et al*. (1997) concluded that additional herbicide, and therefore cost, may be required to adequately control weeds in a delayed flood or unflooded system, particularly in the wet season. Likewise, a herbicide may initially be required to control weeds when opening up undeveloped clay soils for raised bed cropping in eastern Indonesia. Once the system is developed, however, herbicides should generally not be necessary. Instead, a hand tractor could be used early in crop growth to control weeds via inter-row cultivation. Alternatively, a manual inter-row weeding tool could be used (Simpson 1995). This technique has been shown to successfully address labour constraints for weeding in West Timor.

Rotational cropping systems also 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 in West Timor that wet season soybeans quickly reach full canopy cover providing crop establishment is good, choking out competing weeds. The subsequent dry season sorghum crop is drought-resistant, competing well with weeds in this arid environment. Limited data collected in northern Australia also indicate that weed populations were considerably reduced in a controlled traffic direct-drilling system compared with conventional tillage (McPhee *et al*. 1995*c*). The reasons for this were not clear, although it was suggested that weed establishment could have been inhibited by a combination of continuous ground cover from stubble and competition from growing crops, combined with the lack of soil disturbance.

Therefore a combination of stringent herbicide use, mechanical cultivation, manual weeding and rotational cropping systems could be used to control weeds on permanent raised beds in south-eastern Indonesia.

Erosion control

The islands of south-eastern Indonesia generally have a topography comprising of a mountainous interior surrounded by coastal lowlands. Mountains often cover 70% of the terrain, and slopes of greater than 50% are common (Pellokila *et al*. 1991). Farmers crop areas with slopes of greater than 20%, resulting in high soil losses. Intense rainfall on exposed land at the start of the wet season may result in soil losses as high as 200 t/ha.year (Carson 1979). Hence the contemporary surface of the region is a degraded landscape (Duggan 1991). As well as natural instability, the history of land use has exacerbated this degradation, creating an environment characterised by landslides, surface erosion, weedy secondary vegetation, turbid surface run-off and large river sediment loads. It is not surprising then, that soil erosion is considered to be one of the most important environmental problems facing eastern Indonesia.

A major limitation to soil conservation in developing countries is the argument that it introduces an additional labour component to communities which cannot readily absorb it (Duggan 1991). Yet future generations must be considered. The present rates of soil erosion cannot be sustained if the growing population is to be fed.

Cropping systems based on permanent raised beds can reduce erosion in two ways. First, the existence of raised beds on clay soils in the lowlands adds considerable stability to the system because the beds are a permanent structure and, with the intercropping proposed, crops can provide all-year ground cover. Therefore bare soil is not exposed to high rainfall at the start 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. Genetic diversity of native tree species is also maintained and a haven provided for wildlife. 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 raised beds. Replacement of upland cropping areas with forests assumes that all of the basic food/cash crop requirements can be met by the growth of a diverse intercrop on large raised beds, interspersed by smaller raised beds planted to monocultures of rice or soybeans in the wet season and sorghum or mungbeans in the dry season (see 'An integrated approach to food and cash cropping' section below).

An integrated approach to food and cash cropping

Cropping systems in semi-arid eastern Indonesia must meet the dual criteria of food production (food crops) and income generation (cash crops). The most important issue for subsistence farmers is to provide sufficient food for their families. Not only is the volume of food important, but the quality of food must meet the nutritional needs of the household. Food security is paramount in semi-arid regions such as West Timor, and cropping systems have evolved in these areas to reduce total crop failure due to drought or flooding (Pellokila *et al*. 1991). Only after household needs are met can farmers consider entering the cash economy. Income generated from cash cropping is required for housing, health care and education.

Another important factor in food security is the tolerance of crops to periods of intermittent drought during the wet season and terminal drought during the dry season. Determinate crops such as maize, sorghum and rice are more susceptible to periods of drought compared with indeterminate crops such as mungbeans, pigeon pea (*Cajanus cajan*) and peanuts (*Arachis hypogaea*), and crops that accumulate their yield over time such as tubers (Pellokila *et al*. 1991).

