MANAGEMENT OF RICE PRODUCTION SYSTEMS TO INCREASE PRODUCTIVITY IN THE GAMBIA, WEST AFRICA

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Rice (Oryza sativa L.) is one of the leading food crops of the world. Demand for rice is rapidly increasing in West Africa. The Gambia imports more than 80% of its rice requirement. Local production is low and efforts to increase production are hindered by high input costs, low prices for rice, and low yields, especially in the uplands. This is true in most West African nations. There is an urgent need for cultivars and production technologies in the both the upland and lowland ecosystems that will help increase yields at lower monetary costs. Upland rice is mainly grown under a shifting cultivation system. This involves slashing and burning of virgin forest to acquire new and more fertile lands. Environmental concerns and increasing human density are discouraging this practice and research on permanent cropping of the land is being promoted. One strategy to facilitate cultivation of the same piece of upland rice field without yield loss and without high input of human labor, fossil energy, fertilizer, and herbicide is the use of low-input rice varieties. These varieties present a major challenge for research because upland rice often needs a higher level of fertilization than does lowland rice. The West Africa Rice Development Association (WARDA) is developing low-input varieties primarily from selections among African varieties and exotic varieties. In a 3-year varietal screening exercise, conducted in the Gambia, *cv* WAB 377-B-16-LB-LB and WAB56-125, bred by WARDA were found to be higher yielding and more stable than the commonly used Asian variety (Peking) at low fertilizer application rates. The

low-input varieties were also found to have higher NUE than the Asian variety (Peking). In lowland rice farming, water control is the most important management practice that determines the efficacy of other production inputs. Poor drainage that keeps soil saturated is detrimental to crops and degrades soil quality. In many rice irrigation systems in The Gambia, water control is highly inefficient. Drainage mechanisms are dysfunctional or inadequate because farmers believe that rice grows best when water is supplied in abundance. Poor drainage mechanisms makes it necessary for farmers to transplant tall, very old seedlings, usually 4 - 6 weeks old, and 3 – 4 seedlings per hill. Rice fields are kept continuously flooded and are flood-free only at time of harvest. This practice is not only wasteful in terms of water use efficiency, but also leads to leaching of soluble nutrients, blocks aerobic soil microbial activities and biological nitrogen fixation as well as slows mineralization and nutrient release from the soil complexes. New management practices that address lowland rice production constraints in The Gambia are needed. The System of Rice Intensification (SRI), used in Madagascar, proposes a methodology that has the potential to increase rice productivity without a high investment in external inputs or introduction of new cultivars. SRI changes the ways in which plant, soil, water and nutrients are managed. In 2000, 2001, and 2002, SRI experiments were conducted in The Gambia. The SRI water management practices of repeated soil wetting and drying were found to be beneficial to rice plant growth probably through increased biological nitrogen fixation, more nutrient availability, profuse root development, increased tillering, and a high panicle setting ratio leading to higher grain yields. Grain yields of rice under SRI management are 2-3 times higher than the national average in The Gambia.

BIOGRAPHICAL SKETCH

The author was born to Fatou Jallow and Muhamed Ceesay in the Sub-Saharan republic of The Gambia. He completed both his primary and high school education in The Gambia. Through his early education he had a keen interest in biological sciences and the environment. He did his undergraduate and graduate studies in the field of Agriculture at the Kuban Agricultural Institute in Krasnodar, Russia where he obtained a Masters Diploma in Agronomy in May, 1989. From December 1989 through November 1993, the author worked as research assistant with The Gambia Ministry of Agriculture, Department of Agricultural Research. From November 1993 to January 1995, the author did a professional training with the German Food and Agricultural Organization in Bavaria, and six months on-the-job training with the Soils and Plant Nutrition Department of the Rhineland Pfalz State Agricultural Research Institution in Speyer.

From January 1995 to 1998, the author worked with the Gambia National Agricultural Research Institute, where he coordinated the Cereals Research Program, and managed the institute's out-station office and research farm in Sapu. In 1998, the author enrolled in an MS/PhD program at Cornell University, in Ithaca, New York. In 2000, the author completed the Masters part of the program and proceeded on to fulfill the PhD requirement.

Dedicated to all those who strive to harvest a panicle of rice there where none grew before and to my mother FaJa.

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CHAPTER ONE:
RICE PRODUCTION TRENDS IN THE GAMBIA, WEST AFRICA

1.1. Introduction

Cultivated rice (*Oryza sativa* L.) was probably introduced into the eastern parts of Africa a little more than 1500 years ago, when sea trade between East African and India was flourishing. Portuguese traders introduced Indian rice either directly from India or from East Africa and Madagascar into The Gambia, Senegal, Guinea Bissau, and Sierra Leone. The Asian rice established well in many parts of West Africa, spreading quickly into areas where the indigenous African rice (*O. glaberrima* Steud) was being cultivated (WARDA, 1996).

Rice is one of the leading food crops of the world. Currently, it is the major staple for 2.7 billion people in the world, almost half of the total population of the globe.

Demand for rice from less advantaged areas in Africa is certain to increase, replacing much of the coarse grains such as sorghum (*Sorghum vulgare* L.), millet (*Pennisetum glaucum* L.) and starchy root crops such as taro (*Colocasia esculenta* L.) and cassava (*Manihot esculenta* Crantz) as the major source of dietary calories. Demand for rice has in fact been increasing rapidly in much of Africa. Between 1985 and 2001 rice imports to Africa more than doubled, rising from 3 million to 7.5 million tons per annum (FAO, 2003). Rice is the staple food in The Gambia, Guinea, Guinea Bissau, Liberia, Senegal, Cote D'Ivoire and Sierra Leone. It is the principal dietary item providing more than 40% of the nation’s food need. It is rapidly becoming the staple food in other countries of West Africa, hence becoming an important crop in the context of food security. As there are many people in the major rice-consuming countries living at sub-optimal nutritional levels, there is need to increase rice production by as much as 70% in order to raise nutritional levels to satisfy current dietary needs (Greenland, 1997).

The Gambia has a per capita rice consumption of 117.33 kg. This is the highest among Sahelian countries, and third highest in West Africa (WARDA, 1993; Marong et al., 2001). Due to a high population growth rate of 4.2% per annum, and a high influx of refugees and immigrants from the sub-region of West Africa, total rice consumption has been increasing over the years; meanwhile there has been a steady decline in rice-growing area and productivity. With a projected population of 1.5 million for the year 2005, and a per capita consumption of 117.33 kg, the total rice requirement of the country will be 175,000 metric tons (Marong et al., 2001). At present, the total national production represents only 17% of the total rice requirement of the country. The huge deficit is met through importation from Asia. In 2000, US$10.9 million was spent on the importation of 93,900 metric tons of rice (The Gambia Central Statistics Department, 2001). For these reasons the government of The Gambia is keen to increase rice productivity, and research input from national scientists is being requested. The goal of this research work is to achieve food self-sufficiency. Thus the general objective of this research work, is to increase rice productivity and/or reduce production costs.

In The Gambia the rice production systems can be grouped into five categories: upland, lowland rainfed, irrigated, freshwater, and mangrove swamps. Production constraints differ from one environment to another, and so do the kinds of technology packages needed for the farmers in the different growing environments.

In situations where there are limited controls on the growing conditions, it is more difficult to pinpoint the factors responsible for a particular yield. However such knowledge is of prime importance for people who are engaged in agricultural planning and development because it forms the basis for any attempts to improve the situation. In the developing world, where agricultural research institutions lack adequate resources and capacity, such knowledge is often lacking.

Recent approaches to agricultural development, emphasizing food production and food security, have largely failed to reduce the absolute number of people who are food-insecure or to ensure environmental sustainability (Pretty et al., 1997). The economy of the majority of African countries is agriculture-based, but Africa's per capita food production has not kept up with its population growth. Food insecurity is becoming a critical problem especially in low-income households. African governments and international agricultural research centers as well as international development agencies are looking for ways to improve returns to farmers' resources in a broader context this includes expanded opportunities for non-farm micro-enterprises, higher returns from cash and subsistence cropping, and agricultural labor.

International agricultural research centers' progress in plant genetic research has been effective in addressing numerous production constraints such as tolerance to various biotic and abiotic stresses, and increasing yield. However, practical experience has proven that the contribution of crop management practices toward alleviating production constraints is somewhat greater than that contributed by genes alone. Adequate crop management practices could be the key to addressing production constraints such as poor management of soil nutrients and soil health management, and high production costs, coupled with low net economic returns.

At the end of December 2002, several countries in Africa were reportedly threatened by famine and starvation due to severe droughts in previous cropping seasons (FAO, 2003). According to FAO, the future is gloomy because world population is predicted to grow from around 6 billion people today to 8.3 billion in 2030. Population will be growing at an average of 1.1% a year up to 2030, compared to 1.7% annually for the past 30 years. Food production will have to increase to provide for this increased population.

According to FAO (2002), much of future food production growth will have to come from higher productivity. In developing countries; almost 70% of the increase in crop production will come from higher yields, around 20% from an expansion of arable land, and around 10% from multiple cropping and shorter fallow periods. Climate change could increase the dependency of some developing countries on food imports. Hardest hit will be small-scale farmers in areas affected by drought, flooding, or salt intrusion or sea surges. Many countries in Africa are likely to become even more vulnerable to food insecurity unless effective measures for increasing productivity, reducing production costs, and protecting the natural resource base are taken.

Irrigation is crucial to the world's food supply. The developing countries could expand their irrigation area from 202 million ha in 2002, to 242 million ha by 2030. The 40 million ha constitutes a 20 % increase in irrigated area. This could easily increase food production by 20 to 30%, but this will require more investment than presently planned or available. Globally, there is enough water available, but certain regions will face serious water shortages, especially those in the Sahel region of West Africa. They will therefore have to employ more efficient irrigation technologies and cultural practices that increase water-use efficiency as well as minimize contamination or pollution of water bodies.

1.2. Performance of the Rice Sector in The Gambia, West Africa

In The Gambia the agricultural sector's share of the gross domestic product (GDP) decreased from 40% to 24% between 1980 and 1996. Despite the decrease in output, agriculture still remains the principal source of employment in the country. Currently 75% of the total population of 1.3 million depend on agriculture for their livelihood. Of the farming population, only 40% are male. Women are the predominant farmers in The Gambia, in fact 67% of the female population are engaged in agricultural production (1993 census). Female farmers are those predominantly involved in rice cultivation. Sixty-three percent of the total population lives in the rural area, a majority of which are resource-poor, subsistence farmers. Sixty-eight percent of the total population lives below the poverty level. The Gambia's Human Development Index ranking in 2001 was 149 out of 162 countries. The literacy rate is only 36%.

Rice production can contribute significantly to poverty alleviation in The Gambia. Unfortunately, rice farm productivity in The Gambia is on the decline. This is an indication that improved technology adoption has been low, what adoption has occurred, e.g. use of high yielding varieties (HYVs) depended heavily on government subsidization. With government subsidies, enough fertilizer was available to support the cultivation of high fertilizer demanding High Yielding Varieties. However, when government subsidies on agricultural inputs were removed, most farmers ceased to cultivate HYVs.

The Gambia and most other African nations now import a large proportion of their food grain and other food commodities. Households must generate enough wealth to be able to purchase their required food.

Depletion of soil fertility, along with the concomitant problems of weeds, pests, and diseases, is a major biophysical cause of low per capita food production in Africa. In the 1970s and early 1980s, fertilizer and other farm inputs were made available to farmers through a subsidized supply network. This supply system is no longer sustainable by West Africa governments, and subsidies have been removed from fertilizer and other agricultural inputs. Imports of agricultural inputs to West Africa totaled almost US $345.6 million in 2001. These amounts are not affordable by West Africa governments, unless returns from such investment are significant.

Over decades, small-scale farmers have removed large quantities of nutrients from their soils without using sufficient quantities of manure or fertilizer to replenish the soil. Sanchez et al. (1997) estimated the annual depletion rate to be as high as 22 kg of nitrogen (N), 2.5 kg of phosphorus (P), and 15 kg of potassium (K) per hectare of cultivated land over the last 30 years in 37 African countries. This is definitely on the high side considering farmers use fair amounts of manure and other methods to replenish their soils. The nutrient loss is also a result of leaching, erosion, etc. associated with poor landscape management. The traditional way to overcome nutrient depletion is the use of mineral fertilizers. Although Gambian farmers acknowledge the benefits of fertilizer use, the consumption of fertilizer is declining in Africa. Fertilizer usage in SSA is the lowest in the world.

The extremely low usage of inorganic fertilizer in Africa is associated with the high cost of fertilizer importation and transportation to rural areas (Table 1). Consumption in 1998 was 45.5 kg/ha. This is 55% less than the average world consumption of 100 kg/ha. In The Gambia, in absolute values, nitrogen costs between $2 and $3 per kilogram when applied as 15-15-15 NPK or 8-24-24 NPK compound fertilizer, while phosphorus and potassium cost between $1 and $2 when applied as one of the two combinations.

Table 1. Fertilizer Importation and Usage in Africa

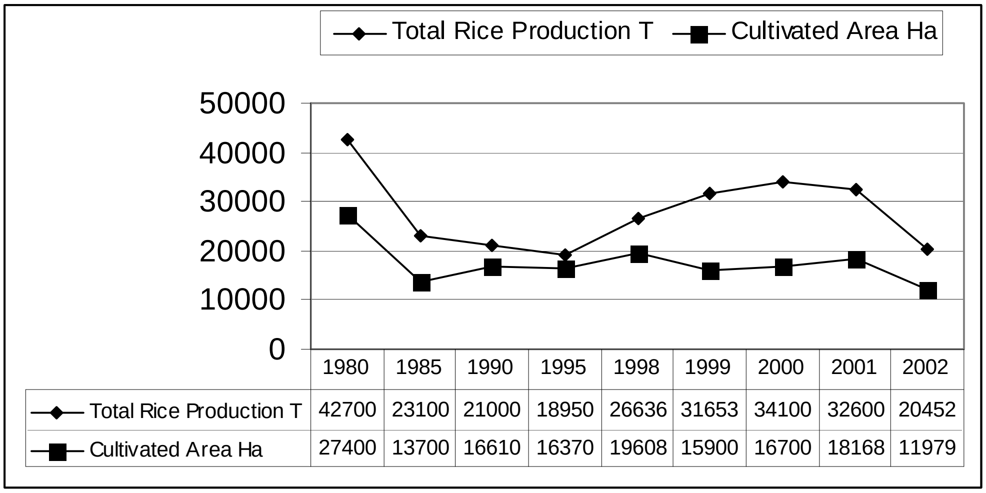
	1980	**1985**	**1990**	**1995**	**1998**
Fertilizer Consumption (Kg/Ha)	43.2	51.8	54.1	44.4	45.5
Fertilizer Imports (billion Mt)	1.6	1.7	1.7	1.4	1.9

Source: FAO Database, World Bank Development Indicators for Africa, 2002.

Also inappropriate fertilizers are used in many areas because there is a lack of soil testing, thus uneconomic blanket applications of expensive and scarce fertilizer are used. Most crops are, of necessity, organically produced in Africa. Shifting cultivation and fallowing is still the predominant means of restoring soil nutrients. Fallow periods are becoming shorter, and acquiring new land is now much more difficult with the increases in population and urbanization. As stated earlier, government subsidies have been removed on the importation of agricultural inputs. Although in The Gambia and some other African nations the import duty on agricultural inputs is waived, the foreign exchange required for importation is often not available. The cost on imported inputs can be extremely highly especially when transported from seaports to sites of usage. Spot checks indicate that a metric ton of urea costs about U.S. $90 FOB (free on board) in Europe, $120 delivered in the ports of Mombasa, Kenya, or Beira, Mozambique, $400 in Western Kenya (700 km away from Mombasa), $500 across the border in Eastern Uganda, and $770 in Malawi (transported from Beira)(Sanchez, 2002). The scenario is quite similar to that in West Africa.

The subsidy system in Africa has failed because it was conceived as “free money” a gift from the government, and in fact, the governments used it for political leverage. Subsidies may be seen as an early sharing of profits before the foreseen profits are actually made, and is meant to promote production of major cash crops that are for export. There is a need, therefore, to consider a re-conceptualization of subsidies in Africa, or facilitate a productivity-led change rather than a subsidy-induced one, in order to enhance a rapid development in agriculture and to alleviate food insecurity.

In the last 20 years, both rice productivity and area under cultivation in The Gambia has been declining (Figure 1). This could be attributed to the steady decline in rainfall for the past 20 years, adverse growing conditions, limited resources available to farmers, and lack of suitable rice cultivars.



	1980	1985	1990	1995	1998	1999	2000	2001	2002
Total Rice Production T	42700	23100	21000	18950	26636	31653	34100	32600	20452
Cultivated Area Ha	27400	13700	16610	16370	19608	15900	16700	18168	11979

Figure 1. Rice Productivity and Cultivation Trends in The Gambia

The decline in rice area under cultivation is greater in the lowland ecology than in the upland (Figure 2). This is because the mangrove swamp ecosystem which is critically affected by drought, acidification and salinization as well as the rain-fed swamps are classed under the lowland ecology. Due to reduction in available moisture, close to 40% of the mangrove swamp area is no longer fit for cultivation or requires intensive amelioration efforts before rice could be re-cultivated. The Gambia government is financing lowland development projects aimed at increasing the area under irrigated rice production. Water retention dikes have been constructed in several rain-fed ecosystems to retain run-off water for rice irrigation.

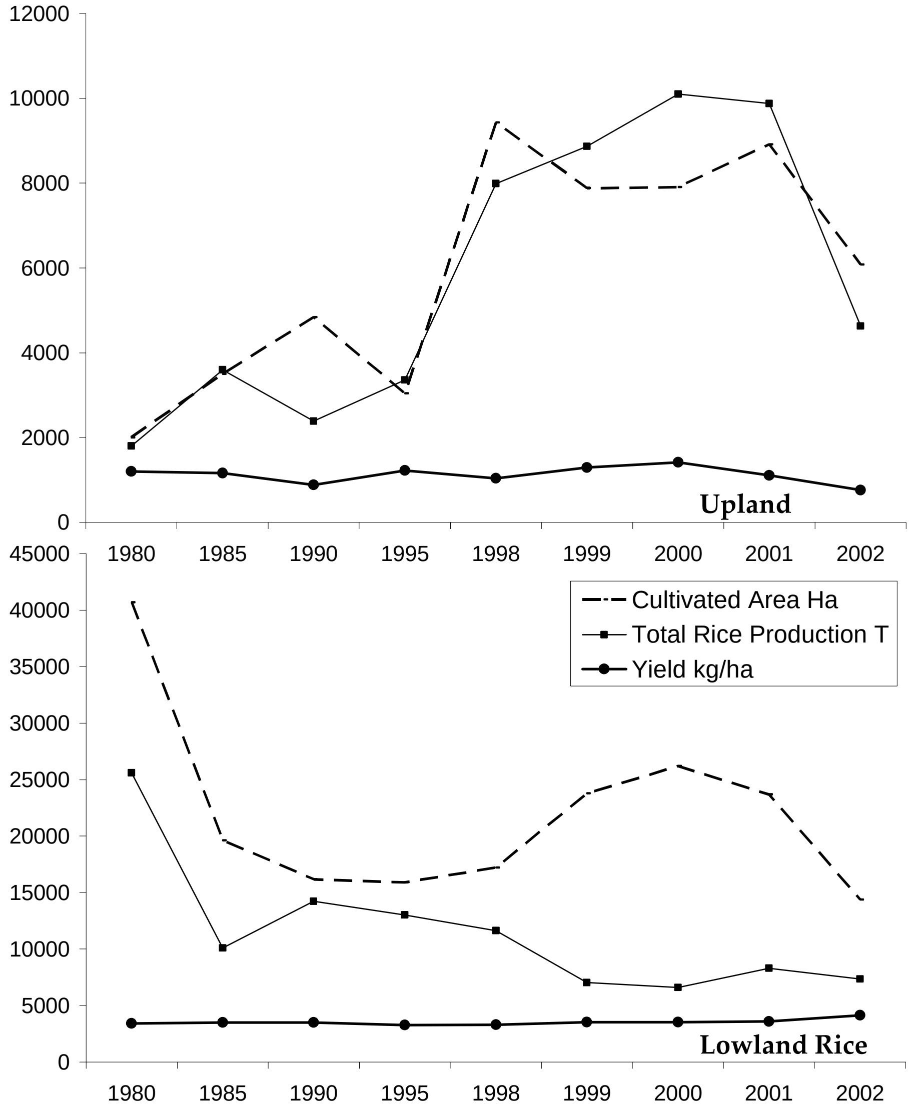


Figure 2. Rice Productivity and Cultivation Trends in the Upland and Lowland Ecologies of The Gambia

A decline in area under rice cultivation is also experienced in other West African countries, especially those in the drier Sahel region (Figure 3). In Nigeria, however, there has been significant increase in area under rice cultivation, most probably as a result of government restrictions on rice importation in order to reduce competition with domestic production.