Recent experiments in West Timor have shown that rice (Borrell *et al*. 1998) and soybeans (R. M. Kelly pers. comm.) 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, soybeans yielded 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.). Soybean is also an excellent source of protein, complementing the carbohydrate supplied by the various cereals.

Garlic is an important cash crop and is grown mainly in the highlands of West Timor during the southeast monsoons (Pellokila *et al*. 1991; Simpson 1995). Garlic can be grown on raised beds in rotation with other crops (Simpson 1995). We also found garlic grew well on raised beds in the lowlands near Kupang when planted between April and June. We observed that sequential cropping on raised beds of wet season rice, soybeans or cassava followed by dry season sorghum, garlic, cassava or mungbeans was a viable system providing a balance of food (carbohydrate and protein) and cash income. Peanuts are another important cash crop in West Timor, being grown mainly as a monocrop in small areas (Pellokila *et al*. 1991).

Intercropping is an important part of existing cropping systems in south-eastern Indonesia. Although yields may be lower for individual crops within this system, total crop production is optimised regardless of the type of wet season (Pellokila *et al*. 1991). Intercropping is an example of risk averse management used by subsistence farmers to maximise rainfall utilisation, ensuring that production levels satisfy household needs with minimal use of inputs (Simpson 1995). In Timor, intercropping generally involves crops that mature after the maize harvest and can grow on residual soil moisture (Pellokila *et al*. 1991) i.e. cassava, sorghum and pigeon pea. Crops with a similar growing season to maize such as peanuts should not be intercropped because they compete for available resources, reducing the potential maize yield and therefore the amount of food available for the household. The effects of intercropping peanuts and maize on maize yields have been studied in some detail by Salam Wahid *et al*. (1989*a*, 1989*b*), Bahtier *et al*. (1989) and Zubachtirodin (1989).

During the 1997–98 wet season we examined intercropping on large raised beds in the village of Oenesu, West Timor. Maize, yam bean (*Paccyrrizuz erosus*), cassava, traditional sorghum and pigeon pea were intercropped on raised beds of height 0.5 m and width 4 m. Between the large beds, rice and soybean were grown on smaller beds of height 0.2 m and width 1.3 m. The surface of the large beds was flat (3 m), with sloping edges (0.5 m) into which yam beans were 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. Sorghum was planted in the third week in December followed by yam bean in the first week in January. The crops were harvested sequentially upon maturity, beginning with maize at the end of March (2.6 t/ha). Yam bean (0.8 t/ha), sorghum (1.8 t/ha) and cassava (2.3 t/ha) were harvested in June and pigeon pea (0.3 t/ha) was harvested in the second week in July. The yields quoted are fresh weights, since no drying facilities existed in the village. These experiments highlight 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 fresh weight) is far greater than that achieved with a rice monoculture (about 1.5 t/ha dry weight, Borrell *et al*. 1998). Moreover, crops were harvested over a considerable period 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.

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). 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.

Living fences

The success of intensive cropping on raised beds in the more fertile lowland areas is dependent on the ability of farmers to exclude animals from these areas. Simpson (1995) noted that livestock intrusion into irrigated plots was a major constraint to the adoption of irrigated mungbean cropping in the dry season. Traditionally in a shifting slash and burn system, farmers slash their fields and use the timber to construct fences before burning off. Such timber fences are highly susceptible to attack by termites and fire. Suitable timber for fencing is becoming increasingly scarce due to continuing deforestation. Farmers are spending up to one-third of their land preparation time building and maintaining these fences (Field 1986*a*).

Living fence technology (Field 1986*a*; Nitis *et al*.