Nigeria is West Africa’s largest producer of rice, producing an average of 3 million tons of rice per annum. Government policies contributed to the expansion in rice production by putting a ban on rice imports in 1986. The ban appears to have effectively stalled the further growth of rice imports, though, and has ensured high domestic prices for rice relative to other food crops. Although the ban was officially lifted in early 1995, imports have not overtaken domestic production. In January 2001, the Nigerian government raised the rice import duty from 50 percent to 75 percent in order to protect domestic production. Currently rice imports account for approximately one-third of Nigeria’s rice supplies.

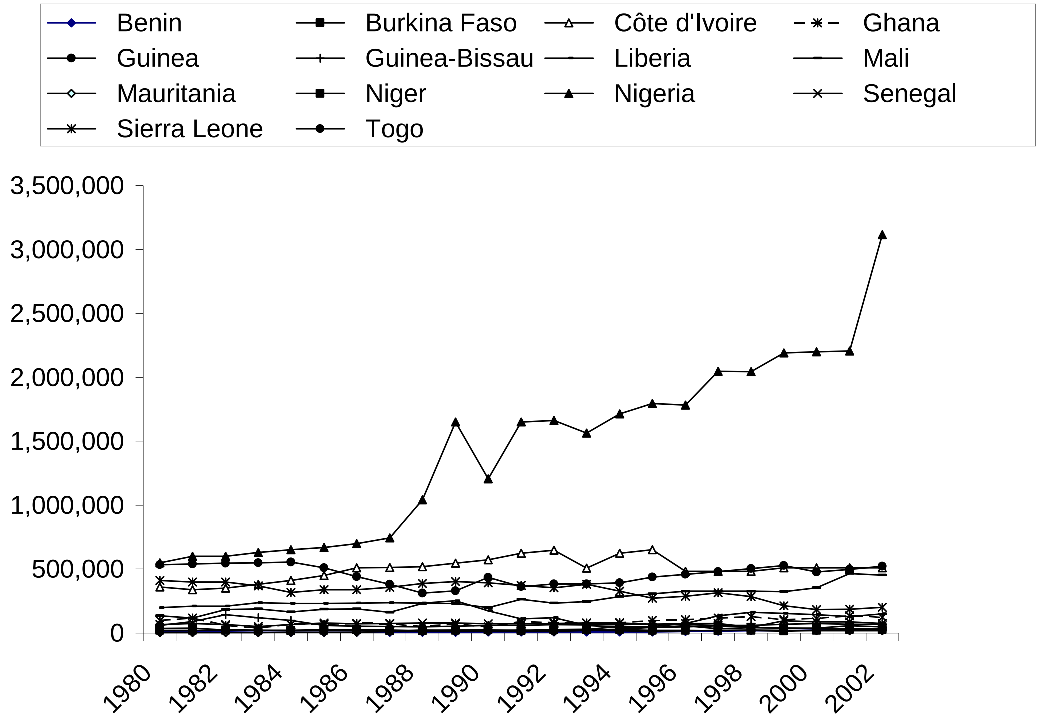


Figure 3. Rice Cultivation Trend in West Africa shown in Cultivated Hectares under Cultivation

The reason for the decline in The Gambia and most other West African countries could be attributed to the following production constraints:

- Drought
- Environmental degradation (deforestation, erosion)
- Low soil fertility status
- High production costs
- Low net returns
- Cheaper prices on imported rice
- Poor production management practices

Another major problem is access to markets. In the event that productivity increases, farmers are unable to sell the surpluses because of non-existent roads and/or absurdly low prices.

The present rice production and food security situations are not promising; a large proportion of the country's rice requirement is imported. Although the government of The Gambia has been committed to a policy of attaining rice self-sufficiency, while diversifying the incomes of the rural poor, as well as increasing agricultural production, and conserving the natural resource base of the overall environment on a sustainable basis, little progress has been achieved.

Fortunately, there is good news in that current research on rice production systems management found solutions to increase rice productivity in The Gambia. Research results confirm the fact that rice yields can be increased in both the upland and lowland ecologies at a very low production cost. These solutions could go a long way in reducing the gap between domestic production and importation in the future. Continued growth in rice production will be possible through intensification and expansion into high potential areas, especially the alluvial lowlands along the River Gambia and the inland valley swamps. Additional gains may be achieved through investments in low-cost systems water control. Optimistic estimates for the next 10 years predict that demand for rice will be nearly balanced with the introduction of newly tested management practices.

CHAPTER TWO:
LOW-INPUT UPLAND RICE PRODUCTION SYSTEM

2.1. Introduction

In The Gambia, the upland rice ecosystem is defined as having free-draining soils where the water table is permanently below the roots of the plant so that the crop depends entirely on rainfall. This is in agreement with the IRRI's Standard Evaluation System for rice which defines upland as level to steeply sloping fields; rarely flooded, aerobic soil; rice direct seeded on plowed dry soil or dibbled in wet non-puddled soil (IRRI, 1996).

In The Gambia upland rice growing environment, drought and a short growing season together with low soil fertility and rice blast disease are the major constraints to productivity. Upland rainfed systems are associated with higher production risk factors due to the unpredictable nature of rainfall. In 2000 rainfall was 7% above normal, in the following two years it was much below normal (Table 2). This is an example of the unpredictable nature of rainfall that farmers have to endure in The Gambia. This has a great impact on the farmers' cropping system and production risk factors.

Table 2. Rainfall Data at the Low-Input Trial Site, Brikama, The Gambia

Year	**June**	**July**	**August**	**September**	**October**	**Total**
2000	60.1	275.3	247.5	253.6	134.2	970.7
2001	111.9	250.8	208.4	241.1	55.1	867.3
2002	37.9	66.1	204.7	226.3	56.3	591.3

This causes fluctuation in both yield and area under cultivation from year to year. Yields of rice in rainfed systems are always subject to the vagaries of the monsoon. Their yields are invariably lower than for irrigated rice, and the magnitude of yield lost due to water shortage depends on the degree of stress and on the time at which the water stress occurs (Greenland, 1997).

Environmental concerns and increasing human density have led to research on permanent cropping of the land. One strategy to facilitate cultivation of the same piece of upland rice field without high input of human and fossil energy, nutrients, and chemicals is the use of low-input rice varieties. This is a major challenge for research because upland rice often needs a higher level of fertilization than does lowland rice. Nitrogen is most often the limiting nutrient and is required in the greatest quantity for rice production. The nitrogen effect is manifested quickly on plant growth and ultimately on crop yields. Hence, the fertility status of a soil depends to a great extent on the nitrogen status of the soil (Sinha and Prasad, 1980).

High input costs, low yields and low prices for rice constrain upland rice production in The Gambia and other West African nations. Low prices for rice have in fact placed farmers all over the world in a cost-price squeeze. There is an urgent need for cultivars and production technologies that will help increase yield at lower monetary cost (De Datta and Broadbent, 1988). Drought tolerance and nitrogen-responsiveness are recognized as desirable characteristics of crop plants in breeding for high-yielding cultivars in semi-arid regions (Otoo et al., 1989).

African rice varieties are generally well adapted to the major stresses found in upland areas. When grown under non-intensive management these tend to produce moderately higher yields in farmers' fields than introduced Asian varieties.

The West African Rice Development Association (WARDA), in collaboration with The Gambia and other national programs in West Africa, developed varieties primarily from selections among the African varieties or from hybridization between African and exotic varieties. This approach involves simultaneously breeding and evaluating improved varieties developed by the WARDA under different levels of fertility management and environmental conditions. Between 1995 and 1998 the performance of 12 elite low-input varieties developed by WARDA were tested under Gambian environmental conditions. The best three varieties from the set were identified and tested in The Gambia under different fertility levels between 2000 and 2002. The research objectives were as follows:

1) To assess the productivity of WARDA's low-input upland rice varieties as influenced by different nitrogen levels;
2) To determine if rice cultivars differ in N-use-efficiency;
3) To determine if the improved low-input varieties indeed possess a higher nutrient-use-efficiency than conventional varieties;
4) To find out what are the most important operating mechanisms that resulted in improved nitrogen efficiency;
5) To identify the more stable and higher-yielding varieties for use in The Gambia under conditions of low fertility and less intensive management practices;
6) To help upland rice breeders focus on the more important physiological and morphological characters affecting nutrient-use-efficiency in the Sahel.

The results will also be used to calibrate the Nitrogen Module of the Nutrient Management Support Software (NuMaSS) for the Sahel region.

2.1.2. The Upland Production System

The Gambia is primarily an agricultural country on the southern fringes of the semi-arid Sahel region of West Africa. More than 75% of the population depends on the agricultural and natural resource sectors for its livelihood, but over the past two decades, production of cash and food crops has steadily declined. This decline can directly be attributed to environmental degradation. Dense forest and woodland covered 80% of the country during the 1940s, but currently it accounts for less than 10% of the total land. Uncontrolled burning is prevalent, fallow periods have been shortened or eliminated, and deforestation for fuel wood is indiscriminate. An estimated 85% of the natural savannah woodland vegetation is burned each year for agricultural and other purposes. Agriculture and burning contribute to erosion, decline in soil fertility, prevalence of pests and disease, and deforestation. Environmental degradation and decreased agricultural production are serious issues in The Gambia, and conservation of natural resources is a high priority for the government. Climatic changes since the 1970s have created further problems for the nation's agricultural base.

In The Gambia, it is estimated that there are probably 5,000 to 7,000 ha that could be cultivated under upland rice. However, in 1995, it was estimated that only 3,043 hectares were cultivated, with an average yield of 1.2 tons/ha (NASS 1995). Growth-limiting factors such as limited water, low plant available nitrogen and phosphorus result in yield levels that are commonly 20 to 50% below potential yield (Penning de Vries and Babbinge, 1995). Continuous cropping in upland rice without adequate nutrient addition results in depletion of nutrients from the soil and frequently requires fertilizer inputs to improve yields. Response of upland rice to nitrogen fertilizer has long been recognized.

The range and complexity of upland rice environments are such that varietal improvement and management studies to boost production and enhance stability of the crop's farming systems should be directed toward components of the upland rice environments rather than rice itself (Oldeman and Woodhead, 1986). An upland environment is favorable and sustainable when the following conditions are satisfied:

- ⇨ Adequate and assured soil moisture reserves during critical periods of crop growth;
- ⇨ Regular rainfall during the cropping season;
- ⇨ Fertile soil with low risk of erosion;

Environments are unfavorable and unsustainable where some of all of these conditions are not fulfilled.

The Gambia is located in the Senegal Sedimentary Basin. The surface formation is tertiary sandstone known as the Continental Terminal. This formation averages 40m deep and is composed mainly of quartz and kaolinite believed to have resulted from erosion of soils formed in granite and gneiss to the east of The Gambia.

The Continental Terminal has been dissected by the River Gambia since the early Pleistocene era. Successions of arid and sub-arid periods have alternated with relatively humid periods that appear to coincide with marine transgressions (Dunsmore et al., 1976). Considering the parent material in which soils of The Gambia were formed, a generally low fertility status might be expected.

With the inherently low clay and organic matter contents of the upland soils of The Gambia, sustainable natural sources of plant nutrients are very limited (Peters and Schulte, 1996). This is particularly critical for micronutrients which are not typically found in the limited selection of commercial fertilizer sources available.

In a study of soil nutrients in The Gambia, Peters and Schulte (1996) reported the following widespread deficiencies Z>S>N>P>K.

Soil organic matter (SOM) is low, in general, in Gambian upland soils (<2%). With the long dry season and the consumption of crop residues off the field by livestock, there is little above-ground residue returned to the soil except what is added as organic wastes (Table 3). Burning of crop residues also `considerably reduces the amount of residue potentially available for soil incorporation.

Lack of surface residue and low organic matter makes the soil more susceptible to erosion. Soil organic matter makes a critical contribution to soil fertility. It contains 95% or more of the total N present in most soils, and in some, it may contain as much as 60% of the total phosphorus and 80% of the total sulfur. In low activity clay soils, SOM is probably more important as a source of pH dependent charge that contributes to CEC and water holding capacity.

Table 3. Soil Test Data from Upland Rice Sites in Western Region of The Gambia

Soil Test	Average 0-15 cm
pH (1:1 H_2O)	6.0
Soil Organic Matter (%)	1.1
Available P (ppm) Bray -1	0.2
Exchangeable K meq/100g NH_4OAc	1.0
Exchangeable Ca meq/100g NH_4OAc	0.1
CEC meq/100g NH_4OAc	3.0
B (ppm)	0.4
Zn (ppm)	0.5
Mn (ppm)	15.5
S (ppm)	7.1
Sand	68.7
Silt	21.3
Clay	10.0
Textural Class	Sandy loam

In The Gambia, drought combined with rapid population growth (the population numbers about 1.3 million, and is growing at an estimated rate of 3.4 %) has placed tremendous demands on natural systems. Even though The Gambia has enacted many laws to achieve natural resource sustainability, environmental degradation still continues at an alarming rate.

2.1.3. Environmental Concerns of Upland Rice Cultivation

The main upland rice cropping system is slash-and-burn shifting cultivation with a bush fallow of 3-5 years. Rice is grown as the first crop after virgin forest or after long-term fallow. Upland rice cultivation raises a lot of environmental concerns, because it involves destruction of forest fauna and flora, and also permits soil erosion in the process of shifting cultivation. Bush fires are a common result of slash-and-burn cultivation. The environmental concerns for growing upland rice is far greater than that of other annual crops.

Policy makers, scientist and the public are increasingly concerned about deforestation in The Gambia and its negative consequences, such as climate change, biodiversity loss, reduced timber supply, flooding, erosion, siltation, and soil degradation. Population and migration both affect deforestation rates, but in a complex fashion that it cannot be simply concluded by saying that population growth promotes deforestation. Major doubts remain regarding the relationships between deforestation and productivity growth, input prices, land markets, land and forest tenure security, and household income (poverty) that can only be resolved through future research (Kaimowitz and Angelsen, 1998).

Forests are cleared by burning, in order to create new fertile land for rice cultivation. This undoubtedly contributes to build-up of carbon in the atmosphere, part of the 'greenhouse gas' effect. Forests act as a sponge sheltering fragile soils from the extremes of torrential rain in the wet seasons and searing heat in the dry seasons. There is ample evidence that the removal of trees enhances flooding and is often followed by drought. In short, tree removal intensifies the extremes of the tropical climate, initiating a flood/drought cycle, which is proving disastrous for agriculture in The Gambia.

Unfortunately for The Gambia's National Agricultural Research System (NARS), the research priorities of its international collaborating partners in the Consultative Group for International Agriculture Research (CGIAR) are geared towards addressing problems of soil erosion and degradation. These problems often emerged as the most significant threat to sustainable agriculture. Efforts in the CGIAR have taken two forms: micro-adjustments, to indirectly adjust through breeding for tolerance to drought, low soil fertility, salinity and acidity, or through research on improved soil and water management. The next research priority deals with problems of the narrowing the plant genetic resource base for agriculture. The sustainability of much of the Green Revolution technologies may be jeopardized by erosion of the genetic base of the most popular rice lines. Climatic factors and adjustments to them is another area for priority research (De Boer, 1993). Therefore decreasing the risk associated with climatic variability, particularly in low and/or variable rainfall areas, is an important research area for The Gambia and semi-arid Sahel region.

2.1.4. The Crop - Environment Dynamics in the Sahel and Drier Tropics

Adaptation mechanisms for adverse conditions can be identified by examining resources that are most limiting yield. Grain yield can be analyzed in relation to capture (acquisition) and utilization efficiency of resources for growth. Genotypic variation in grain yield in rainfed conditions can be analyzed by determining of genotypic variation in water uptake and how the water is used in the processes that lead to formation of grain yield (Fukai and Cooper, 1995). Once genotypic variation in resource capture or utilization efficiency (yield produced per unit nutrient uptake) is found, then physiological or morphological factors that are responsible for such variation can be further examined.

Of the major determining factors of phenology, at least two can be ruled out in the tropics. Low temperature during the growing season of upland rice, and photoperiodism. However, drought is clearly a major limiting factor, especially drought that develops during panicle development which delays flowering of rice in upland conditions (Inthapan and Fukai, 1988; Fukai, 1999). Under upland field conditions, Lilley and Fukai (1994) showed that the magnitude of delay in flowering was associated with the severity of drought conditions. Development of the panicle is very sensitive to soil water availability, and the rate of development is reduced by a small water deficit and ceases completely with the occurrence of severe drought.

Drought is thus a major problem for upland rice. Yield loss due to drought in upland rice was estimated at 60% in the 2002 growing season in The Gambia when rainfall declined by 40% from the 10-year normal average of 760 mm. In fact, earlier results with upland rice production in The Gambia showed that upland rice grown under 700 mm to 1,000 mm rainfall may be subjected to moisture stress at any stage of crop growth due to periodic drought spells and uneven distribution. Drought-related problems of crop establishment occur in many of the world's rainfed rice growing areas (O'Toole, 1981). Drought affects plant growth primarily because of the shortage of water in the plant. Water is essential for plant growth, and reduced transpiration due to soil water deficit almost always results in reduced photosynthesis, because gas exchange for both water vapor and CO_2 takes place simultaneously through stomata. While there may be some scope to improve water use efficiency (dry matter growth per unit of water use) by selecting lines for high photosynthesis/transpiration ratio (Dingkuhn et al., 1989), a strong linkage between water use and plant dry matter production limits development and the potentiality of drought-resistant cultivars when water is a constraint.

In drying soil, nutrients become less or totally unavailable because their transport to the root-soil interface is impeded by the diminished rate of diffusion and mass flow (Viets, 1972; Yamboa and O'Toole, 1984). Plant water stress brought about by either high atmospheric evaporative demand or decreased solution water potential can cause reduction in nutrient uptake by its effect on the rate of water flow through plants (Greenway and Klepper, 1969; Yamboa and O'Toole, 1984), or possibly by its effect on active ion uptake mechanisms and passive efflux of ions (Erlandsson, 1979).

The disturbance in mineral nutrition may contribute to the reduced growth observed during moderate water deficits (Begg and Turner, 1976). When little soil water is available, all ions become less mobile because air replaces water in the pores between the soil particles, making the pathway for the nutrient ions across the soil to the root surface less direct (Nye and Tinker, 1977; Chapin, 1991).

These effects of nutrient mobility are important even over ranges of soil water content that would have little effect on plant water relations. Ion mobility can decrease by two orders of magnitude between -0.01Mpa and -

1.0Mpa, a range in soil water potential that does not strongly restrict water uptake by most plants (Nye and Tinker 1977; Chapin, 1991).

Because the rate of ion diffusion to the root surface is usually the rate-limiting step in nutrient uptake by plants, reduction in water availability may affect plant growth substantially. According to Chapin (1991), the effects of low soil water content on nutrient availability may be nearly as important as the direct effects of water stress on plant growth. Evidence is that tissue concentrations of growth-limiting nutrients (nitrogen and phosphorus) often decline during water stress, whereas one would expect these elements to increase in concentration if water directly restricts growth more strongly than it affects nutrient uptake. Second, experimental manipulations indicate that adding nutrients enhances growth of some desert annuals more than adding water (Gutierrez and Whitford, 1987; Chapin, 1991). Nitrogen is the most limiting nutrient, but under drought conditions, phosphorus is relatively important.

The timing, frequency and amount of rainfall during the growing season determine the land productivity in a rainfed environment. For increasing productivity and stabilizing yield, technologies and strategies that minimize the effects of uncertain water availability are needed (Saleh, 1995).

One management option for upland rice is the use of low-input rice varieties. The requirement of nitrogen by rice varies with location, variety, season, and management practices. The amount of nitrogen to be applied for rice is dependent upon a number of factors, such as likely losses of N through leaching, immobilization, mineralization and denitrification, environmental factors (solar radiation and temperature), plant characteristics (tillering potential, leaf area index, resistance to lodging and length of growing cycle), management practices (dry land/irrigated systems, sowing/planting density, pest and diseases and weed control) and source, time and method of application of fertilizer materials. Input-output curves are situation-specific. Differences in response curves from one situation to another may be a consequence of differences in uptake of the nutrient by the crop, and management practice, or both (Black, 1993).

It is however possible to develop cultivars that use the limited water more effectively, either directly through improvement in photosynthesis/transpiration ratio or indirectly through mechanisms such as more extraction of the limited water available in the soil (Pantuwan et al., 1997.)

Drought is not a stable phenomenon, and soil water availability changes over time within a season. It often starts as mild stress and then may become severe with time, possibly lasting for a long period. In some cases, drought develops early during the vegetative stage, while in others it develops later, toward crop maturity (Fukai, 1999). Drought occurring at different growth stages has different effects on rice yield. Boonjung and Fukai 1996 reported that drought that develops just prior to flowering affects yield more severely.

The drought patterns differ among locations and among years. Cultivars adapted to one type of drought are not necessarily resistant to other types of drought. Identification of common drought patterns and their likelihood of occurrence are important for development of cultivars that are suitable to a specific region (Fukai, 1999). In the Gambia, drought at the time of crop germination (just after planting) and late-season drought (terminal drought) are often the most critical. In order to avoid these drought stages, seed priming and use of early-maturing varieties as an escape mechanism are being introduced into the rice farming systems.