1990; Simpson 1995) can be used to address these problems. Fences can be developed from a single tree species such as *Gliricidia sepium* (Simpson 1995), with 3 m long cuttings planted at a 30–40 degree angle and then woven between upright posts to form a hedge. Alternatively, living fences can be developed from a range of tree species (Field 1986*a*; Nitis *et al*. 1990) to provide fodder in addition to security. Field (1986*a*) describes the ideal living fence as having three strata. Inside the traditional wooden fence a row of *Actinodaphne velutins* is planted around the perimeter of the garden at a high rate. About 0.2 m inside this, scarified seed of *Leucaena leucocephala* is also sown at a high rate. These trees will grow quickly to form a double barrier that should be impenetrable to animals. Any gaps can be filled by planting cuttings or seedlings. As well as forming a barrier to keep animals away from cropping areas, the living fence also provides a valuable source of fodder for livestock. In a preliminary survey of the indigenous and localised fodder trees of Nusa Tenggara Timur, 46 plant species were identified as sources for cattle feed (Faint and Van Cooten 1997), and the suitability of these species as living fences requires further study.

Another possibility is to place a living fence around the perimeter of a whole village. This requires less length of fence compared with fencing each individual garden (i.e. resources are used more efficiently), and also ensures that all members of the village community benefit rather than just a few. This may reduce the theft and sabotage that is common when one group progresses faster than another in the village community (Simpson 1995). We are currently implementing this approach in the village of Oenesu where 3 km of fencing encloses an area of 56 ha. Providing the fence is adequately maintained by the village community, cropping areas within the enclosure should be protected from livestock.

Availability of labour

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). In an attempt to reduce the risk of crop failure, farmers may cultivate 3 or 4 swidden gardens, 5–10 km apart, as well as cultivating 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 also increase the labour and time required to walk between these gardens.

The permanent raised bed system combines upland swidden gardening and rice cultivation in the one field, thus reducing the labour and time involved in walking between widely dispersed fields and increasing the opportunities for farmers to protect their crops from livestock intrusion, bird damage and stealing. The higher water holding capacity of the lowland soils and the ability to store excess rainfall in the furrows better utilises rainfall, reducing the need for widely dispersed gardens. Labour requirements for weeding can be reduced by the use of intercropping and crop rotation. However, this system requires considerable labour to initially form the raised beds and furrows. To overcome this limitation, farmers need to work together or be helped with a revolving credit scheme, enabling them to hire the additional labour or mechanisation needed to introduce the system to their fields.

Discussion

Crop production in south-eastern Indonesia is constrained by both drought and waterlogging. In the wet season, lowland cropping on the more fertile alluvial soils is limited to rice production because other crops do not grow well under waterlogged conditions. Depending on the proximity of rice fields to water sources, crops may be supplemented with irrigation from springs or streams during this period. On the other hand, upland cropping is rainfed and limited by water supply and soil fertility. In particular, the calcareous soils are depleted in nitrogen, phosphorus, zinc and iron. The exposure of cultivated upland soils to intense rainfall at the commencement of the wet season has contributed to significant erosion, resulting in a degraded landscape.

Labour is a scarce resource at the beginning of the wet season. In order to spread risk in a semi-arid environment, farmers divide their labour between establishing upland cropping areas (primarily maize) and lowland rice fields (Simpson 1995). Generally these areas are some kilometres apart, requiring considerable time and energy to prepare both sites. The upland areas are often cultivated first, resulting in late planting of the rice crop. Delaying the sowing of the rice crop from mid December to mid January dramatically increases the risk of end-of-season drought (Borrell *et al*. 1998). Having more than 1 cropping site is also a security risk, for when the farmer is away, it is difficult to control livestock intrusion, bird damage and theft (Simpson 1995).

Recent studies in West Timor between 1993 and 1999 suggest that alternative cropping strategies can be adopted to overcome some of these constraints. The key strategy arising from these studies is the development of permanent raised beds on the more fertile lowland soils.