Genotypes with larger canopy size tend to be more severely affected by early-season drought, as leaf water potential decreases rapidly and a large number of green leaves are lost. However, they may still possess a higher leaf area index at the end of the drought period because of their larger canopy size at the beginning, and they could then recover more quickly and produce more biomass and grain yield (Mitchell et al., 1998; Fukai, 1999). The recovery ability may as well be associated with post-drought tillering ability of the cultivar (Lilley and Fukai, 1994). Similarly when the soil is well fertilized, plants grow well before a dry period, and they may suffer more from drought stress, but they could recover more rapidly to produce higher yield compared with a crop that is grown under a lower rate of fertilizer application (Prasertsak and Fukai, 1997).

2.1.5. Genetic Variation in Nutrient Uptake

One strategy for improving the utilization of soil and fertilizer nitrogen in upland rice production systems is to exploit the plant genotypic differences in nitrogen absorption ability. Genotypic differences in N uptake and utilization have been found in wheat (Cox et al., 1985), corn (Chevalier and Schrader, 1977), and sorghum (Maranville et al., 1980). Based on these findings, it seems possible not only to identify efficient crop species or genotypes for N uptake but to isolate and develop a cultivar with a reduced plant N requirement (Alagarswamy, 1988).

Sta Cruz et al. (1994) identified different morphological and physiological features that enhance soil nutrient-use-efficiency. The following were identified: growth type, panicle type, and growth duration. Genotypic difference can also interact with cultural practices and environmental variables.

Roots can moderate the effects of drought by growing deeper, longer, or at higher densities within the soil to reach more water, thus increasing the plant's water supply, or by changing the rate at which water becomes available (Gregory, 1989; Sta Cruz and Wada, 1994). Genetic variations are in several root characteristics associated with increased capacity in rice to extract available soil water which may be responsible for increased drought avoidance, have been reported by O'Toole and Chang (1979), Yoshida and Hagegawa (1982), Ekanayake et al. (1986), and Nguyen et al. (1994).

Generally, genotypes that perform well at low nitrogen levels are tall, have a low percentage of productive tillers, have high dry matter production, are susceptible to lodging, and have low panicle-to-straw weight ratios. They grow relatively fast and cover the fields even without nitrogen addition. At high nitrogen levels, higher growth rates in the early growth stages result in mutual shading during the middle and late growth stages. This reduces nitrogen uptake because net photosynthesis is decreased, resulting in fewer tillers and weaker roots and lower dry matter production. By contrast, genotypes that respond productively to high nitrogen have short stature, high panicle-to-straw weight ratios, a high percentage of productive tillers, and slow growth in the early growth stages. This plant type shows little mutual shading (Tanaka et al., 1964; Sta Cruz and Wada, 1994).

Sta Cruz and Wada (1994) found substantial variation in nitrogen uptake between rice ecotypes (upland and lowland type cultivars), plant types, hybrids, and plants with different growth duration. Plant types based on leaf erectness, panicle number and growth duration were the most important. Nitrogen uptake during spikelet initiation, flowering, and maturity reportedly increased with growth duration. The variation in nitrogen uptake among genotypes with different growth duration is due to differences in the duration of the vegetative lag period (Sta Cruz and Wada, 1994).

Weed competitiveness and yield potential under low input conditions of upland rice also need improvement. It is important to examine the relationships between grain yield and nitrogen utilization and the economics of production.

Traditional African rice varieties are generally well adapted to the major stresses found in upland areas such as drought, blast and panicle diseases, but generally their yields average a low 1 t/ha. Selections from traditional varieties, when grown under rainfed and low fertilizer input, tend to produce moderately higher yields in farmers' fields than do introduced varieties, particularly those introduced from Asia. The West African Rice Development Association (WARDA) embarks on developing varieties primarily from selections among African varieties or from hybridization between African and exotic varieties.

2.1.6. Nutrient Dynamics in Tropical Soils

Most of the fertilizer nitrogen currently used by small farmers of the world for food production purposes is on high yielding varieties (HYVs), which are more responsive to nitrogenous fertilizer than traditional cultivars. In spite of the responsiveness of rice HYVs to nitrogen fertilization, the efficiency of its use is low, often below 40% and in some cases even less than 30%. This leads to massive and undesirably energy losses in both production and transportation. Therefore, improving nitrogen use efficiency should be given a top research priority. Raun et al. (2002) have calculated that the 67% loss of applied N to cereal crops globally is equivalent to \$15.9 billion. Yet the fastest growing sector of the fertilizer market is for N fertilizers.

Depending on the source of fertilizer, N costs approximately \$0.49 kg^{-1}. It is more affordable in the developed countries than in the developing countries, where access to fertilizer is limiting and usage very low, especially among subsistence farmers in The Gambia and those in other Sub-Saharan nations.

Replenishing depleted and poor soils with inorganic amendments is not given high priority. The immediate goal is economic survival, not preservation of the environment (Campbell et al., 1995). Upland rice is repeatedly grown on the same plot of land for several years, and when the fertility level goes down the farmer clears a new forest using slash-and-burn techniques, and shifts his or her cultivation to this new more fertile plot. This shifting cultivation practice causes deforestation and loss of biodiversity.

Upland rice often needs a higher level of fertilization than does lowland rice per unit of production. In The Gambian farming system more fertilizer is applied to lowland rice than upland rice because of the higher returns from lowland rice, and lesser risk associated with its production. Both nitrogen and phosphorus play important roles in its growth and yield, but nitrogen is most often the limiting nutrient and is required in the in greatest quantity for rice production. The nitrogen effect is manifested quickly on plant growth and ultimately on yields. Hence the fertility status of a soil depends to a great extent on the nitrogen status of the soil (Sinha and Prasad, 1980). Organic matter is the major source of nutrients, especially N, in low-input rice cultivation systems. Experiments have shown that, even in the case of high yields of rice, N derived from soil still makes up about 76 to 80% of the total uptake of N of a single-cropped rice (Ponnamperuma, 1984). Generally, the higher the organic matter content, the higher is the N-supplying capacity of the soil.

Ideal cultivars would be those that perform well under low soil fertility but also respond well to applied fertilizer and are drought-tolerant. Cultivars with relatively high harvest index (HI) are generally found to be more efficient in nutrient-use, i.e. giving higher yield per unit of nutrient uptake (Vose, 1990, Inthapanya et al., 2000). Grain yield can be analyzed in relation to acquisition and utilization efficiency of nitrogen. Genetic variation for grain yield under different nitrogen fertility conditions is examined. Once genetic variations in nitrogen uptake and utilization efficiency are found, then physiological or morphological factors that are responsible for such variations can be further examined. The traits responsible for high yield once identified can be used as selection criteria in plant breeding programs, if suitable screening procedures can be developed.

The increase in rice production to feed a growing world population will require a threefold increase in applied N at present levels of N fertilizer-use efficiency (Cassman and Harwood, 1995). It is therefore important to increase fertilizer-N recovery and internal N-Utilization efficiency (NUE) in rice production systems through cultivar improvement and better crop management (Ying et al., 1998). It is reasonable, therefore, to expect increases from low-input rice varieties to make up for the incremental rice yield needed to feed the increasing population.

Fertilizer-N recovery efficiency can be estimated by the ratio of increased plant N that results from N application to the amount of applied N (Novoa and Lomis, 1981). Nitrogen-utilization efficiency may be defined as the amount of grain produced per unit N acquired by the crop. The amount of N uptake and the NUE of crops depend on the yield level and environmental conditions (Ying et al., 1998). Fertilizer-N recovery equal to 50% to 70% of what is applied can be achieved when N is applied in the proper amount, in the proper form, and at the proper time (Peng and Cassman, 1998).

Grain yield increase can be achieved either by increasing biomass production or harvest index, or both (Yoshida, 1981). It is controversial as to which component should be emphasized to further improve yield potential of current cultivars. Comparisons between modern and traditional cultivars of major cereal crops attribute improvement in yield potential in many cases to the increase in harvest index rather than in biomass production (Evans et al., 1984). When comparisons were made among modern cultivars, however, high yield was achieved by increasing biomass production (Amano et al., 1993). Hybrid rice cultivars have reportedly about 15% greater yield than inbreds mainly due to an increase in biomass production rather than in harvest index (Yamauchi, 1994). The number of spikelets per unit land area, or sink size, is the primary determinant of grain yield in cereal crops grown in high-yield environments without stresses (Kropff et al., 1994). Sink size in rice can be increased either by increasing panicle number or panicle size or both. Due to the fact that a strong compensation mechanism exists between the two yield components, an increase in one component will not necessarily result in overall increase in sink size. Sink size would be increased by selecting for large panicles only if the panicle number per m^2 were maintained. The way to decouple the strong negative relationship between the two components is to increase biomass production during the critical phases of development when sink size is determined (Slafer et al., 1996).

In rice, spikelets per m^2 were highly related to dry matter accumulation from panicle initiation to flowering (Kropff et al., 1994), whereas grain filling largely depends on biomass accumulation from flowering to maturity (Yoshida, 1981). This is indicative of the fact that further increase in rice yield potential must come from increased biomass production (Ying, et al., 1998).

Biomass production can be increased by increasing growth duration or crop growth rate, or both (Yoshida, 1983). Crop growth rate is a function of canopy gross photosynthesis and crop respiration (Evans, 1993). Respiration is strongly influenced by temperature (Akita, 1993), while canopy photosynthesis is determined by solar radiation, temperature, leaf area index, canopy architecture, and single-leaf photosynthetic rate (Loomis and Connor, 1992).

Yamagata and Noriharu (1999) found rice to grow better with organic nitrogen than chemical fertilizer. Rice plants reportedly took up more nitrogen than other crops during the first 100 days after amendment with organic nitrogen. This was attributed to 2 factors.

(1) Higher mineralization rate in the rhizosphere of upland rice compared with other crops. Upland rice may enhance nitrogen mineralization in soils by the secretion of some enzymes such as protease and/or materials promoting microorganism activity.

(2) Upland rice has greater ability to take up organic nitrogen directly. If a crop is capable of taking up organic nitrogen in the form of amino acids, peptides and protein, the crop could absorb nitrogen with less competition from microorganisms, as compared with crops which absorbs nitrogen mainly as nitrate (Yamagata and Noriharu, 1999).

Nitrogen, usually found as ammonium in anaerobic lowland soils, is found as nitrate in aerobic upland soils. Nitrate is sufficiently mobile in the soil that root morphology and uptake properties do not limit uptake until soil N levels are very low (Drew, 1990). When ammonium nitrate is applied, the plant absorbs the ammonium faster than the nitrate. The optimum pH is lower for nitrate uptake than ammonia. At optimum pH, nitrate is as effective as ammonia as a source of nitrogen for rice (Tanaka et al., 1984), but nitrate leaches from an upland field faster than in lowland culture (Yoshida, 1975).

Increases in the cost of inorganic fertilizers make it important to examine the relationships between grain yield and nitrogen utilization. Parr (1973) defines fertilizer N use efficiency as the percentage recovery of fertilizer N by the crop. This may be estimated as the difference in uptake by the aboveground portions of fertilized and unfertilized plants and expressed as percent of the N applied. This method is often used by researchers to interpret results obtained from fertilizer N experiments. This conventional method of expressing the fertilizer N utilization includes the uptake of both applied fertilizer and native soil N (Reddy and Patrick, 1980).

Crops have high nitrogen requirements and often respond with dramatic growth and yield increase to the addition of nitrogen. Some consider it the most important nutrient. Certainly, the magic of plant growth cannot properly take place without phosphorus and potassium, the other major nutrients, and essential secondary and micro-nutrients found in rice grain are shown in Table 4. It is clear that only in combination can nitrogen do its best.

Table 4. Average Nutrient Concentrations in Kilogram per Ton Rice Grain at 14% Moisture

N	P	K	S	Mg	Ca	Cu	Fe	Mn	Na	Zn
10	2.5	3.1	0.8	1.0	0.2	0.004	0.025	0.096	0.071	0.018

RIRDC, 2002

From an investigation conducted by Batten (2002), it is evident that accumulation of N in the vegetative body is high during the initial growth stages and declines with age during the later growth stages (Table 5).

Table 5. Nitrogen Concentration in Rice Straw at Different Growth Stages

Growth Stage	N %
Mid-Tillering	3.43 – 3.85
Panicle Initiation	2.03 – 2.56
Harvest	0.62 – 0.69

Batten, 2002

Translocation of N from the vegetative organs to the grain becomes significant only after flowering. There is also some translocation of carbohydrates from the vegetative plant parts to the grains after flowering, and a large amount of carbohydrates accumulates in the grains.

Protein synthesis is active during the vegetative stages. During the reproductive stage, synthesis of cell wall substances (cellulose, lignin, etc.) becomes active, although the pace of protein synthesis also continues. It is only at the ripening stage that starch synthesis becomes active.

Nutrient mobility in the rice plant is in the sequence P>N>S>Mg>K>Ca. The elements that form immediate components of proteins have a high rate of mobility, while those that are continuously absorbed until senescence have a relatively low mobility. Thus N, P and S, which are essential constituents of proteins, are absorbed rapidly during active vegetative growth and are subsequently translocated to the grain after flowering (Pillai, 1990).

In studies conducted by De Datta and Broadbent (1990), genotypic variation in N content was significant under conditions of low soil fertility. In a two-year study at IRRI, Tirol-Padre et al. (1996) found out that where soil fertility was reduced by continuous cropping without fertilizer application, crop maturity type was important in determining grain yield. Late-maturing cultivars accumulated more N, perhaps as a result of increased N mineralization, and produced higher grain yield.

However, the opposite is true when moisture was limiting and terminal drought is a risk factor. Since N fertilizer represents a major portion of the cost of rice production in many areas of the world, there is a great need to improve the N utilization efficiency of crop cultivars (Alagarswamy et al., 1988). Given these circumstances, emphasis should be placed upon optimizing the efficiency of fertilizer N use.

A relatively higher NUE has been observed in rice with high harvest index (grain yield divided by total dry matter) by Bufogle et al. (1997). Eghball and Maranville (1991) noted that NUE generally parallels water use efficiency (WUE) in corn. Wheat varieties with a high harvest and low forage yield have low plant N loss and increased NUE (Kanampiu et al., 1997). Work by Karrou and Maranville (1993) suggests that wheat varieties that produce more seedling dry matter with greater N accumulation are not necessarily the ones that use N more efficiently. Furthermore, N assimilation after anthesis is needed to achieve high yield (Cox et al., 1985) and high NUE. Rice grain yield may be considered to be the product of total above-ground dry matter at harvest and the proportion of it partitioned to grain, i.e., harvest index (HI).

Yield (**Y**) = Total Dry Matter (**TDM**) x Harvest Index (**HI**) (1)

The nitrogen content in grain is the product of Yield and the **N**itrogen concentration of grain (Ng%). The content in straw is the product of straw dry matter (TDM) and straw nitrogen concentration (Ns%). Nitrogen content in the whole plant (NPLANT) is the sum of nitrogen in the grain and straw, if one should ignore the nitrogen in roots for simplicity sake.

$$\text{NPLANT} = \text{NGRAIN} + \text{NSTRAW} \qquad (2)$$

Nitrogen-use efficiency for the plant (NUEp) or physiological efficiency is defined as:

$$NUEp = TDM / NPLANT \qquad (3)$$

From equations 1 and 3

$$Y = NPLANT \times NUEp \times HI \qquad (4)$$

Using equation 4 differences among genotypes in yield under various soil fertility levels can be considered in terms of the following:

- Efficiency in N uptake
- Efficiency with which absorbed N is used (NUEp)
- Harvest Index (HI)

Nitrogen-use efficiency for grain production (NUEg) is defined as the grain yield per unit nitrogen in the plant. The equation below thus indicates the importance of HI, Ns% in determining NUEg.

$$\begin{aligned} NUEg &= Y / NPLANT \\ &= TDM \times HI/TDM * (1 - HI) * Ns\% + TDM \times HI \times Ng\% \\ &= 1/(1/HI - 1) * Ns\% + Ng\% \end{aligned}$$

When HI is small, the genotype variation in Ns% will contribute more to the variation in NUEg. As HI increases, however, the contribution of Ns% decreases, and at HI = 0.5, the genotype differences in the values of Ns and Ng% will contribute equally to NUEg.

Research Objectives and Hypotheses

The research objectives are as follows:

1) To assess the productivity of WARDA's low-input upland rice varieties as influenced by different nitrogen levels;
2) To determine if rice cultivars differ in N-use-efficiency;
3) To determine if the improved low-input varieties indeed possess a greater nutrient-use-efficiency than conventional varieties;
4) To find out what are the most important operating mechanisms that result in improved nitrogen efficiency;
5) To identify which variety is more stable and higher-yielding for use in The Gambia under conditions of low fertility and less intensive management practices;
6) To help upland rice breeders focus on the more important physiological and morphological characters affecting nutrient-use-efficiency in the Sahel.
7) The results will also be used to calibrate the Nitrogen Module of the Nutrient Management Support Software (NuMaSS) for the Sahel region.

The hypotheses are as follows:

1) The yields of the Low-input varieties will not decrease significantly with decrease in N-fertilizer input;
2) The Low-Input varieties will yield higher than the conventional check variety at low-input N application rates;
3) The Low-Input varieties have a higher NUE than the conventional check variety;

4) The NuMaSS can be used to predict N need for The Gambia.

2.2. Materials and Methods

2.2.1. Trial Location: The Gambia

The Gambia is a small country located on the western coast of Africa. It is surrounded on three sides by Senegal and opens to the Atlantic Ocean to the west. It is situated between 13.2 and 13.7° N latitude. It consists of a 50-km-wide ribbon of land extending eastward 475 km from the Atlantic coast and dissected by the River Gambia. It has an area of 11,700 km^2. The Gambia lies within the Sahelo-Sudan climate zone.

Upland Trial Site: NARI Research Station, Brikama

▲

Figure 4. Map of Republic of The Gambia, West Africa, Showing
Upland Rice Trial site location

The rainy season typically extends from late May to early October; however, both ends of the rainy season have shortened in recent years. Average annual rainfall for the country in 1999 was 1,083 mm. The 10-year normal average in 2000 was 804.3 mm in the western half of the country, and 700.3 mm in the eastern half. Average annual minimum temperatures in this tropical country is 21C°, with a maximum mean of 33C°.

2.2.2. Field Experiment Design

The field experiments were conducted during the rainy season of 2000, 2001 and 2002 at the Gambia National Agricultural Research Institute's experimental fields in Brikama, Western Gambia.

The experimental design was split-plot, with fertilizer level as the main plot, and variety as sub-plot. Four fertility levels and four varieties were studied. The main plots were not replicated. Each variety was replicated 3 times in each main plot. The test varieties were the best entries from a previous 3-year low-input varietal screening exercise of 10 new low-input varieties from WARDA. Peking being the most widely grown upland rice variety in The Gambia was selected as the local check. It is a short-stature variety maturing within 80 to 85 days. There were a total of 48 sub-plots in the trial (see Appendix 1). The treatment levels were as follows:

Main plots: Fertilizer application rates

1. Zero application (Control)
2. Low-Input: 40-40-40 Kg/ha NPK
3. High-input: 80-40-40 kg/ha NPK
4. Very High-Input: 160-80-80 kg/ha NPK

Sub-plots: Varieties

1. WAB 56-125
2. WAB 377-B-16-L3-LB
3. WAB 56-50
4. Peking (Local check)

The plot sizes were 2.7 x 4m (10 rows, 4m long). The plots were direct seeded by drilling in rows 30cm apart.

Weed control was completely manual by hand pulling the weeds at 20, 40 and 60 days after emergence.

The data collected include the following:

Days to 50% flowering
Plant height at harvest
Tiller count
Panicle count
Number of grains per panicle
Percentage filled grains per panicle
1000 grain weight
Harvest Index
Grain yield
Soil nutrient level

Rainfall data

The model for analyzing the individual variables is as follows:

$Y_{ijkl} = \mu + Yr_i + Fert_j + Var_k + (Yr{*}Fert)_{ij} + (Yr{*}Var)_{ik} + (Fert{*}Var)_{jk} +$

$+ (Yr{*}Fert{*}Var)_{ijk} + \varepsilon_{ijkl}$

($i= 1,2,3;\ j = 1,2,3,4;\ k =1,2,3,4; l = 1,2,3,\ldots \ldots,48$)

Where:

Y_{ijkl} – the response from l^{th} plot in the j^{th} block in the
i^{th} year using the k^{th} treatment variety

μ – overall mean

Yr_i – effect of the i^{th} year - iid $N(0, \sigma^2_{Yr})$

$Fert_j$ – effect of j^{th} fertilizer level - iid $N(0, \sigma^2_{Fert})$

Var_k – effect of k^{th} variety treatment - $\sum Trt=0$

ε_{ijkl} – experimental error - iid $N(0, \sigma^2_{\varepsilon})$

All of the above are pairwise independent

Significant differences among treatments were determined using a three-factor analysis of variance (ANOVA) model. Comparison of treatment means was done using the least significant difference (LSD) test. Data points for all the measured variables were independent, normally distributed, with equal variance. No transformation of data was necessary. All results reported are averages of duplicated assays and analyses. The SAS statistical package was used for all the statistical analyses.

2.2.3. *Results and Discussions*

During the 2000 cropping season, 970.7 mm of rainfall was experienced. Applied fertilizer had a significant effect on plant height (Table 6), especially that of Peking, the local check. In local production systems, Peking has an average height of 60 cm.

Table 6. Low-Input Upland Rice Trial, Yield Parameters,
Brikama, The Gambia, 2000

Fertilizer Level	**Variety**	**Plant Ht (cm)**	**Tiller per m²**	**Panicle per m²**
Zero Application 0-0-0	WAB56-50	84.7	57	41
	WAB56-125	83.6	56	41
	WAB377-B	78.8	63	45
	Peking	82.7	44	31
Low-Input 40-40-40	WAB56-50	91.3	48	39
	WAB56-125	94.8	51	35
	WAB377-B	96.0	50	36
	Peking	96.0	53	39
High-Input 80-40-40	WAB56-50	98.8	83	52
	WAB56-125	94.8	89	57
	WAB377-B	96.7	70	42
	Peking	96.6	79	51

Very High Input **160-80-80**	WAB56-50	109.3	77	52
	WAB56-125	111.7	65	49
	WAB377-B	110.7	100	69
	Peking	106.9	75	44
$\text{Lsd}_{.05}$		31.3	24	27
Cv(%)		21.3	26.9	36.6
P_{Fert}		0.08	<0.0001	0.018
P_{Variety}		0.01	<0.0001	0.008
$P_{\text{Fert*Variety}}$		0.15	0.12	0.045

From zero application to very high application rates, the increase in plant height for *cv* Peking was 29%. The same trend was observed with all the varieties especially with *cv* WAB377-B, that had a 40.5% increase in plant height.

Tillering was equally affected by fertilizer application rates, and there was a correlation of 0.85 between tiller count and panicle count per m^2. In terms of panicle setting there was no significant difference between the zero and low-input application, likewise the high and very high application rates. However, there was a significant difference between the treatments with little or no fertilizer and those with high and very high application rates.

The 1000 grain weight (Table 7) of all the test varieties increased significantly from the zero to very high application rates except *cv* WAB377-B. There were no significant differences for 1000 grain weight between the Zero application rate and low-Input or High-Input rates for all varieties with the exception of *cv* Peking.

The low-input varieties did not show any significant difference in 1000 grain weight at Low and high input levels, however at very high input both *cv* WAB 377-B and WAB 56-50 had a significant increase in 1000 grain weight.

The increase in fertilizer input had a significant linear effect on dry matter production for the local check Peking. The Low-Input varieties did not show any significant differences between Zero application and Low-Input rates except for *cv* WAB56-50, which had a significant increase in biomass. Similarly there was no significant difference between the High-Input and Very High-Input rates for all the Low-Input varieties. At the very high N application rate all the varieties had a significant increase (p=0.0001) in dry matter weight, especially *cv* WAB 35-125 which responded with massive biomass production.

Table 7. Low-Input Upland Rice Trial, Yield Data, Brikama, The Gambia, 2000

Fertilizer Level	**Variety**	**1000 Grain Wt (g)**	**Stover Wt T/Ha**	**Yield T/Ha**
Zero Application 0-0-0	WAB56-50	27.3	1.51	1.208^{BC}
	WAB56-125	27.2	2.10	1.115^{BC}
	WAB377-B	27.3	2.12	0.879^{C}
	Peking	23.8	1.38	0.907^{C}
Low-Input 40-40-40	WAB56-50	29.9	2.88	0.782^{C}
	WAB56-125	30.2	2.08	1.296^{BC}
	WAB377-B	30.6	1.78	1.771^{BC}
	Peking	29.3	1.86	1.013^{BC}
High-Input 80-40-40	WAB56-50	27.3	2.33	1.650^{BC}
	WAB56-125	28.5	2.57	1.087^{BC}
	WAB377-B	28.1	2.08	2.115^{AB}
	Peking	29.6	2.33	1.597^{BC}
Very High Input 160-80-80	WAB56-50	34.1	3.40	2.777^{A}
	WAB56-125	29.4	3.64	1.708^{BC}
	WAB377-B	34.8	2.95	1.041^{BC}
	Peking	31.8	2.72	0.731^{C}

$Lsd_{.05}$		3.5	0.9	0.942
Cv(%)		8.2	38.6	40.8
P_{Fert}		0.2	0.0001	0.057
$P_{Variety}$		<0.0001	0.18	ns
$P_{Fert*Variety}$		<0.0001	0.004	0.014

At very high N application rate the varieties were severely affected by neck (*Pericularia oryzae*) infestation and lodging. With the exception of cv WAB 56-50, which demonstrated some level of tolerance and produced the high yield of 3.7 T/ha, none of the varieties had a significant yield increase even at very high application rates. Peking, the local check, is highly susceptible to blast.

In 2001, the rainfall amount decreased by 10.7%. Organic matter and total N was lower than at planting the previous year (see Appendix 2). Corresponding yields were relatively lower than in 2000 (Table 8). The same trend was observed with biomass production. There was no significant different in yield of *cv* WAB 56-125 at any fertility level. It had a relatively stable yield at zero and low-input application rates. At high fertilizer input, all the varieties had a significant yield increase with the exception of *cv* WAB 56-125. At very-high input, despite high biomass production neck blast and lodging were major problems and often grain yields were reduced.

There was a serious drought during 2002 cropping season. Rainfall levels dropped by 32% of the previous year's, and by 33% of the 10-year normal. It was estimated by the Ministry of Agriculture in The Gambia that close 50% of all upland crops failed, and crop yields decreased by 60%. Upland and lowland rainfed rice yields were severely affected.

Table 8. Low-Input Upland Rice Trial, Grain Yield, and Yield Parameters, Brikama, The Gambia, 2001

Fertilizer Level	**Variety**	**1000 Grain Wt (g)**	**Stover Wt T/Ha**	**Yield T/Ha**
Zero Application 0-0-0	WAB56-50	25.6	1.2	0.6
	WAB56-125	27.2	1.5	1.2
	WAB377-B	28.9	1.4	0.4
	Peking	23.1	1.4	0.8
Low-Input 40-40-40	WAB56-50	29.7	1.2	0.8
	WAB56-125	28.5	2.0	1.2
	WAB377-B	27.9	1.8	0.8
	Peking	21.9	1.3	0.5
High-Input 80-40-40	WAB56-50	30.7	1.8	1.6
	WAB56-125	26.5	2.0	1.4
	WAB377-B	27.6	2.0	0.9
	Peking	19.3	1.8	1.2
Very High Input 160-80-80	WAB56-50	28.7	2.2	1.4
	WAB56-125	35.0	2.1	1.4
	WAB377-B	30.7	2.6	1.5
	Peking	20.7	2.0	0.8
$\text{Lsd}_{.05}$		5.0	0.9	0.4
Cv(%)		11.2	30.7	32.5
P_{Fert}		0.125	0.0024	0.0006
P_{Variety}		<0.0001	ns	0.0116
$P_{\text{Fert*Variety}}$		<0.0001	0.0943	0.00018

At low fertility levels such as at Zero and Low-input application rates there was stunted growth and wilting as well as high incidence of crop loss due to termite attack. The plants growing under high and very high application rates were significant more tolerant to wilting and termite attack. Spikelet fertility (Table 9) was low at zero fertilizer application for all the varieties with the exception of *cv* WAB 56-125. The local check Peking was the most affected at zero and low fertilizer application rates. Spikelet fertility was low at very high fertilizer application rate due to blast infestation. Stover weight at zero application, low-input, and high-input level were not significantly different for all varieties. At very high input though, there was a significant difference. Yields were highest for all varieties at high application rate. WAB 56-125 gave 2.9 t/ha, which is relatively the highest yield at the different application rates. Yields were low at the zero and low-input levels because of poor plant stand due to termite attack. At low N application, seedling vigor was poor, and the weak stems were highly susceptible to termite infestation and damage. Precipitation was unevenly distributed during the growing season. Seventy-five percent of the rains fell during the last decade in August and the first and second decades of September. Severe drought was experienced between emergence and panicle initiation. Development of the panicle is very sensitive to soil water availability, and the rate of development is reduced with a small water deficit and ceases completely with the development of severe drought.

Weed infestation was relatively lower in 2002 than in previous years. It is apparent from the results that the low-input varieties did much better at the high fertilizer application rate of 80-40-40 kg/ha NPK. Under the drought stress conditions that prevailed during the growing seasons, nitrogen was a limiting factor at zero and at low-input (40-40-40 kg/ha NPK) application rates.

Table 9. Yield Parameters from Low-Input Upland Rice Trial, Grain Yield and Yield Parameters, Brikama, The Gambia, 2002

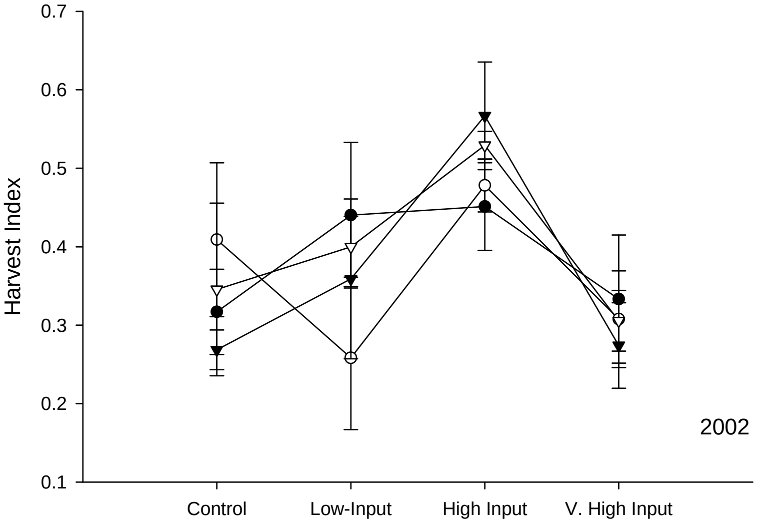
Fertilizer Level	**Variety**	**Spikelet Fertil. %**	**Stover Wt T/Ha**	**Yield T/Ha**
Zero Application 0-0-0	WAB56-50	50.5	1.5	1.1^{DE}
	WAB56-125	72.5	2.1	1.1^{DE}
	WAB377-B	56.6	2.1	0.8^{E}
	Peking	49.7	1.4	0.6^{E}
Low-Input 40-40-40	WAB56-50	70.1	2.9	1.0^{DE}
	WAB56-125	69.1	2.1	1.4^{CDE}
	WAB377-B	69.6	1.8	1.0^{DE}
	Peking	64.9	1.9	1.5^{BCDE}
High-Input 80-40-40	WAB56-50	66.6	2.3	2.3^{ABC}
	WAB56-125	75.8	2.6	2.9^{A}
	WAB377-B	75.0	2.1	2.5^{AB}
	Peking	71.0	2.3	2.0^{ABCD}
Very High Input 160-80-80	WAB56-50	53.7	3.4	1.5^{BCDE}
	WAB56-125	67.3	3.7	1.6^{BCDE}
	WAB377-B	66.4	3.0	1.1^{DE}
	Peking	60.0	2.7	1.5^{BCDE}
$Lsd_{.05}$		17.7	1.2	1.0
Cv(%)		16.1	32.3	44.6
P_{Fert}		0.0005	0.0007	<0.0001
$P_{Variety}$		0.1539	ns	ns
$P_{Fert*Variety}$		0.0037	0.0396	ns

Over the three years of testing (Table 10) *cv* WAB 56-125 gave the highest and most stable yield. The high-input yields for all varieties remained about the same as with *cv* WAB 56-125 or slightly less for the drought year.

Table 10. Grain Yield from Low-Input Upland Rice Trial, Brikama,
The Gambia, 2000, 2001, 2002

Fertilizer Level	**Variety**	**Grain Yield T/Ha**			
		2000	**2001**	**2002**	**Ave**
Zero Application 0-0-0	WAB56-50	1.2	0.6	1.1	1.0^{BC}
	WAB56-125	1.1	1.2	1.1	1.1^{BC}
	WAB377-B	0.9	0.4	0.8	0.7^{C}
	Peking	0.9	0.8	0.6	0.8^{C}
Low-Input 40-40-40	WAB56-50	0.8	0.8	1.0	0.9^{C}
	WAB56-125	1.3	1.2	1.4	1.3^{ABC}
	WAB377-B	1.8	0.8	1.0	1.0^{BC}
	Peking	1.0	0.5	1.5	0.9^{C}
High-Input 80-40-40	WAB56-50	1.7	1.6	2.3	1.8^{A}
	WAB56-125	1.1	1.4	2.9	1.8^{A}
	WAB377-B	2.1	0.9	2.5	1.8^{A}
	Peking	1.6	1.2	2.0	1.6^{AB}
Very High Input 160-80-80	WAB56-50	2.8	1.4	1.5	1.8^{A}
	WAB56-125	1.7	1.4	1.6	1.6^{AB}
	WAB377-B	1.0	1.5	1.1	1.2^{ABC}
	Peking	0.7	0.8	1.5	1.0^{BC}
$Lsd_{.05}$		0.9	0.5	1.0	0.6
CV(%)		40.8	32.5	44.6	48.2
P_{Fert}					<0.0001
$P_{Variety}$					0.0494
P_{Year}					0.0015
$P_{Fert*Year}$					0.0364

Drought affects plant growth, biomass production as well as grain production. The level of drought resistance in the tested low-input rice varieties was not sufficient under the extreme conditions that prevailed during the 2002, even though most crop varieties failed completely during this period. Water is essential for plant growth, its shortage reduces transpiration due to soil water deficit, which results in reduced photosynthesis, since gas exchange for both water and CO_2 takes place simultaneously through stomata. Although some drought resistant varieties are known to have a high photosynthesis:transpiration ratio, it has been proven (Dingkuhn, 1989) that a strong linkage between water use and plant dry matter production limits development of varieties that are supposedly drought resistant when water becomes a significant constraint. Soil water content is the predominant factor affecting the rate of N uptake. The rate of absorption of nitrate N from the soil is highly correlated to absorption. Transpiration induces soil solution flow towards the root surface carrying dissolved solutes with it by convection or mass flow. A soil profile just before harvesting prevailed that the bulk density of the test varieties' roots is concentrated within the 0-10 cm depth, contrary to prior hypothesis that they possibly processed a highly diffused root system. It has also been proven by Mitchell et al. (1998) that genotypes with larger canopy size tend to be severely affected by early season drought, leaf water potential decreases rapidly and a large number of young green leaves are lost, although it may not necessarily reflect on the harvest index (Figure 5).



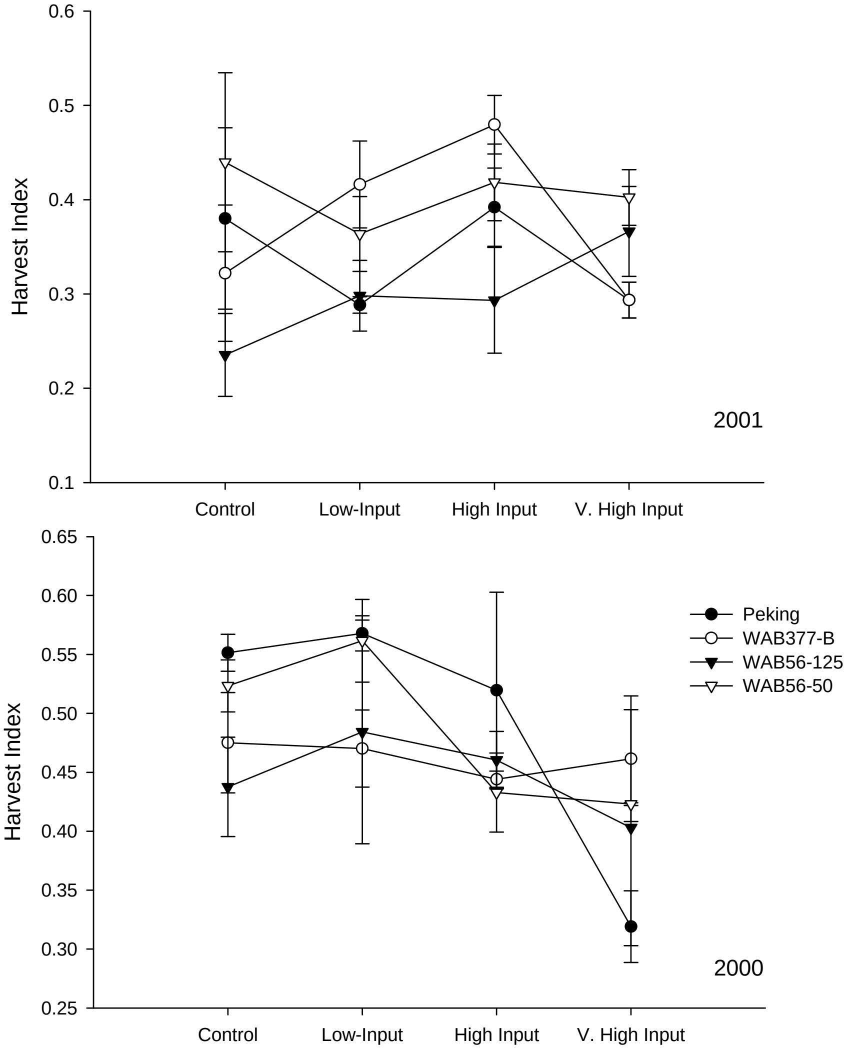


Figure 5. Harvest Index of Low-Input Upland Rice Varieties in 2000, 2001 and 2002 Cropping Seasons in Brikama, The Gambia

The low-input varieties being tested have larger canopy, a mechanism found useful to suppress weeds during the early stages of growth. Under drought conditions nutrients become relatively less available because their transport to the root-soil interface is impeded by the diminished rate of diffusion and mass flow (Yamboa and O'Toole, 1984). The low nitrogen concentration under zero and low-input application rates was not conducive for effective nitrogen uptake under the dry soil conditions that prevailed for most of the growing season.

According to Fukai et al. (1999); Graham and Welch (1996) plant species and varieties within species do differ in nutrient uptake efficiency, and dry matter accumulation per unit time and growth duration. Genotypes also differ in the efficiency with which nutrients are used in the proportion of total dry matter production and in the proportion and quantity of nutrients translocated to the grain. The low-input rice varieties develop a massive biomass during the early growth stages forming a broad canopy, and phenomenally after panicle initiation becomes compacted and the leaves seem to reduce in size. It is hypothesized that this relative reduction in canopy size is as a result of nutrient translocation from stem and leaves into the panicle for grain production. The stem N content is affected both by fertility and available moisture levels. During the driest year of experimentation stem N content increased drastically, even though grain production diminished (Figure 6).

Tissue N concentration was below 1.2% in 2000 and 2001 cropping seasons independent of N application rates. In 2002, a relatively drier year, the N tissue concentration ranged between 0.8 and 1.0% for zero the application rate. For the 160 N application rate tissue N concentration ranged between 1.1 and 1.5%. This is much higher than that recorded in the years with normal rainfall.