Providing the height of the raised beds is adequate to ensure drainage, crops other than rice can be grown, taking advantage of improved water supply and soil fertility for a range of crops. Rice does not appear to be well suited to the harsh environment of West Timor, with yields often limited to 1.5 t/ha (Borrell *et al*. 1998). Other crops such as soybean (R. M. Kelly pers. comm.) appear to be better adapted to this environment, and drought-resistant species such as cassava, pigeon pea, sorghum and maize are even more suitable. Growing a range of these species (including rice) on raised beds during the wet season provides a balance of food (carbohydrate and protein) and cash crops. Phenological variation among species ensures that periods of intermittent drought will not adversely affect all species to the same extent. In addition to this drought-escape mechanism, species also vary in drought-resistance mechanisms, further minimising risk to subsistence farmers. These lowland cropping areas can be bounded by living fences to exclude stock and discourage theft, reducing the security risk associated with more intensive farming.

An inability to match crop growth to water supply has significantly constrained crop production in south-eastern Indonesia, with late planting of the wet season crop being the single largest constraint. Late-sown crops mature after the wet season has ceased, experiencing end-of-season drought. The construction of raised beds before the commencement of wet season rains, either manually or with two-wheeled hand tractors, provides a mechanism for sowing crops immediately after the onset of the wet season, thereby minimising the risk of drought during grain filling. Sowing into raised beds in December rather than January increased rice and soybean yields by 16% and 82%, respectively (Borrell *et al*. 1998; R. M. Kelly pers. comm.). Permanent raised beds are the key to improving water management by providing excellent drainage during periods of intense rainfall in the wet season, yet capturing and storing water in the furrows during periods of low rainfall (Borrell *et al*. 1998). Utilisation of stored soil water is the key to dry season crop production in Timor. Since less than 5% of the annual rainfall occurs in the 6 months to October in the Kupang region of West Timor (1985–1995 data), it is critical that a drought-resistant crop such as sorghum be sown in late March or early April to ensure adequate soil water reserves for the completion of grain filling. Early sowing of the dry season crop is dependent on early harvesting of the wet season crop. Such timeliness can only be achieved with raised-bed cropping. In addition, rotational cropping systems have the potential to limit the build-up of weeds, insects and diseases, since the environment is constantly changing, thereby preventing the proliferation of any single weed species, insect or disease.

Another important strategy of the raised bed system is the restoration of degraded upland cropping areas. Meeting farmers needs through improved cropping practices in lowland areas opens the way for upland areas to be returned to agro-forests. Restoration of the degraded landscape must be a high priority to ensure food security for the region’s growing population. It has been argued that rural communities cannot readily absorb the additional labour component required to conserve their soils (Duggan 1991). The labour savings associated with the more intensive lowland cropping system proposed in this paper should enable more labour to be allocated to the management of upland forests, thereby slowing the current rates of erosion.

Providing farmers have access to some land, whether it be upland or lowland, the principles outlined in this paper can be implemented. For example, those farmers with access to only rice soils can grow a range of annual and perennial species on large beds, thereby reducing the risk of total crop failure, yet increasing the diversity of food available. Even upland regions have soil in the valleys, a result of erosion from the surrounding slopes. Raised beds could be formed in these fertile valleys and used for annual cropping, thus reducing the need to crop the slopes.

Conclusions

The permanent raised bed system proposed in this paper recommends modifications to the current upland and lowland agricultural systems of south-eastern Indonesia, resulting in higher annual production from a more sustainable system. Experiments conducted 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. Assuming that the basic food/cash crop requirements of subsistence farmers can be met from intensive lowland production, the option exists to reforest the eroded upland cropping areas with a range of perennial species to provide food, fodder, firewood, building materials and medicines. Initial construction of raised beds prior to 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. Soybean yields were almost doubled by sowing in December rather than January, highlighting the advantage of early sowing into raised beds. Since manual construction of raised beds took more than 200 man-days/ha, appropriate mechanisation in the form of a two-wheeled hand tractor and associated bed-maker were developed for the construction and maintenance of the beds. Early sowing and harvesting of the wet season crop opens the way to plant a drought-resistant species such as sorghum in late March or early April, better utilising 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. These combined strategies provide a means of enhancing food security for subsistence farmers in semi-arid eastern Indonesia.