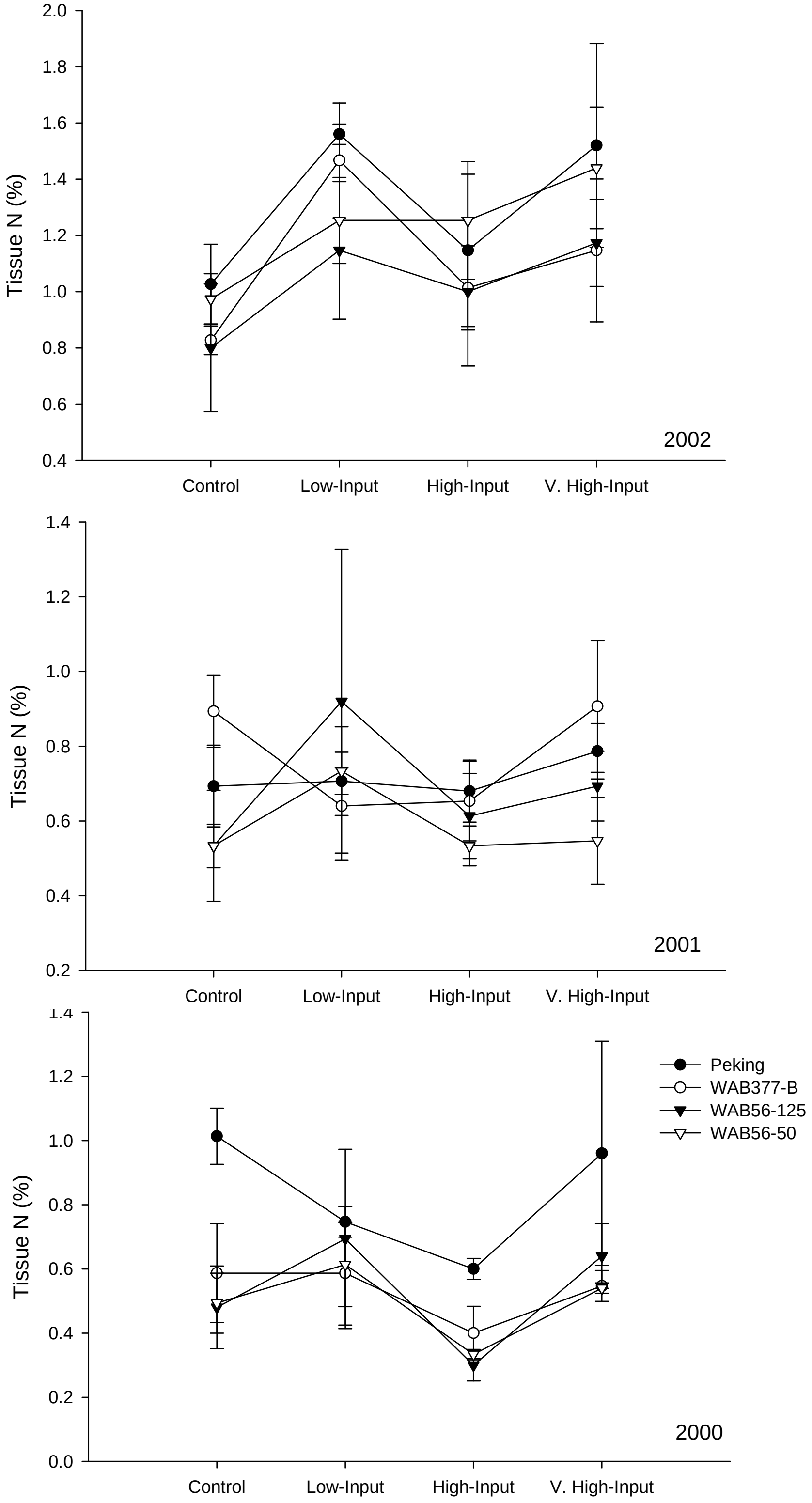


Figure 6. Tissue N content of Low-Input Varieties at Harvest in 2000, 2001 and 2002 Cropping Seasons

The amount of N in the stem increased for all varieties with increases in N fertilizer application rates.

A high variation in stem N content at maximum tillering stage and harvest (Figure 7) was observed.

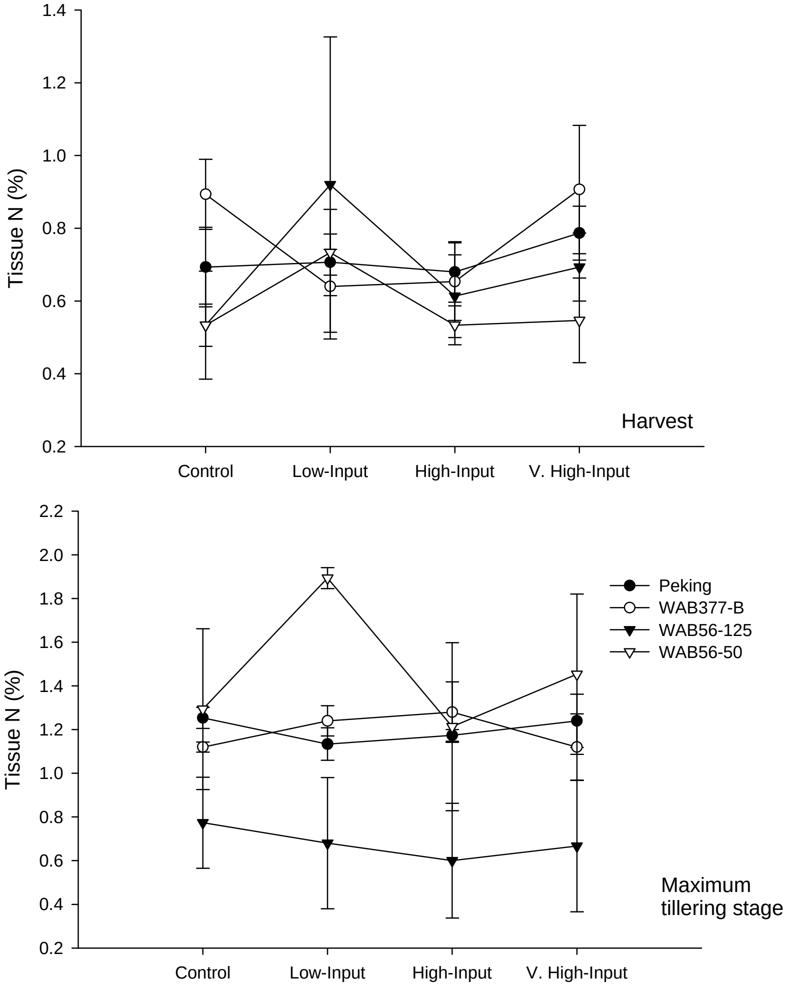


Figure 7. Tissue Nitrogen Content at Maximum Tillering Stage and at Harvest of Low-Input Rice Varieties in 2001, Brikama, The Gambia

According to Fukai et al. (1999) high N content in stem is associated with low N use efficiency. Overall, the total above ground biomass (stover and grain) did not correlate with grain yield. Total above ground biomass in 2002 increased by 80% in comparison to 2000 a relatively drier year, but at the same time an increase in grain yield of just 18% was recorded (Figure 8). This is an indication that nitrogen uptake for stem dry matter production was higher in drier years and did not necessarily impact grain production.

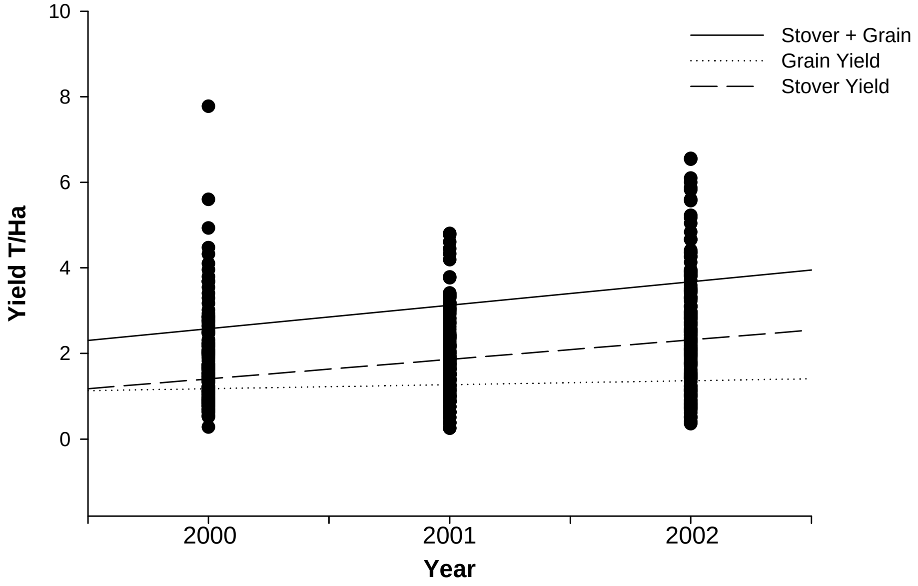


Figure 8. Scatter Plot of Biomass and Grain Yield Data from Low-Input Rice Varieties Trials in 2000, 2001, and 2002 Cropping Seasons in Brikama, The Gambia

Overall, stem N content at maximum tillering stage was higher than that at time of harvest. This could possibly be explained by the fact that translocation occurs after tillering thus the low N contents thereafter. In the very dry year a low N uptake at maximum tillering is predictable, resulting in lesser N available for grain production. The N use efficiency was considerably affected by the amount of precipitation during the cropping season. In 2002, the severe drought condition that prevailed caused a significant reduction in the N use efficiency for grain production at all levels of nutrient application except the high-input level. Yield loss at the very high input rate was as a result of blast (Figure 9). In 2000, which was a drought free year, NUEg was relatively highest at the low-input level of fertilizer application, but in drier years the point of high NUEg was at the high-input level. The low-input variety WAB56-50 had the highest NUEg at all levels of fertilizer input in 2000 and 2001. In the driest year WAB377-B-16-L3 had the best NUEg at high-input fertilizer application level. There are genotypic differences in NUEg, and the level apparently depends on amount of available nutrient and moisture. Very low NUEg and relative high N stem content were recorded in 2002 at the zero and low-input application levels. This may be explained by the fact there may have been reduced translocation due to reduced mass flow in the plant. This caused N stagnation in the stem and less translocation for use in grain production. It is estimated that 70% of the plant's needs at grain-filling stage comes from remobilization from within the plant.

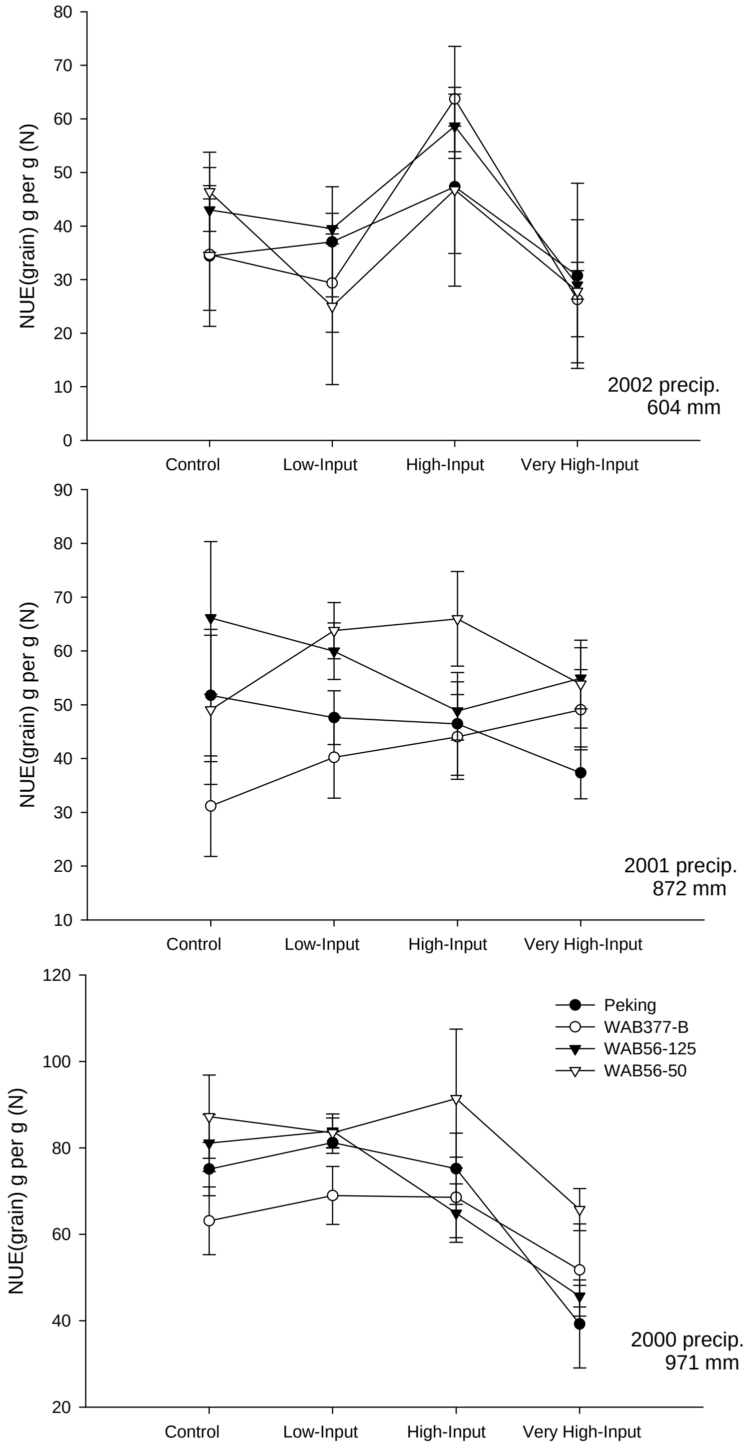


Figure 9. Nitrogen Use Efficiency for Grain Production of Low-Input Rice Varieties in 2000, 2001 and 2002 Cropping Seasons in Brikama, The Gambia

The Nutrient Management Support System (NuMaSS)

The NuMaSS software was developed by scientists from Cornell University, University of Hawaii, North Carolina State University, and Texas A&M University to improve the diagnosis and recommendations for nitrogen, phosphorus, and soil acidity problems, especially for tropical regions. It enables soil scientists to access, evaluate and transfer nutrient management information from a global database on cereals, legumes, and root and tubers. The NuMaSS software provides a quick and cost-effective means of diagnosing, predicting, and responding to local soil fertility management needs of farmers globally. It was financed primarily by United States Agriculture and International Development (USAID).

NuMaSS software runs under Microsoft windows operating systems and requires at least 32MB of RAM and 60MB of available hard-disk space. A CD-ROM is required to download the software. Recommendation may be printed with a printer or stored in the program.

A copy of the NuMaSS software can be obtained from Dr. Jot Smyth, NC State University, Soils Department, Box 7619, Raleigh, NC 27695 (email: umass@ncsu.edu). It can also be downloaded from the internet at: http://intdss.soil.ncsu.edu/

The NuMaSS software is a synthesis of five distinct programmatic sections - *Geography*, *Diagnosis*, *Prediction*, *Economic Analysis*, and *Results* - each differentiated by a tab. Information is inputted through the use of input boxes, though not all input boxes need information for NuMaSS to work. The input information needed for the integrated system to run is dependant on the information needed by the individual modules. Databases have been constructed that will provide default values in some, but not all, input boxes.

Necessary inputs for the nitrogen module consist of intended crop, crop yield, plant N content, and, if you use organic inputs, the amount of manure or residues that you apply. Depending on the location and crop, some other necessary inputs can be accessed from the database. However, the precision of the N recommendation improves dramatically with more information supplied (Osmond et al., 2002).

The **Nitrogen module** is primarily designed to help you determine appropriate N fertilizer rates after accounting for any organic applications. NDSS depends on an extensive database of crop yields, soil N, HI etc, and can be supplemented with local information. For each cropping and soil system option you select, NuMaSS helps analyze projected costs and returns on investment.

Diagnosis: N is almost always deficient in tropical soils unless a legume is being grown or the crop is preceded by a fallow or green manure system. Therefore, diagnosis of N deficiencies almost always produces the need to add N.

Prediction: Unlike most other nutrients, there are few reliable soil tests to determine crop N needs. This is particularly true in humid regions where N can be readily transformed and moved below the rooting zone. Generally N fertilizer recommendations are based on extensive data sets developed over many years.

When extensive field data is not available for determining N fertilizer rates, crop N fertilizer needs can be calculated using available soil and crop data. The equation below predicts the N fertilizer requirement for a crop.

$$Nfert = (Yr*Ncr) - [(Nsoil) + (Nresidue.*Cr) + (Nmanure*Cm)] /Ef$$

Where:

Nfert = N fertilizer needed;

Yr = Target dry matter yield, both vegetative and/or reproductive and/or total dry matter ;

Ncr = Concentration of nitrogen (%N) in vegetative and/or reproductive and /or total dry matter;

Nsoil = Nitrogen absorbed by the plant that is derived from soil organic matter and previous drop residue mineralization, and from atmospheric deposition during growing season;

Nr = Nitrogen mineralized from green manures or residues, such as stover or compost that are added to the field;

Cr = Proportion of nitrogen mineralized from green manures or residues that are absorbed by the plant;

Nmanure = Nitrogen mineralized from animal manure;

Cm = Proportion of nitrogen mineralized from manure that the plant absorbs;

Ef = Fertilizer efficiency.

Determining Crop N: The first step is to determine the total crop N need. The equation for this determination is:

$$\text{Total Crop N Needs} = Yr * Ncr = Yg*\%Ng + Ys*\%Ns$$

Where:

Yr = Total dry matter;

Ncr = Nitrogen concentration in the total plant;

Yg = Reproductive yield;

%Ng =Nitrogen concentration in the reproductive portion of the crop;

Ys = Vegetative yield;

%Ns = Nitrogen concentration in the vegetative portion of the plant.

The input information necessary to determine the amount of N that the crop needs is entered in the Diagnosis section of NuMaSS. The amount of additional N needed to produce the targeted yield that you want is a function of the capacity of the soil to supply N and the total amount of crop N needed. In order to determine the total crop demand for N and fertilizer N requirement, it is important to have a target yield in order determine the amount of N fertilizer needed. Better results are obtained by entering either the total amount of dry matter or a realist attainable grain yield. If this information is absent, a default value may be obtained from the database for the specific location, sub-region, or region. Total crop N is a function of both total crop dry matter and the N content. If information for N content is not available, again a default value may be obtained from the database. For NuMaSS to run, the minimum data set that must be entered (or pulled from default values in the database) in the Diagnosis section of NuMass are:

1. Crop reproductive yield, Crop vegetative yield, Crop reproductive N content, Crop vegetative N content; OR
2. Crop total dry matter, Crop total N content; OR
3. Crop reproductive yield, Harvest ratio, Crop reproductive N content, Crop vegetative N content

Determining Crop Available N: Once the amount of N is calculated for the target yield, NuMaSS calculates the amount of N available to the plant from the soil (NSoil), manure (NManure) and organic amendments (NResidue), and green manure crops (NResidue). The equation used to calculate crop available N is:

$$\text{Crop available N} = \text{NCrop(available\_to)} = \text{NSoil} + \text{NManure} + \text{NResidue}$$

Determining Soil N: There are four different methods that you can use to determine the amount of N supplied by the soil (NSoil). The program automatically selects the method for calculating NSoil based on the data availability. The hierarchy for determining NSoil is outlined below. If sufficient data is available for Method 1, then that is the method used. However, if there is insufficient data the program will continue sequentially checking for available data until a method can be found. The precision for calculating NSoil changes as the program moves through the methods. Method 1 is the most precise calculation of NSoil, Method 4 is the least precise.

Hierarchy for NSoil:

1. You will enter the N supplying capacity of the soil. You must enter the input value. This value is entered in the *Nitrogen Application* of the *Prediction* section.
2. The N supplying capacity of the soil will be pulled from a default table. You simply click on the default check box. However, default soil N values are not available for all locations.
3. The amount of N contained in an unfertilized crop gives you an indication of the N supplying capacity of the soil. If the previous crop and the current crop are the same and the previous crop was not fertilized, than soil N can be calculated. You will have already entered this information in the *Diagnosis* section under *Crop History*.
4. The least precise method for determining soil N supply is by calculating N mineralization either from soil organic matter, C or N content. The default rate of mineralization is 3% per year. User supplied soil N, C, or organic matter content will come from the *Diagnosis* section. If none of the three numbers were supplied by you, then a default value for either soil N, C, or organic matter may be accessed from the default data base.

Determining Manure N: If manure material is added in the current crop production season, then the N supplied by the manure must be accounted for. Information on manure is entered in the Prediction section under Applied

Amendments. The amount of N from manure can either be calculated from information you supply or from the default data tables.

Determining Residue N: Green manures that remain in place or residues, such as stover or compost, that are moved from one location to another also provide N to the crop and thus reduce the amount of fertilizer that must be added.

You will enter information on green manures in the Diagnosis section under Crop History. You MUST select the green manure from the list. If you select the "other" green manure then you must also enter the total dry matter and dry matter N content.

You will be asked about residue information in the Prediction section under the Applied Amendments. Again, you will be asked to supply specific information, but if you do not have this information, values may be supplied from the data tables. To calculate the contribution of nitrogen from these organic sources, you MUST supply the amount of residue that is added and the N content of these materials.

Determining Fertilizer Requirement: At the end of the Prediction section, the crop N requirement and N sources (N supplied by the soil and added organic sources) have been determined. By subtracting the amount of N supplied by the soil and organic sources from the amount of N needed by the crop at the target yield, the amount of extra N needed as fertilizer is calculated. To determine fertilizer N, the amount of N needed by the crop is divided by the efficiency of the N fertilizer (See Prediction section – N Application). You can either supply the fertilizer efficiency value or you may be able to access a value from the database. Fertilizer efficiency must be supplied for the system to provide an N fertilizer recommendation.

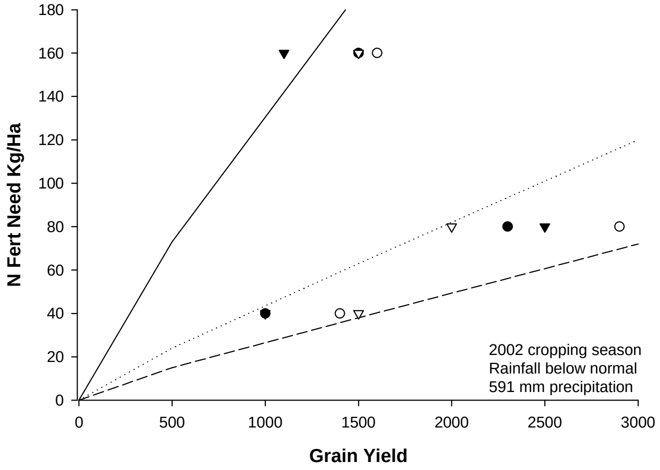
The amount of N available to the crop is a function of the amount of soil N, either from manure or crop residues and the NUE of the crop in a given environment (Osmond et al., 2002).