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References

Bahtier, Zubachtirodin, and Subandi. (1989). Pengaruh tumpangsari jagung kacang-kacangan dan populasi jagung terhadap pertumbuhan gulma dan hasil. Laporan Komponent Technologi Tanaman Pangan 1988–89. The influence of corn and legume intercropping and corn population on the growth of weeds and on yields. Report of the Food Crops Technology Component, 1988–89'. (Kupang: NTASP.)

Beech, D. F., Garside, A. L., and Wood, I. M. (1988). Response of soybeans to sowing date during the wet season in the Ord Irrigation Area, Western Australia. *Australian Journal of Experimental Agriculture* **28**, 357–65.

Borrell, A. K. (1993). Improving efficiencies of nitrogen and water use for rice in semi-arid tropical Australia. PhD Thesis, The University of Queensland.

Borrell, A. K., and Douglas, A. C. L. (1996). Maintaining green leaf area in grain sorghum increases yield in a water-limited environment. *In* 'Proceedings of the 3rd Australian Sorghum Conference'. Tamworth, 20–22 February 1996. Australian Institute of Agricultural Science Occasional Publication No. 93. (Eds M. Foale and R. G. Henzell.) pp. 315–22. (The Australian Institute of Agricultural Science: Melbourne.)

Borrell, A. K., Bidinger, F. R., and Sunitha, K. (1999). Stay-green associated with yield in recombinant inbred sorghum lines varying in rate of leaf senescence. *International Sorghum and Millets Newsletter,* **40** (in press).

Borrell, A. K., Fukai, S., and Garside, A. L. (1991). Alternative methods of irrigation for rice production in tropical Australia. *International Rice Research Newsletter* **16**, 28.

Borrell, A. K., Garside, A. L., and Fukai, S. (1997). Improving efficiency of water use for irrigated rice in a semi-arid tropical environment. *Field Crops Research* **52**, 231–48.

Borrell, A. K., Kelly, R. M., and Van Cooten, D. E. (1998). Improving management of rice in semi-arid eastern Indonesia: responses to irrigation, plant type and nitrogen. *Australian Journal of Experimental Agriculture* **38**, 261–71.

Braunack, M. V., McPhee, J. E., and Reid, D. J. (1995). Controlled traffic to increase productivity of irrigated row crops in the semi-arid tropics. *Australian Journal of Experimental Agriculture* **35**, 503–13.

Campbell, D. J., Dickson, J. W., Ball, B. C., and Hunter, R. (1986). Controlled seedbed traffic after ploughing or direct drilling under winter barley in Scotland, 1980–1984. *Soil and Tillage Research* **8**, 3–28.

Carson, B. R. (1979). Use of the universal soil loss equation to predict erosion of the Timorese landscape. (University of British Colombia: Vancouver, Canada.)

De Datta, S. K. (1981). Principles and Practices of Rice Production. (John Wiley and Sons: New York.) 618 p.

De Datta, S. K., Krupp, H. K., Alvarez, E. I., and Modgal, S. C. (1973). Water management practices in flooded tropical rice. *In* 'Water Management in Philippine Irrigation Systems: Research and Operations'. pp. 1–18. (International Rice Research Institute: Los Banõs, Philippines.)

Duggan, K. (1991). Land and environment in NTT. *In* 'Nusa Tenggara Timur: the Challenges of Development. Political and Social Monograph 12'. (Eds C. Barlow, A. Bellis and K. Andrews.) pp. 31–8. (The Australian National University: Canberra.)

Eggum, B. O. (1979). The nutritional value of rice in comparison with other cereals. *In* 'Proceedings of the Workshop on Chemical Aspects of Rice Grain Quality'. pp. 91–111. (International Rice Research Institute: Los Banõs, Philippines.)

Faint, M., and Van Cooten, D. E. (1997). A preliminary survey of the indigenous and localised fodder trees of Nusa Tenggara Timur. YBM Monograph 2, Yayasan Bina Mandiri, Kupang.

Field, S. P. (1986*a*). Living fences for food gardens—practical or not? *In* 'Indonesia–Australia NTT Livestock Development Project Completion Report'. Vol. 4. pp. 39–46. (Directorate General of Livestock Services: Kupang.)

Field, S. P. (1986*b*). Report on the food crop experimental program for the 1984–1985 wet season. *In* 'Indonesia-Australia NTT Livestock Development Project Completion Report'. Vol. 4. pp. 132–213. (Directorate General of Livestock Services: Kupang.)

Garside, A. L., Borrell, A. K., Ockerby, S. E., Dowling, A. J., McPhee, J. E., and Braunack, M. V. (1992*a*). An irrigated rice-based cropping system for tropical Australia. *In* 'Proceedings of the 6th Australian Agronomy Conference'. The University of New England, Armidale. (Eds K. J. Hutchinson and P. J. Vickery.) pp. 259–61. (The Australian Society of Agronomy: Melbourne.)

Garside, A. L., Lawn, R. J., and Byth, D. E. (1992*b*). Irrigation management of soybean (*Glycine max* (L.) Merrill) in a semi-arid tropical environment. III. Response to saturated soil culture. *Australian Journal of Agricultural Research* **43**, 1033–49.

Johnson, D. R., and Major, D. J. (1979). Harvest index of soybean as affected by planting date and maturity rating. *Agronomy Journal* **71**, 538–41.

Kelly, R. M., and Van Cooten, D. E. (1997). Useful Plants of Alor. YBM Monograph 1, Yayasan Bina Mandiri, Kupang.

Mayers, J. D., Lawn, R. J., and Byth, D. E. (1991). Agronomic studies on soybean [*Glycine max* (L.) Merrill] in the dry season of the tropics. II. Interaction of sowing date and sowing density. *Australian Journal of Agricultural Research* **42**, 1093–107.

McPhee, J. E., Braunack, M. V., Garside, A. L., Reid, D. J., and Hilton, D. J. (1995*a*). Controlled traffic for irrigated double cropping in a semi-arid tropical environment: Part 1. Machinery requirements and modifications. *Journal of agricultural Engineering Research* **60**, 175–82.

McPhee, J. E., Braunack, M. V., Garside, A. L., Reid, D. J., and Hilton, D. J. (1995*b*). Controlled traffic for irrigated double cropping in a semi-arid tropical environment: Part 2. Tillage operations and energy use. *Journal of agricultural Engineering Research* **60**, 183–9.

McPhee, J. E., Braunack, M. V., Garside, A. L., Reid, D. J., and Hilton, D. J. (1995*c*). Controlled traffic for irrigated double cropping in a semi-arid tropical environment: Part 3. Timeliness and trafficability. *Journal of agricultural Engineering Research* **60**, 191–9.

McWilliam, A. (1986). Profile on the domestic economy of smallholder farmers in the Besi Pae project area 1984–85. *In* 'Indonesia-Australia NTT Livestock Development Project Completion Report'. Vol. 7. pp. 221–303. (Directorate General of Livestock Services: Kupang.)

Metzner, J. K. (1980). Disequilibrium of agricultural regions in the eastern Lesser Sunda Islands. *Applied Geography and Development* **15**, 62–8.

Murray, S. T., and Tullberg, J. N. (1986). Controlled traffic cropping system. *In* 'Proceedings of a Conference on Agricultural Engineering'. pp. 234–8. Publication No. 88/9. (Institution of Engineers: Australia.)

Nitis, I. M., Lana, K., Sukanten, W., Suarna, M., and Putra, S. (1990). The concept and development of the three-strata forage system. *In* 'Shrubs and Tree Fodders for Farm Animals'. Proceedings of a workshop in Denpasar, Indonesia, 24–29 July 1989. (International Development Research Centre: Canada.)

Ormeling, F. J. (1957). 'The Timor Problem: a Geographical Interpretation of an Under-developed Island.' (Groningen: Wolters.) 248 p.

Pellokila, C., Field, S., and Momuat, E. O. (1991). Food crops for Nusa Tenggara Timur. *In* 'Nusa Tenggara Timur: the Challenges of Development. Political and Social Monograph 12'. (Eds C. Barlow, A. Bellis, and K. Andrews). pp. 121–43. (The Australian National University: Canberra.)