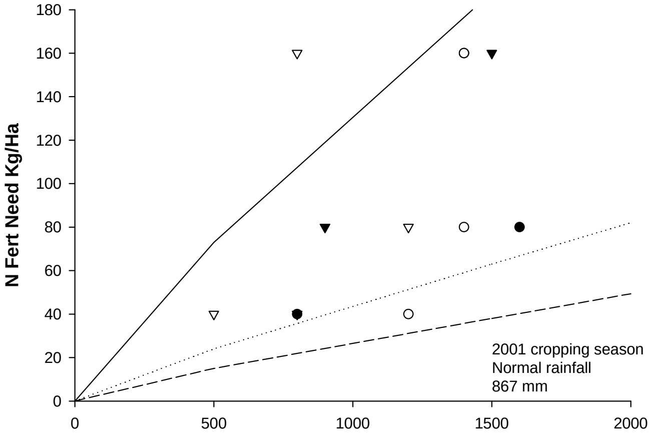
In order to compare the predicted N need for the low-input varieties with the achieved yields at 40, 80, and 160 kg/ha N application rates, 3 levels of NUE (10, 30 and 50%) were used to find out what the real NUE was in each cropping season for a given variety (Figure 10).

The predicted N application rates and the corresponding real yield values indicate that the NUE for the low-input varieties does not exceed 50%. In 2000, the highest yield at 40 and 80 kg/ha N application rate was from WAB377-B, with NUE of 40 and 20% respectively. At 160 kg/ha N application rate the NUE fell below 10% with all varieties. At very high N application rates (160 kg/ha) lodging and blast disease incidence were observed.

In 2001, at 40 kg/ha N application rate WAB56-125 gave the highest yield with a NUE of 40%. At 80 kg/ha N application rate WAB56-50 had the highest yield with a NUE close to 30%.

In 2002, a relatively drier than normal year, NUE was higher for all the varieties and ranged from 30 to 50 % at 40 and 80 kg/ha N application rates. In 2001, it was relatively wetter than normal. Nitrogen use-efficiency was lower in the wetter years than in the drier ones. This was probably due to high leaching and N loss to run-off and topsoil erosion in the wetter years. Overall, in a normal or drier year WAB56-125 has the best NUE of the low-input varieties. The NuMaSS predictions were more realistic in the drier year than when it was wetter. The default NUE of 50% is too high during wetter than normal years, but it is perfect in drier years.





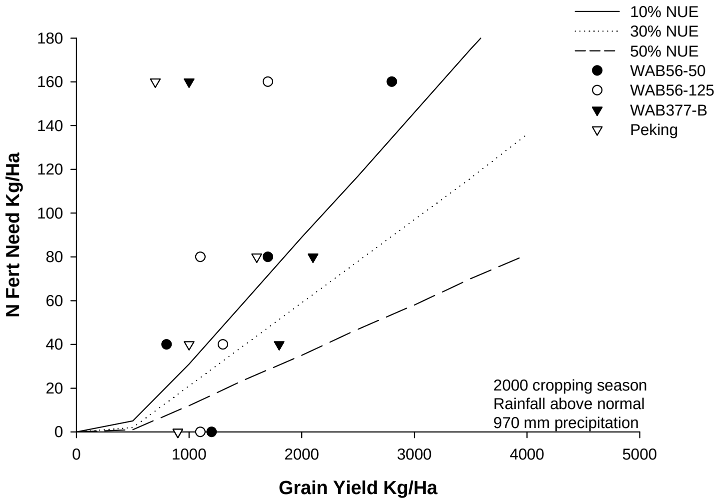


Figure 10. Grain Yield at Different N Application Rates and NuMass Predicted Yields at Different NUE Values, 2000, 2001, and 2002 Cropping Seasons in Brikama, The Gambia

The predicting N for upland rice, NuMaSS should use yields from the drier year; 591 mm rainfall. The amount of precipitation should have a more dominant role in predicting N for upland rice in semi-arid regions. The NUE appears to be high during drier years. Positively correlating predicted N amount and rainfall amount should be considered for NuMaSS N prediction for upland rice in the semi-arid regions. Applied N also needs to be managed in a different way.

2.2.4. Conclusions

All the low-input varieties performed better than the local check (Peking); however WAB377-B-16-L3-LB and WAB56-125 gave the highest most stable yields.

The best NUE (65-85g grain per gram N) was recorded with WAB56-50 at low-input (40-40-40 kg/ha NPK) fertilizer application rates.

Increasing biomass production or harvest index, or both resulted in yield increases. However, grain filling did not necessarily depend on biomass accumulation, but the possibility for the plant to utilize N already accumulated in the biomass for grain production. This is indicative of the fact that research to increase rice yield potential in the upland should aim at increasing biomass production as well as carbohydrate translocation potential for grain production after panicle initiation. The level of N in plant tissue at maximum tillering stage was found to be higher than at harvest. However, in the drought year (2002, with 590 mm rainfall), N-levels in plant tissue at harvest remain high, as result of which, probably, grain yield was lowered.

The results suggest that low-input varieties have better potential to capture and utilize N. High yield potential in the low-input varieties is due to increased biomass production rather than HI. The massive biomass produced in the low-input varieties during the vegetative phase is a huge sink for N. After flowering, translocation of N from the vegetative organs to the grain becomes active. There is also some translocation of carbohydrates from the vegetative plant parts to the grains after flowering, a large portion of which goes into grain.

Increased biomass production in low-input varieties provided them with an ability to outgrow and suppress weed development by shading them. Weed infestation was less than 50% in plots with Low-Input varieties than in those with the conventional variety. Early canopy closure is also cited in some work as having the potential to reduce NH_3 volatilization.

The NuMaSS predictions were more realistic in the drier year (590 mm) than when it was wetter (970 mm) probably because of N loss by leaching during the wetter year. The NuMaSS default NUE of 50% may be too high during the wetter year as a result of higher leaching and run-off than normal years, but it was more appropriate for the drier years. In the normal year, NUE was about 35%. Given these efficiencies for different rainfalls, split application of N is highly recommended. A low-input level of fertilizer application (40-40-40 kg/ha NPK) may be budgeted for at the beginning of the season, but in the event that major leaching occurs, late season application of N at a rate of 40 kg/ha (in 2 splits) is recommended.

The high level of heterosis present in the low-input varieties causes them to produce massive biomass during the vegetative growth stage. Although this is not usually efficient in terms of nitrogen use efficiency, but these varieties have the potential to translocate carbohydrate from the vegetative biomass for grain production. This is very efficient in terms of nutrient-use, future breeding efforts should consider possibilities of incorporating this phenomenon in newer upland varieties.

CHAPTER THREE:

LOWLAND RICE PRODUCTION SYSTEMS

3.1. Introduction

Rice is grown in agroecosystems that range from rainfed uplands to the flood-prone and coastal wetlands. Thus, its adaptive mechanism can be characterized by the supply of water. Lowland rice yields are much higher than upland rice yields. The average lowland rice yield in Africa is 2.2 t/ha under rainfed conditions and 4.9 t/ha under irrigation. Approximately 75% of the world's rice is currently produced under irrigated systems.

Modern irrigated rice culture in tropical and subtropical environments is perhaps the most intensive cereal production system in the world (Fisher, 1998). In West Africa, it is estimated that rice irrigation schemes cover about 520,000 ha, cutting across, from north to south, the Sahel, Sudan Savanna, Guinea Savanna; and Humid Forest agro-ecological zones (Matlon et al. 1996; Wopereis et al., 1999). Massive investments in irrigation infrastructure started in Mali with the Office du Niger Project, in the 1930s, in The Gambia, in 1966 with the Taiwanese Agricultural Technical Mission (Ceesay, 1997), and across the whole region in the 1970s and 1980s, when severe droughts devastated rainfed crops and livestock.

In many cases, results did not meet expectations. Actual production figures were often well below anticipated level, averaging only 3 to 5 t/ha in the irrigated Sahel (Matlon et al., 1996), although records show that initial yields during the first years of production averaged 8-10 t/ha in Mali Office du Niger, Burkina Faso Kou Valley, and The Gambia Jahaly Pacharr Projects. Among the major causes of yield reduction often sited were water control, nutrient deficiency, inconsistent planting calendar, and problems associated with reduced chemical use as a result of high chemical input cost.

3.1.1. Management of Lowland Rice Systems

In The Gambia the management practices that constrain lowland rice productivity can be ranked in the following order of importance:

1. Poorly planned cropping calendar – due to poorly planned cropping calendars, dry season rice crop often gets in the way of wet season crop.
2. Untimely transplanting – older seedling are preferred to younger ones because they are taller and better tolerate flooding.
3. High post-harvest losses – due specifically to poor drying and threshing facilities, this is even more serious when dry season rice crop is harvested during the rainy season as a result of poor planning.
4. Poor water control – there is poor canal maintenance and drainage systems are rarely in place.

5. Very low nutrient-use efficiency – fertilizer is often applied to flooded fields because farmers cannot risk draining their fields because there may not be water when they want to re-irrigate. This problem is even more serious in communal irrigation systems.
6. Beyond optimum plant population or poor plant stand due to insect pest damage or inadequate planting geometry.
7. Insufficient weed control– insufficient time is allocated to weed control, and weeding is often done too late.

Unless farmers adopt management practices that alleviate many, if not all of these constraints, they will not reap full benefits from modern high-yielding rice varieties and related improved production technologies.

Lowland rice yield responds significantly to applied N on nearly all soils when irrigation is adequate and weeds and pest problems do not limit growth.

There is a need to introduce management practices that address problems of untimely transplanting, water control, nutrient management and pest management. One system that addresses these problems is the System of rice Intensification (SRI). This system aims at increasing rice yields through a combination of simple, timely and cost effective management practices.

3.1.2. The System of Rice Intensification (SRI)

The System of Rice Intensification (SRI) was developed in Madagascar in the early 1980s by Father Henri de Laulanié, S.J., who between 1961 and

1995 worked with Malagasy farmers and colleagues to increase rice production in that country. It is now being promoted by a Malagasy NGO, Association Tefy Saina. Until 1999, it was known only in that country; today it is being evaluated and promoted, in more than 15 countries in Asia, Africa and Latin America. It has demonstrated potential to double yields (or more) without requiring use of chemical fertilizer or crop-protection agrochemicals. SRI has already helped several thousand farmers in Madagascar to at least double their yields (Uphoff, 1999).

With SRI practices, the structure of the rice plants is changed, both above ground and below. In particular, the density and number of roots is increased. This supports more fertile tillers per plant, with more grains per fertile tiller, and often larger grains. The techniques of SRI include planting rice seedlings widely apart so they have more room to grow. With more space, rice root systems become larger, more extensive, and grow deeper, acquiring more nutrients from the soil. This enables them to produce more tillers and more grains per panicle.

Early Transplanting: The key to success with SRI is the transplanting of very young seedlings, before they are 15 days old, and as young as 5 or 10 days after emergence. Seedlings then have only their first small root, with seed still attached, and a first (main) tiller and two tiny leaves.

With SRI, the soil only needs to be kept moist during the period of growth when the plant is putting out tillers, leaves and roots, before it begins to flower and to produce grains. Once flowering begins, a thin layer of water is applied and remains continuously on the field (Uphoff, 1999).

Spacing: With SRI single seedlings are planted quite far apart, usually at least 25 cm by 25 cm, and with possibly even wider spacing when the technique of all management components have been mastered. They are placed in a square (grid) pattern, rather than in rows to facilitate bi-directional mechanical weeding (Uphoff, 1999).

Water control: Water is applied only as needed to keep the soil moist, but never letting it become saturated. If there has been no rainfall during the day, irrigation water is applied in the evening or late in the afternoon, and any water still standing on the field the next morning is drained off. This leaves the soil and plants fully exposed to the sun and air during the day. Several times during the growing period, the field is left unwatered for 2-6 days so that the soil dries out to the point where there is some surface cracking.

During the vegetative growth phase, the principle to be followed is that rice roots should not be continuously in saturated soil so that oxygen supply is not cut off from the roots, or at least not for very long (Uphoff, 1999).

Labor: Some farmers find that SRI requires a little more labor, but once they have become proficient with its methods, particularly transplanting tiny seedlings, the process becomes quicker. With SRI fewer seedlings are used. The seeding rate is 5-10 kg/ha, compared to 50-100 or more kg/ha conventionally. Recently, some farmers in Sri Lanka have calculated that once they have mastered SRI techniques and can do them confidently and quickly, their total labor invested per hectare with SRI is actually less than with conventional modern practices (Uphoff, 1999).

3.1.3. Water Management

Water control is the most important management practice that determines the efficacy of all other production inputs (nutrient, herbicide, pesticide, farm machines, etc.) in lowland rice farming. Poor soil drainage is highly damaging to crops and, in the long run, degrades soils with the eventual development of salinity and alkalinity (Balasubramanian, 1999). In an irrigation system of 1,200 ha, with 2 crops per year in the Kou valley of Burkina Faso, mean rice yields declined from 6.7 t/ha in 1970 to 4 t/ha in 1994, mainly due to poor water control and crop management (FAO, 1994). In the Gambian Jahaly Pacharr Project, identical constraints caused yields to fall from their 1979 record high of 10 t/ha to recent 4 t/ha yield average maximum yield, even with high fertilizer inputs. Farmers tend to flood their fields with excess water whenever they get the opportunity to do so, because they believe that rice does better under flooded conditions. Rice grown under traditional practices requires approximately 700-1,500 mm of water, 60-80% of which is required from transplanting to maturity to meet the evapotranspiration demand and unavoidable seepage and percolation in maintaining a saturated root zone (Guerra et al. 1998).

In lowland rice production, water is not considered an integral part of the production cost by farmers and irrigation engineers in most of Africa. Although there are water charges in most rice irrigation projects, this applies only to the mechanical system delivering the water. When irrigation is by gravitational flow from rivers and other water bodies, then these charges are not applicable. However, when water becomes limiting farmers will consider water saving strategies in order to produce a good rice crop, but when water is in abundance, water saving strategies are almost never enforced.

3.1.4. Improved Water Management System – Repeated Wetting and Drying

Many irrigation systems do not maintain adequate drainage mechanisms. Drainage canals are rarely cleaned, and because farmers believe that rice does best if water is supplied in abundance, they do not see a need for a drainage system except at harvest time. This practice is not only wasteful, but it also leads to leaching of soluble nutrients, inhibits or changes soil microbial finally activities, slows down mineralization and nutrient release from the soil complexes. Celton and Marquette (1972) reported that good water control on Madagascar Tananarive Plains resulted in rice yield increases of 155 to 261%. In 1993 the Madagascar's Agricultural Extension Ministry reported similar increases in rice yield due to water control. Bhuiyan et al., (1994) reported yields of 6.7T and 7.4T in the Philippines under soils saturated throughout the growing period for wet-seeded and transplanted rice, respectively.

3.1.5. Influence of Repeated Wetting and Drying on Soil Microbial Activity and Nitrogen Mineralization

Worldwide nitrogen is the most limiting nutrient to rice production; therefore increased nitrogen use efficiency will translate into yield increase. In spite of extensive research and advances in fertilizer management, rice in the lowlands generally utilizes less than 40% of applied N, mainly because of N losses that occur via NH_3 volatilization from the floodwater after NH_3

diffusion from the soil-water interface (Vlek and Craswell, 1979; Schneiders and Scherer, 1998). However, rice obtains a great part 60-70%, or even 80% of its N requirement from the organic N pool of the soil even when fertilized (Broadbent, 1979). It is therefore essential not only to optimize mineral N nutrition, but also to promote an integrated N management, that makes use of all available N sources both organic and inorganic.

The natural nitrogen supply for plants and microorganism result principally from the mineralization of organic N compounds. This process occurs in two steps: ammonification and nitrification (Runge, 1983; Das et al., 1997). Less than 1% of the total soil N is in inorganic form readily available for plant uptake (Das et al., 1997). Usually only about 1–3% of organic N is mineralized a year.

The mineralization of N in the field is often balanced by microbial immobilization. The microbial biomass N is an important repository of plant nutrients that is more labile than the bulk of soil organic matter. It can contribute substantial amounts of nutrients to the rhizosphere. The microbial biomass is in a constant state of turnover (Das et al., 1997). Soil microbial biomass is a sensitive indicator of changes in the quality and quantity of soil organic matter (SOM). It responds more rapidly than SOM to changes in organic inputs to the soil or in soil management (Gijsman et al. 1997).

Measurements of microbial biomass have been used to assess the effect of different farming systems on soil fertility (Maire et al., 1990; Hassink et al., 1991; Gijsman et al., 1997). Microbial biomass plays a central role in soil nutrient cycling. Strong positive correlations have been found between the amount of nutrients held in the microbial biomass and amounts of mineralizable nutrients in the soil, indicating that nutrient cycling is tightly linked to the turnover of microbial biomass (Carter and Macleod, 1987; Smith, 1993; Gijsman et al., 1997).

Birch (1958) reported that a flush of N mineralization occurs after rewetting a dry soil. This intensive pathway of N mineralization and N availability later became known as the Birch effect. Several factors may contribute to the N flush that follows rewetting dry soil. A significant proportion of the soil microorganisms can die during drying and rewetting, and dead microbial cells are ready mineralized by the remaining microflora and can cause part of the N flush (Marumoto et al., 1977; Cabrera, 1993; Das et al., 1997).

The youthful state of the microbial population that develops after rewetting can also be responsible for part of the enhanced N mineralization (Birch, 1958; Soulides and Allison, 1961; Cabrera, 1993). Inubushi and Wada (1987) also found that drying and rewetting of Japanese soils not only generated or enlarged a pool of N that mineralized rapidly according to first-order kinetic, but also increased the size of a more stable N pool that mineralized more slowly. This could be explained by an increase in the availability of organic substrates through desorption from the soil surface (Seneviratne and Wild, 1985; Cabrera, 1993) and through an increase in organic surfaces exposed (Birch, 1959; Cabrera, 1993).

This suggests that wetting-and-drying cycles are one of the mechanisms by which soil N pool is replenished from successively more recalcitrant or physically protected N pools (Elliot, 1986). All this supports the hypothesis that SRI water management practice of drying-and-wetting cycles is beneficial to plant growth through increased nutrient availability. In essence, drying and rewetting of soils as practiced in SRI is comparable to inducing a series of successive Birch effects during a single cropping season.

Drying and rewetting can also result in increased NO_3 uptake by the rice plant rather than other N forms.

3.1.6. Influence of Repeated Wetting and Drying on Micro-Nutrient Availability

A flooded rice soil is a complex of an aqueous phase, a solid phase, an interchangeable gaseous phase, and various flora and fauna. The main chemical changes brought about by flooding a soil have an impact on micronutrient supply; the decrease in redox potential due to the depletion of molecular oxygen leads to reduced Fe and Mn. Submergence for 10 to 12 weeks increases the Fe^{2+} and Mn^{2+} concentration in the soil solution, regardless of soil type (Savithri et al., 1999). The concentration of Zn and Cu decreases in lowland soils, and Zn deficiency is a widespread nutritional disorder of wetland rice (Neue and Lantin, 1994; Savithri et al., 1999).

3.1.7. Influence of Repeated Wetting and Drying on Methane Gas Emission

Recently the importance of methane as a greenhouse gas has been recognized and studies have been carried out to assess its contribution to global warming. About 70% of CH_4 production arises from anthropogenic sources, and agriculture is estimated to be responsible for about two-third the anthropogenic sources globally (Minami, 1997). Significant CH_4 production generally occurs only after a field has been flooded for a few days. The major pathways of CH_4 production in flooded soil are the reduction of CO_2 with H_2, fatty acids or alcohols as hydrogen donor, and the transmethylation of acetic acid or methyl alcohol by methane producing bacteria (Conrad, 1989).

Redox potential is cited as the most important measurable factor for production of CH_4 in soils. The redox potential of soil gradually decreases after flooding due to a decreased activity of the oxidized phase and increase activity of the reduced phase (Cicerone et al. 1988; Yagi et al., 1990). Low redox potential (-200mv) favors CH_4 production. The highly anoxic conditions in flooded rice soil support a large methanogenic bacterial population and hence create a large supply of CH_4 (Min et al, 1997; Dubey and Singh, 2001).

Methane gas evolution from the soil can be greatly reduced if a field can be drained briefly or intermittently (Sass et al., 1992; Lindau et al. 1993; Minami, 1997), as practiced in SRI water management system.

Research Objectives and Hypotheses

The research objectives are as follows:

1. To identify to best rice seedling age for transplanting
2. To find out if SRI management practice is superior to conventional management practice
3. To find out if the current fertilizer recommended rate for The Gambia, meets the nutrient demand of SRI production
4. To promote SRI management practices on-farm

The research hypotheses are as follows:

1. Transplanting is best with younger seedlings

2. SRI will increase rice yields because the SRI management practices are superior to conventional ones
3. Rice yield can be increased with SRI using the current fertilizer recommendations in The Gambia

3.2. Materials and Methods

3.2.1. Trial Location: The Gambia

The trial was conducted in eastern Gambia, on the bank of the river Gambia. The farm is part of the Gambia Integrated Rice Development Project. The project cultivates about 3,000 ha of tidal and 620 ha of pump irrigated rice in eastern Gambia. About 10,000 farmers work within this rice irrigation scheme. Rice is double-cropped except westward where salt intrusion from the Atlantic Ocean becomes a limiting factor. The 1-part-per-thousand salt-line is located mid-way along the river around December, and pushes eastwards, rarely reaching Sukuta in eastern Gambia before the onset of the rainy season in June, except in very dry years such as 1986.

Lowland Trial Location, Sapu Research Station

Figure 11. Location of Trial Site for Lowland Rice Evaluations, Sapu, The Gambia

3.2.2. Field Experiment Design

The field experiments were conducted during the wet seasons of 2000, 2001 and 2002. They were conducted at the Gambia National Agricultural Research Institute's irrigated rice experimentation fields and at the Integrated Rice Development Project tidal irrigation site in Sapu, Eastern Gambia. A total of 6 lowland rice experiments were conducted.

I. Diagnosing seedling growth rate and seedling quality

Two rice varieties IET 3137 and ITA 306 were used. Both of these varieties are widely grown in The Gambia and in West Africa. IET 3137 matures 10 days earlier than ITA 306, which is higher tillering than the latter.

A seedling nursery of the 2 varieties was prepared in August 2002, and 10 seedlings per variety were uprooted at 3, 7, 14, and 21 days intervals after emergence. The number of leaves were counted, and the seedling height measured. The roots of the seedling are then removed with a pair of scissors, and then placed in a jar of water for 7 days. The number of new roots re-growth is counted and bulk root length measured. The seedlings are then sun dried for a week and average seedling dry matter is recorded. The trial was conducted during the wet season of 2000.

II. Effect of seedling age at transplanting under SRI management practice

Three sets of rice nurseries were prepared at different intervals to produce seedlings of 5, 10, and 35 days of age at time of transplanting. Seedlings of different ages were transplanted on the same day in a split-plot design trial with 3 replications. Seedling age was the main plot, and variety was the sub-plot. Two rice varieties were tested, IET 3137, and ITA 306.

Seedlings were transplanted in plot sizes of 3 x 5 m, at plant spacing of 30 x 30 cm. Water control and weeding were done according to SRI management recommendations. Fertilizer was applied at a rate of 70-30-30 kg/ha NPK, of which 30-30-30 kg/ha NPK was applied as basal, and 20 kg/ha N was applied at tillering and again at panicle initiation growth stages. The trial was conducted in the wet season of 2002.

III. SRI vs. conventional management practices

The effect of three plant population densities and SRI management on rice grain yield was investigated in 2000 wet season. The planting distances between hills were as follows:

20 X 20 cm
30 x 30 cm
40 x 40 cm

Two sets of rice nurseries were prepared at different intervals to produce seedlings of 10 and 35 days of age at time of transplanting. Two types of management practices were used: SRI and research recommended local management practices. The trial design was a split-split-plot. The main plot was the management practice, the sub-plot was spacing, and the sub-sub-plot was variety. Two varieties, locally cultivated by farmers in The Gambia;

IET 3137 and ITA 306 were used. Seedlings of different ages were transplanted on the same day in a split-split-plot design trial with 3 replications. Seedling age was the main plot, and variety was the sub-plot. Two rice varieties were tested, IET 3137, and ITA 306.

Water control and weeding were done according to SRI management recommendations in the SRI main plot, and in the other farmer management practice was used. Fertilizer was applied in both blocks at a rate of 70-30-30 kg/ha NPK, of which 30-30-30 kg/ha NPK was applied as basal, and 20 kg/ha N was applied at tillering and again at panicle initiation growth stages.

IV. SRI with different fertilizer application rates

This fertilizer trial with SRI management was conducted in 2001 and 2002 wet seasons. Different fertilizer application rates were tested with SRI management practice. The components of SRI used were as follows:

30 x 30 cm spacing
Repeated wetting and drying
1-week-old seedlings (2-3 leaf stage)

Three fertilizer application rates were investigated:

1. Normal: (The nationally recommended rate for lowland rice)- 70-30-30 NPK kg/ha
2. High: 140-30-30 NPK kg/ha
3. Very High: 280-30-30 NPK kg/ha

Two rice varieties, IET 3137 and ITA 306 were used in the trial. The trial was a split-plot design with 4 replications. The main plot was fertilizer application rate. Bunds, 15 cm high, were constructed between the main plots to restrict inter-flow of water and nutrients between the main plots. The sub-plots were the varieties. Plot sizes were 3 m wide and 5 m long.

Fertilizer was applied as basal and topdressing at tillering and panicle initiation. The 70-30-30 kg/ha NPK was applied as follows: 30-30-30 kg/ha NPK as basal, and 20 kg/ha N topdressing twice.

The 140-30-30 kg/ha NPK was applied as follows: 60-30-30 kg/ha NPK as basal, and 40 kg/ha N topdressing twice.

The 280-30-30 kg/ha NPK was applied as follows: 120-30-30 kg/ha NPK as basal, and 80 kg/ha N topdressing twice.

V. SRI with compost and different urea topdressing rates

This trial was conducted in the wet season of 2002. SRI management practice was tested with compost and urea application. Compost made out of rice straw, rice husk and farm-yard manure was applied at a rate of 5 t/ha. This provided approximately 60 kg/ha N. The fertilizer application rates were as follow:

Compost alone
Compost with 40 kg/ha N topdressing from urea 46% N
Compost with 80 kg/ha N topdressing from urea 46% N
70-30-30 kg/ha NPK without compost from urea 46% N

The amounts of N topdressing rates were based on the amount usually applied by farmers. The components of SRI used were 30 x 30 cm spacing, repeated wetting and drying, and 1-week-old seedlings (2-3 leaf stage).

Two rice varieties, IET 3137 and ITA 306 were used in the trial. The trial was a split-plot design with 3 replications. The main plot was fertilizer application rate. Bunds, 15 cm high, were constructed between the main plots. The two varieties were transplanted in the sub-plots. Plot sizes were 3 m wide and 5 m long. Urea topdressing was applied 50 % at tillering and 50 % at panicle initiation.

VI. On-Farm SRI management trials

The on-farm trial was conducted in 2001. It was a researcher managed. Ten dabadas (households: the smallest divisible unit of a farm community in the Gambia) were selected at random to participate in the on-farm trial.

Each farmer did an SRI and their standard method of production.

A standard variety IET 3137 was supplied to all participating farmers. Ten days old seedlings are transplanted at 30 x 30 cm spacing. Fertilizer was applied at a rate of 70-30-30 NPK kg/ha which is the national recommended rate, 30-30-30 kg/ha NPK was applied as basal, and 20 kg/ha N was applied at tillering and panicle initiation growth stages.

The standard practice is continuously flooded. The SRI practice is intermittently flooded and dried. It is irrigated with enough water to saturate the soil, and is re-irrigated after 2 or 3 days or until the soil starts to show signs of slight water deficit.

Rice Varieties used in the trial:

ITA 306 was introduced by the International Institute of Tropical Agriculture (IITA) in Ibadan, Nigeria. It is also known as Sahel 202. It is widely grown in the Sahel region. It matures in 110 -120 days. It is a high tillering variety, with plant height of 110-120 cm. It bears slightly chalky, slender and intermediate grains.

IET 3137 is an introduction from India. It was bred by the Indian Central Rice Research Institute (ICRRI) in Cuttack. It is widely grown in The Gambia for its highly appreciated slightly translucent, slender and intermediate grain. It matures in 100-110 days, and has a height 95-100 cm.

BG 90-2 is an introduction from Sri Lanka. It was bred by the Sri Lanka Department of Agriculture, in Batalagoda. It is widely grown in West and Central Africa. In The Gambia and Mali it is known for its record high yields of 9-10 t/ha. However, it has been documented that it is highly susceptible to nematodes and rice yellow mottle virus. It matures in 90-95 days. It is a high tillering variety, with plant height of 100-105 cm. It bears slightly chalky, slender and intermediate grains.

Land Preparation: The trial plot sizes were 3 x 5m. Primary land preparation was with a harrow plow drawn by a 4-wheel tractor, and secondary land preparation was with a 2-wheel power-tiller. Leveling was done with a power-tiller drawn leveling board and by hand shifting of soil. All plots were transplanted.

Weed control: In all trial inter-row weed control was carried out mechanically with a roto-weeder, and intra-row weeding was by hand, at 14, 28 and 48 days after transplanting. No herbicide, insecticide, or chemical disease control measures were used.

Data collected from trials: The data collected include the following:

Days to 50% flowering
Plant height at harvest
Panicle count per m^2
Number of grains per panicle
Percentage filled grains per panicle
1000 grain weight
Grain yield
Harvest index
Time spent on transplanting
Soil nutrient level
Seedling growth rate
Root re-growth rate

3.3. Results and Discussions

3.3.1. Diagnosing Seedling Growth Rate and Seedling Quality

The optimum number of days in the nursery bed varies with the variety, air temperature, water temperature, and seeding rate. The optimum-aged seedlings can hardly be expressed by the number of days. Although Gines et al. (1985) noted that photoperiod sensitive cultivars were relatively insensitive to difference in age of seedling at transplanting, it must be noted that during the process of uprooting seedlings, physical damages to the roots occur and recovery from physical damages and adjustment to a new growth media after transplanting need to be taken into consideration.

For SRI management practices, seedlings at 2 leaves stage are recommended for transplanting. The age at which seedlings reach a specific leaf stage depends on agro-climatic factors and genotypic growth rate. Knowledge of the number of days seedlings will need to be ready for transplanting helps farmers plan their land preparation and transplanting calendar adequately. It is also important to identify the critical stage a seedling age has a significant impact on seedling quality. Farmers in The

Gambia prefer bigger seedlings because they are easier to handle and are less susceptible to submergence where water control is inadequate.

At 21 days after emergence, the seedlings reached 5-leaf growth stage (Table 11). They are bigger, taller and easier to transplant than a 3-day old seedling. Big tall seedlings are less susceptible to submergence. However, a 21-days old seedling is more susceptible to transplanting shock. This is because at the 5-leaf stage, tillering has already begun, although not visibly.

Table 11. Seedling Growth Parameters as Affected by Seedling Age, Sapu, The Gambia, 2001

Seedling Age	**Growth Parameter**	**Variety**	
		ITA 306	**IET 3137**
3-Days	Leaf count	2.0	2.0
	Height (cm)	2.97	2.72
	Seedling Dry Wt (g)	0.03	0.03
7-Days	Leaf count	4.0	3.8
	Height (cm)	10.46	8.94
	Seedling Dry Wt (g)	0.13	0.06
14-Days	Leaf count	4.1	4.9
	Height (cm)	16.51	15.19
	Seedling Dry Wt (g)	0.48	0.31
21-Days	Leaf count	5.5	5.6
	Height (cm)	27.68	25.45
	Seedling Dry Wt (g)	0.63	0.52

At 7 days of age, seedlings are still within the recommended leaf stage and are not vulnerable to transplanting shock and moderate submergence, and are also considerably easier to transplant than 3-day-old seedlings. For The Gambian wet season growing conditions, 7 days-old seedlings would be adequate for SRI management practices. The ability of seedlings to regenerate new roots within a specific timeframe is an indication of the seedling's ability to overcome transplanting shock and to continue development undisturbed after transplanting.

The quality of seedlings can be diagnosing by investigating the regenerating ability of roots. All roots are completely removed from the base of a seedling with scissors, and its base is fixed in water, and after a definite period (5 days in this study) thereafter the number of newly produced roots is counted (Figure 12).

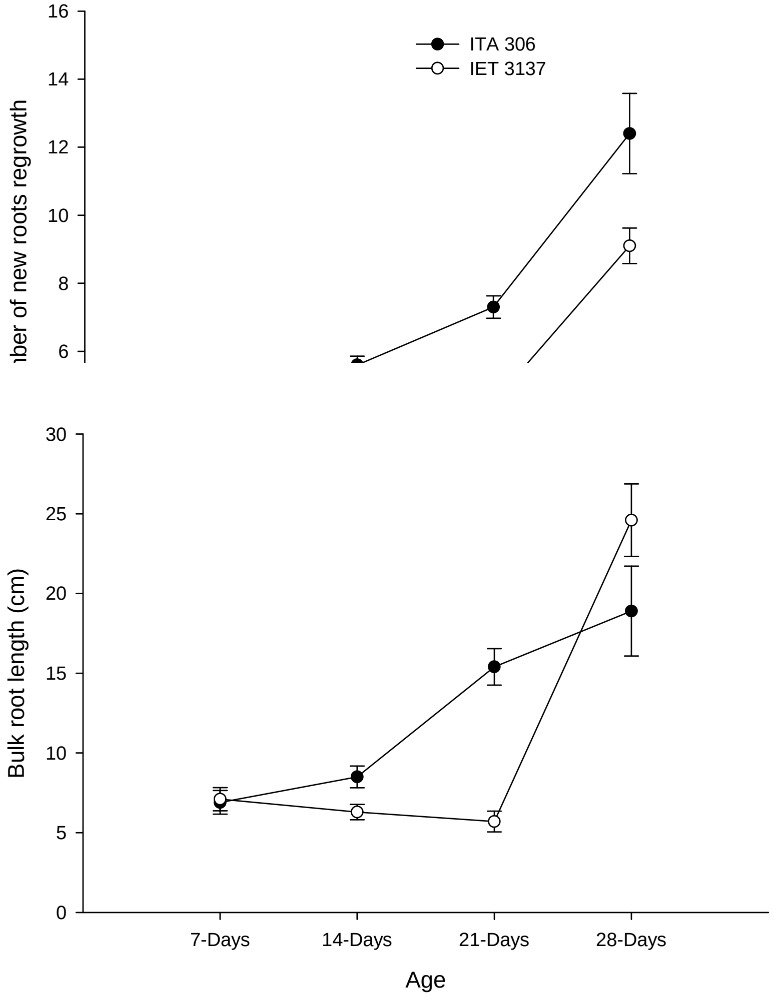


Figure 12. Number of New Roots Re-growth and Bulk Root Length of *cv* ITA 306 and IET 3137

The higher the quantity of new roots and bulk root produced within a specific time span, the better the quality of the seedling. Although the number of new roots produced was higher with age because more rooting buds are produced with age, the bulk density at 21 days was lower than at 7 days for *cv* IET 3137, and the number of new roots regrowth was not significantly different between 7 and 14 days old seedlings.

This further validates the fact that younger seedlings are more viable and have higher vigor after uprooting and transplanting. Older seedlings have less vigor after being uprooted and transplanted, even though they will eventually produce a relatively higher bulk root density, they have a relatively much higher above-ground biomass to support. Before adequate root system is re-established after uprooting and transplanting of an older seedling, almost all its leaves will die back. The ratio of total new root regrowth to above-ground biomass for 7-days old seedlings is much lower than that of older seedlings. This is essential to support faster recovery after uprooting and transplanting.

In practice, when younger seedlings are uprooted, less damage is done to the root system than for older seedlings. Thus there is less die-back of the above-ground biomass while the root system regenerates. During this time the plant is vulnerable to disease infection and insect pest attack. Defoliator caseworm (*Nymphula stagnalis*) attacks and defoliates newly transplanted rice. Robust seedlings and rapid establishment after transplanting is a very important to achieving high rice yields.

3.3.2. Effect of Seedling Age at Transplanting under SRI Management Practice

Seedling age has an impact on the days to maturity. The 35 day-old seedlings matured the earliest after transplanting (127 and 123 days for ITA 306 and IET 3137 respectively), but they took the most number of days to reach harvest, from seeding in the nursery to maturity (Table 12).

Table 12. Effect of Seedling Age at Transplanting under
SRI Management Practice, Sapu, The Gambia, 2002

Seedling Age	**Variety**	**Days Seeding To Maturity**	**Plant Ht (cm)**	**Tiller per hill**	**Panicle per hill**
5-Days	ITA 306	138	84	19	16
5-Days	IET 3137	134	82	22	16
10-Days	ITA 306	141	84	19	16
10-Days	IET 3137	136	73	27	25
35-Days	ITA 306	162	79	20	15
35-Days	IET 3137	158	71	17	12
$LSD_{.05}$			6	5	ns
CV(%)			4.7	14.3	13.0
P_{Age}			0.0101	0.0762	0.179
P_{Var}			0.0013	0.0804	ns
$P_{Age*Var}$			0.1200	0.0197	ns

Early-maturing rice crops spent less time translocating carbohydrate for grain production. They produce less grain yield than those that reach maturity later. The 5-days old seedlings spent the most time in the field after transplanting thereby utilizing more phyllochrons for tillering. Plant height was significantly higher with the 5-day old seedlings. Although there was no significant difference in tillering between the different seedling age groups, there was significant difference in panicle count per hill. This is manifested in the panicle setting ratio (Table 13).

Table 13. Effect of Seedling Age at Transplanting under SRI Management Practice, Sapu, The Gambia, 2002

Seedling Age	Variety	Panicle Setting Ratio (%)	1000 Grain wt (g)	Yield T/Ha
5-Days	ITA 306	82.5	23.5	4.2^{b}
5-Days	IET 3137	73.5	22.7	6.2^{ab}
10-Days	ITA 306	86.0	21.0	5.4^{ab}
10-Days	IET 3137	92.5	22.0	7.5^{a}
35-Days	ITA 306	75.8	25.5	5.4^{ab}
35-Days	IET 3137	74.1	24.3	5.3^{ab}
LSD$_{.05}$		19.9	ns	2.9
CV(%)		13.4	11.8	24.1
P$_{Age}$		ns	0.1383	ns
P$_{Var}$		0.0137	ns	0.0628
P$_{Age*Var}$		0.0724	ns	ns

The percentage of panicle setting was highest with ITA306 at 5 and 10 days seedling age at transplanting. There was no significant different in 1000 grain weight. The seedlings of 10-days of age gave the highest average yield. IET 3137 gave the highest yield at both transplanting ages of 5 and 10 days.

3.3.3. SRI vs Conventional Management Practices

Two rice varieties ITA 306 and IET 3137, locally grown in The Gambia, were used in the trial. The local management practice was continuous flooding, and SRI practice included repeated wetting and drying. Apart from plant height and tiller ability, there was a non-significant varietal effect, and tillering was influenced more by spacing than water control (Table 14).

Table 14. SRI vs. Conventional Practice using Different Varieties and Plant Spacings, Sapu, The Gambia, 2000

Practice	Variety	Inter Space	Plant Ht (cm)	Tiller per hill	Panicle per hill
Local	ITA 306	20x20	100.3	29	10
	IET 3137	20x20	83.7	30	12
	ITA 306	30x30	97.0	47	15
	IET 3137	30x30	82.7	43	12
	ITA 306	40x40	88.7	49	12
	IET 3137	40x40	71.0	44	16
SRI	ITA 306	20x20	108.3	23	18
	IET 3137	20x20	101.3	25	13
	ITA 306	30x30	108.0	41	24
	IET 3137	30x30	103.0	29	21
	ITA 306	40x40	107.7	59	28
	IET 3137	40x40	99.7	46	26
$LSD_{.05}$			10.6	13	11
CV(%)			6.9	20.8	34.9
$P_{Practice}$			<0.0001	ns	0.0002
P_{Var}			0.0416	0.0728	ns
P_{Space}			0.04	<0.0001	0.01

ITA 306 is known to be high tillering under conventional management practices, but under conventional management the ratio of panicle setting is lower than under SRI management practices (Table 15). Highest panicle setting ratio was recorded with *cv* ITA 306 at 20 cm spacing and at 30 cm spacing for *cv* IET 3137.

Table 15. SRI vs Conventional Practice using Different Varieties and Plant Spacings, Sapu, The Gambia, 2000

Practice	**Variety**	**Inter Space**	**Panicle Setting Ratio (%)**	**1000 Grain wt (g)**	**Stover T/Ha**	**Yield T/Ha**
Local	ITA 306	20x20	35.5	20.0	5.4	2.4^{de}
	IET 3137	20x20	40.0	22.8	4.4	2.6^{d}
	ITA 306	30x30	31.9	20.0	5.2	1.4^{fg}
	IET 3137	30x30	27.9	22.1	4.6	1.9^{ef}
	ITA 306	40x40	24.5	24.7	5.2	0.9^{g}
	IET 3137	40x40	36.4	20.7	4.9	1.7^{ef}
SRI	ITA 306	20x20	78.3	27.7	3.5	7.4^{a}
	IET 3137	20x20	52.0	25.7	4.4	5.8^{b}
	ITA 306	30x30	58.5	27.2	6.5	5.5^{b}
	IET 3137	30x30	72.4	25.3	6.4	4.6^{c}
	ITA 306	40x40	47.5	25.5	6.4	4.4^{c}
	IET 3137	40x40	56.5	21.0	7.7	4.1^{c}
$LSD_{.05}$			25.2	1.5	3.6	0.7
CV(%)			30.3	4.2	29.5	13.8
$P_{Practice}$			<0.0001	0.0001	0.11	<0.0001
P_{Var}			ns	ns	ns	ns
P_{Space}			ns	0.03	0.04	<0.0001

Although high tillering was recorded at 40 cm spacing, 40-50% of the tillers were unproductive. Tillering was influenced more by spacing than management practice. There was highly significant difference between SRI and conventional management practice. Both biomass accumulation and 1000-grain weight were higher in the SRI treatments. ITA 306 had average 1000-grain weight for the 3 spacings greater with SRI by 5.2g. IET 3137 had average 1000-grain weight for the 3 spacings greater than the local practice by 3.1g.