Peng, S., and Krieg, D. R. (1992). Gas exchange traits and their relationship to water use efficiency of grain sorghum. *Crop Science* **32**, 386–91.

Perdok, U. D., and Lamers, J. G. (1985). Studies of controlled agricultural traffic in the Netherlands. *In* 'Proceedings of the International Conference on Soil Dynamics'. Auburn, AL, USA, 17–19 June, 1985. Vol 5. pp. 1070–85. (National Machinery Tillage Laboratory.)

Prasetyo, Y. (1996). 'Bertanam Padi Gogo Tanpa Olah Tanah.' p. 65. (Penebar Swadaya: Jakarta.) ISBN 979-489-391-9.

Salam Wahid, A., Fadahly, A. F., Supadmo, H., and Djamaluddin. (1989*a*). Pengaruh jarak tanam dalam barisan dan jumlah tanaman jagung tiap rumpun terhadap hasil tumpangsari jagung dengan kacang tanah. Laporan Komponent Technologi Tanaman Pangan 1988/89. (The influence of planting distances in rows and the number of corn seedlings per cluster on the results of corn and peanut intercropping. Report of the Food Crops Technology Component, 1988–89.) NTASP, Kupang.

Salam Wahid, A., Zubachtirodin, Momuat, S., and Subandi. (1989*b*). Pengaruh waktu tanam kacang tanah pada sistem tumpangsari dengan jagung. Laporan Komponent Technologi Tanaman Pangan 1988–89. (The influence of the planting time of peanuts on the system of intercropping with corn. Report of the Food Crops Technology Component, 1988–89.) NTASP, Kupang.

Sama, S., Rahamma, S., and Faisal. (1989). Pengaruh waktu tanam dan penggunaan varietas padi dalam pengalian hama. Laporan Komponent Technologi Tanaman Pangan 1988–89 (The influence of planting time and the use of rice varieties on the control of plant diseases. Report of the Food Crops Technology Component, 1988–89). NTASP, Kupang.

Simpson, S. L. (1995). Post construction activities to support ground water development for subsistence communities in West Timor, Indonesia.

Tabbal, D. F., Lampayan, R. M., and Bhuiyan, S. I. (1992). Water-efficient irrigation technique for rice. *In* 'Soil and Water Engineering for Paddy Field Management'. (Eds V. V. N. Murty and K. Koga.) (Asian Institute of Technology: Bangkok.)

Taylor, J. H. (1983). Benefits of permanent traffic lanes in a controlled traffic crop production system. *Soil and Tillage Research* **3**, 385–95.

Tisdall, J. J., and Adem, H. H. (1986). The effect of reduced tillage of an irrigated silty soil and of a mulch on seedling emergence, growth and yield of maize (*Zea mays*) harvested for silage. *Soil and Tillage Research* **6**, 365–75.

Troedson, R. J., Lawn, R. J., Byth, D. E., and Wilson, G. L. (1989). Response of field-grown soybean to saturated soil culture. 1. Patterns of biomass and nitrogen accumulation. *Field Crops Research* **21**, 171–87.

Utomo, M., and Nazaruddin. (1996). 'Bertanam Padi Sawah Tanpa Olah Tanah'. p. 52. (Penebar Swadaya: Jakarta.) ISBN 979-489-366.8.

Van Cooten, D. E. (1999). Collecting baseline data on the ethnobotany of Nusa Tenggara Timur, Indonesia. *In* 'Proceedings of a regional Workshop on Domestication of Agroforestry Trees in Southeast Asia'. 4–7 November 1997 (Eds J. M. Roshetko and D. O. Evans.) (in press).

Zubachtirodin. (1989). Pengendalian gulma pada tumpangsari jagung dengan kacang tanah. Laporan Komponent Technologi Tanaman Pangan 1988–89. (Weed control by the intercropping of corn and peanuts. Report of the Food Crops Technology Component, 1988–89.) NTASP, Kupang.

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