The difference in 1000-grain weight between 20x20 and 30x30 cm spacings was larger by 7.45g for SRI and 3.05g for the local with IET 3137.

The highest yields were recorded under SRI management practice (Table 16). ITA 306 yielded 7.4 t/ha and IET 3137 yielded 5.8 t/ha at 20 cm spacing. At 30cm spacing, ITA 306 yielded 5.5 t/ha and IET 3137 yielded 4.6 t/ha. The highest yield under the local practice was 2.6 t/ha.

Table 16. Average Yields at Different Plant Spacings, Sapu, The Gambia 2000

Spacing (cm)	**Average Yields (t/ha), Two Varieties**		
	Local Practice	**SRI Practice**	**Difference**
20x20	2.5	6.6	4.1
30x30	1.7	5.1	3.4
40x40	1.3	4.3	3.0
Average	1.8	5.3	3.5

Averaging the two varieties, the biggest difference between continuous flooding and SRI intermittent irrigation was 4.1 t/ha, with 20 x 20 cm spacing (2.5 vs. 6.6 t/ha). At 30 x 30 cm spacing, the difference was 3.4 t/ha; and at 40 x 40 cm spacing, it was 2.95 t/ha. Clearly, the rice plants responded better to alternate wetting and drying of the soil compared to conventional continuous saturation.

In 2001, IET 3137 grown under SRI management practice yielded 5.3 t/ha under 20 x 20 cm spacing (Table 17).

Table 17. SRI Practice with *cv* IET 3137 and Different Plant Spacing, Sapu, The Gambia 2001

Variety	**Inter Space (cm)**	**Panicle Setting Ratio (%)**	**Stover T/Ha**	**Yield T/Ha**
IET 3137	20x20	49.2	3.7	5.3
IET 3137	30x30	50.8	5.6	3.2
IET 3137	40x40	63.8	4.7	1.8
LSD$_{.05}$		ns	ns	1.4
CV(%)		18.7	25.0	23.1

Comparison with the local management practice of continuous flooding was not possible during the 2001 cropping season, because the continuously flooded crop suffered severely as a result of inadequate moisture conditions after flowering. Spikelet sterility was 100%, there was a complete crop failure. In 2002, an additional variety BG 90-2 was included. BG 90-2 is the most widespread rice variety in the Sahel, it is grown in the Office du Niger and Kou Valley projects in Mali and Burkina Faso, as well as in Senegal river valley irrigation scheme and in Mauritania. BG 90-2 is earliest maturing of the test varieties (Table 18). Tillering was highest for all varieties at 40 x 40 cm spacing, and corresponding panicle production was highest at this spacing.

Table 18. SRI Practice Using Different Varieties and Plant Spacing, Sapu, The Gambia, 2002

Variety	**Inter Space (cm)**	**Days to Flower**	**Plant Ht (cm)**	**Tiller per hill**	**Panicle per hill**	**Yield T/Ha**
ITA 306	20x20	80	120.4	11	10	10.2^{ab}
IET 3137	20x20	75	94.3	16	13	8.9^{abc}
BG 90-2	20x20	64	95.4	11	10	6.2^{cd}
ITA 306	30x30	80	110.6	21	19	11.0^{a}
IET 3137	30x30	75	100.0	27	25	8.4^{abc}
BG 90-2	30x30	64	105.6	19	16	6.7^{c}
ITA 306	40x40	80	106.1	38	31	7.9^{bc}
IET 3137	40x40	75	96.4	29	27	6.4^{c}
BG 90-2	40x40	64	97.4	29	26	3.7^{d}
$\text{LSD}_{.05}$			8.9	8	6	2.6
CV(%)			4.7	22.6	21.0	20.0
P_{Var}			0.0017	0.15	0.15	0.0001
P_{Space}			0.008	<0.0001	<0.0001	0.0029
$P_{\text{Var*Space}}$			ns	0.11	ns	ns

The highest yield (11 t/ha) was recorded with ITA 306 at 30cm spacing, which is not significantly different from its yield at 20cm spacing. ITA 306 is a relatively longer-duration variety than IET 3137 and BG 90-2. Shorter-duration varieties were introduced into the system in order to reduce the water use and to escape terminal drought, especially in systems where water control is poor and both demand and usage are high.

On average 30x30 cm spacing with SRI management practices gave the highest yield (Figure 13). Wider spacing is more economical on seed and labor input, but harvest index is extremely low at spacings beyond 30x30 cm.

Figure 13. Average Yield Over Three Varieties at Different Plant Spacing Densities, Sapu, The Gambia, 2002

Shorter-duration varieties are normally less productive due to the limited time spent translocating nutrient from the soil for grain production. However, SRI management practices reduce water demand, and the yield potential of longer-duration varieties is fully utilized. A significant yield increase of 3 t/ha (p-value = 0.0001) was observed from the first year of production through to the third. Lesser time was spent on land preparation during subsequent years after the first year of testing. There appeared to be an improvement in soil structure, because land preparation was much easier in subsequent years.

SRI management practice using 30 x 30cm spacing gave high yields and is cheaper than the currently recommended spacing of 20 x 20 cm, both in terms of seed requirement and labor cost for transplanting (Table 19).

Table 19. Time Spent on Transplanting SRI Trial of Different Planting Density, Sapu, The Gambia

Inter-Space	**Number of Plants per Ha**	**Time Man-Days per Ha**	**Total Cost**
20	250,000	25	$20.00
30	160,000	17	$13.60
40	125,000	11	$ 8.80

Transplanting at 20 x 20cm spacing with tiny seedlings is very tedious and time consuming; however, at 30 x 30 cm spacing, transplanting is much faster, and farmers prefer this spacing because yields are high and production cost significantly lower.

3.3.4. SRI with Different Fertilizer Application Rates

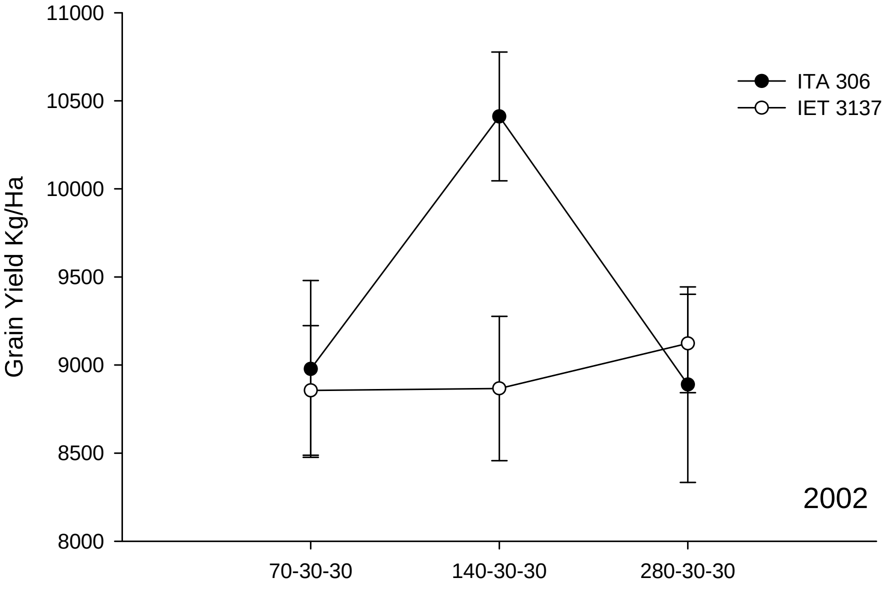
Under SRI management practices, yields are much higher than national averages, and correspondingly the nutrient demand to support such high yields is high. In previous SRI trials, the nationally recommended fertilizer application rate was used. Although yields were high, unproductive tillering also was high. The null hypothesis in this trial was that the addition of extra nutrient would boost effective tillering and alternately increase yield. From the results, however, addition of more nutrients increased tillering, but the ratio of panicle setting did not increase (Table 20).

Table 20. SRI Fertilizer Management Trial with Different Varieties, Sapu, The Gambia, 2001

Fertilizer Level (NPK kg/ha)	**Variety**	**Plant Ht (cm)**	**Tiller per m²**	**Panicle per hill**	**Panicle Setting Ratio (%)**
Normal	ITA 306	104	40	28	70.8
70-30-30	IET 3137	90	48	29	63.0
High	ITA 306	100	39	20	51.1
140-30-30	IET 3137	87	53	33	61.6
Very High	ITA 306	102	38	23	60.9
280-30-30	IET 3137	95	54	30	55.6
$LSD_{.05}$		8.5	10	4	13
CV(%)		5.9	14.6	10.7	13.2
P_{Var}		0.0001	ns	0.13	0.03
P_{Fert}		ns	0.0002	<0.0001	ns
$P_{Var*Fert}$		ns	ns	0.0032	0.067

ITA 306 had best panicle formation and setting ratio with normal fertilizer level (70-30-30 kg/ha NPK). IET 3137 had more tillering with higher fertilizer, but no better panicle formation and poorer setting ratio with high fertilizer rate.

Harvest Index increased from an average of 0.41 with the normal fertilizer application rate to 0.45 with very high fertilizer application rate. There was a non-significant increase in biomass production between the fertilizer application rates, however. An increase in grain yield was observed in 2001 with the application of 240-30-30 NPK (Figure 14), but there was a slight decrease in grain yield, though not significant, with the application 140-30-30 NPK.



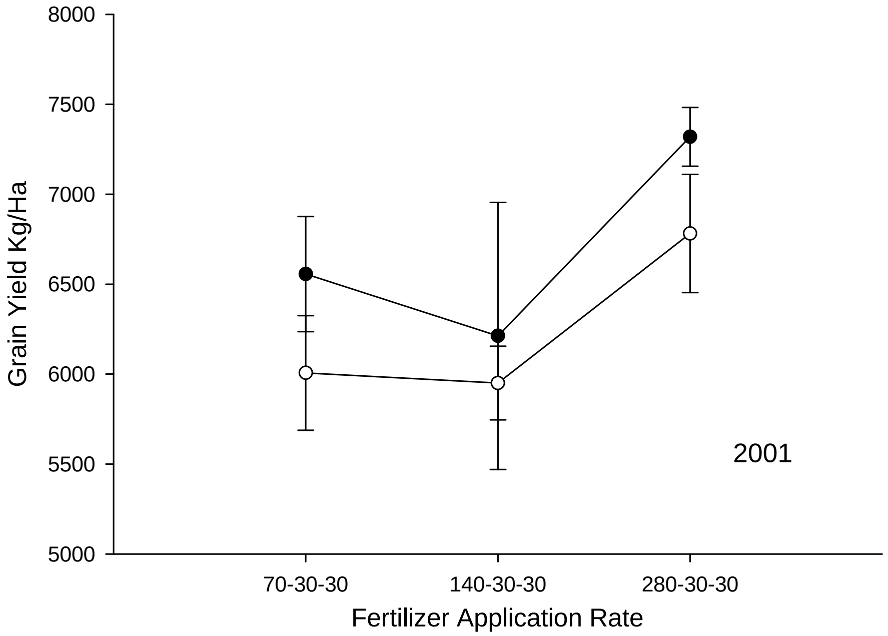


Figure 14. Rice Grain Yield under Different Fertilizer Application Rates, 2001 and 2002 SRI Field Trials, Sapu, The Gambia

In 2002, highest yield was observed with ITA 306 with the application of 140-30-30 NPK. The yield of IET 3137 did not increase significantly with increase in fertilizer application. However, overall yields in 2002 were 42 % on average higher than in 2001. The different responses to fertilizer in 2001 and 2002 probably reflected improved soil conditions following 2001 crop, as a result of residual fertilizer and stover incorporation (Table 21).

Table 21. Nutrient Status of Lowland Rice Soil in SRI Fertilizer Trial Plot, Sapu, The Gambia

	Soil pH 1:2 H_2O	**EC mmhos/cm**	**Organic Matter %**	**Total N %**
2000	5.7	0.1	3.47	0.1
2001	5.2	0.2	3.50	0.4
2002	6.1	0.1	3.80	0.12

This phenomenon of yield increase in subsequent years has been reported in other SRI management trials in Madagascar and Sri Lanka. A common factor being cited is a build up of beneficial microbial organisms and improvement of soil physical properties, although these were not measured in the trials conducted in The Gambia. However, inherent soil fertility status appears to play a more significant role in enhancing rice productivity with SRI management than application of inorganic fertilizer.

3.3.5. SRI with Compost and Different Urea Topdressing Rates

Compost, unlike inorganic fertilizer, is accessible to most farmers in The Gambia. It is inexpensive and can be produced by the farmers from crop residues and farmyard manure. Compost is currently used primarily for horticulture production where plot sizes are smaller. In lowland rice production compost is rarely is used in The Gambia, however, recently because of increased inorganic fertilizer prices, more lowland rice farmers are turning to alternate soil fertility amendment sources such as compost. The Extension Services of the Department of State for Agriculture in The Gambia has been promoting composting, but the adoption rate by lowland rice farmers has been low, because yields from compost applied fields were not as high as those where inorganic fertilizer was applied. This was probably due to the current water management system of continuous flooding, which does not allow beneficial microbial activity and rapid mineralization of N from organic matter during the cropping season, thus insufficient N is made available to the crop.

It is thought that SRI management practices can increase the efficacy of compost applied to lowland rice due to aeration of the soil, increase in microbial activity and mineralization. In 2002 an evaluation of SRI management practice with the use of compost was conducted in Sapu, The Gambia. Although farmers are familiar with the benefits of compost use, accumulating large quantities of compost is not an easy task. Rice straw and rice husk are the most abundant compostable material in the rice production system, and are used in compost production.

In this trial, 5 t/ha of compost made from rice straw, rice husk and farm-yard manure was applied 6 weeks prior to transplanting. After transplanting urea fertilizer was applied as topdressing. The nutrient content of the compost was 1.2% total N; 25.2% C; 2.8% K; and 3.1% P. This provides approximately 60 kg/ha N.

An increase in plant height and tiller count per hill was observed with increase in fertility level (Table 22).

Table 22. SRI Fertilizer Management Trial with Compost and Urea, Sapu, The Gambia, 2002

Fertilizer Level	**Variety**	**Plant Ht (cm)**	**Tiller per hill**	**Panicle per hill**
Compost	ITA 306	84.0	17	14
Compost	IET 3137	76.7	24	19
Compost + 40N	ITA 306	89.7	25	19
Compost + 40N	IET 3137	81.0	22	18
Compost + 80N	ITA 306	93.0	26	21
Compost + 80N	IET 3137	89.3	27	20
70N+30P+30K	ITA 306	97.4	18	18
70N+30P+30K	IET 3137	86.8	23	24
$LSD_{.05}$		14.6	7.7	5
CV(%)		8.2	16.6	13.4
P_{Var}		0.01	0.15	0.03
P_{Fert}		0.03	0.04	0.01
$P_{Var*Fert}$		ns	0.08	0.07

There was a linear increase in plant height and tiller count with urea application. Panicle count per hill increased with an increase in N fertilizer level, but did not strongly correlate with increase in tiller count. The plants did not produce very much biomass in compost treatments, but visually they were very pleasing to see. They produced an outstanding green color which was noticeable even from a distance.

Grain yield was highest for both varieties when 70-30-30 kg/ha NPK was applied without compost (Figure 15). ITA 306 yielded 8.1 t/ha and IET 3137 yielded 8.2 t/ha.

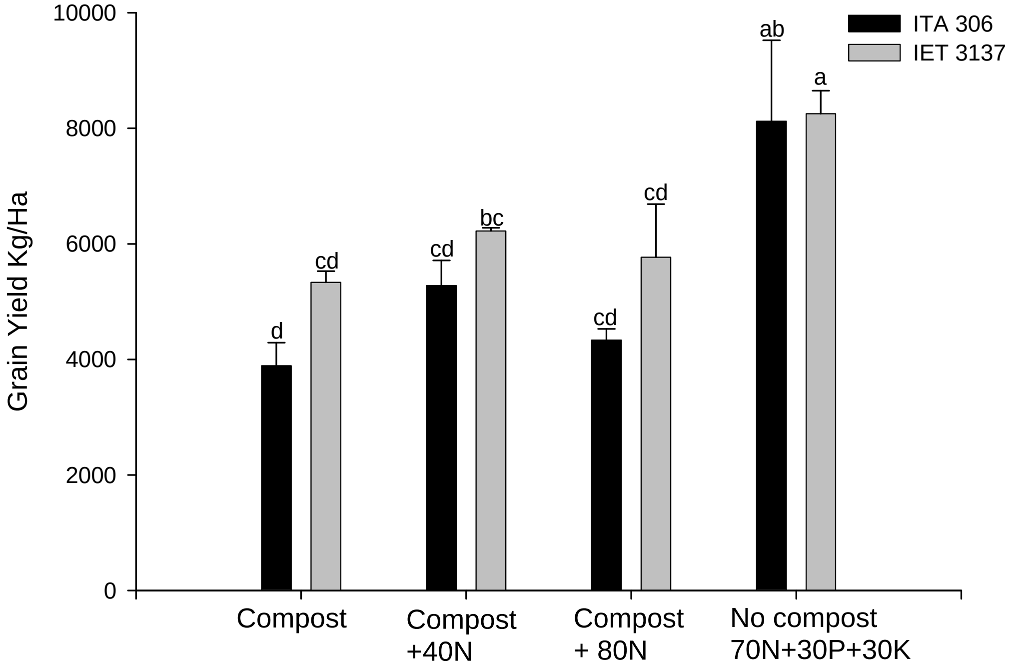


Figure 15. Effect of Compost and Urea Topdressing under SRI Management Practice, Sapu, The Gambia, 2002

Applying just compost alone gave statistically the same yield as compost with 40 and 80 kg/ha N for both varieties. Doubling of the N application did not significantly increase yields for either variety. Although there was no P and K basal application with compost as a treatment, the results suggested that P and K were probably limiting. The 70-30-30 kg/ha NPK gave the highest yield most probably as a result of applied P and K.

Compost applied during the cropping requires some time to adequately mineralize and mix in the soil profile. The subsequent crop usually benefits more from compost application than the current one.

3.3.6. On-Farm SRI Management Trial

The Gambia is the first country in Africa after Madagascar to experiment with SRI management practices. Farmers in the vicinity of Sapu station were invited to participate in a field day of the Gambia National Agricultural Research Institute in December 2000. Farmers had first-hand opportunity to see the results of SRI management practices using the local varieties grown in the area. Farmers expressed interest to try the management practices in their fields. In 2001, an SRI on-farm trial was designed, and 10 households participated.

The major planning constraints were land preparation and water control. Extra time and labor had to be devoted to land preparation; puddling, leveling, bund reconstruction, and cleaning of drainage canals. Second, farmers in The Gambia do not have a well developed culture of water control. Drainage mechanisms are often not utilized. Fields are kept flooded after transplanting until the rice plants reach maturity. Fertilizer application and weeding are done under flooded conditions. These were major challenges for the adoption of SRI practices by local farmers.

In most of the farmer trials, grain yields from the SRI management plots were 2 to 6 times higher than the average yields (2.5 t/ha) from the current farmer management practice (Table 23).

Table 23. Grain Yields from Farmer Management Practices and SRI Management Practices, Sapu, The Gambia, 2001

Farmer	Farmer Management Practice (T/Ha)	SRI Management Practice (T/Ha)	Increase by SRI (T/Ha)
1	3.7	8.5	4.8
2	2.0	7.8	5.8
3	2.5	9.3	6.8
4	1.8	9.4	7.6
5	1.6	9.0	7.4
6	1.4	8.0	6.6
7	2.8	6.0	3.2
8	2.5	7.0	4.5
9	3.8	7.6	3.8
10	2.5	1.8	-0.7
Average	2.5	7.4	4.9

Under SRI management practices, yields were as high as 9.4 t/ha. The average yield was 7.4 t/ha, and would have been higher if the bund between the SRI and farmer practice plot had not been given way for farmer # 10, submerging the 7-day old seedlings and resulted in seedling mortality, retarded growth, poor plant stand, and ultimate low yield. During the tillering period there was a defoliator caseworm (*Nymphula stagnalis* Zell) outbreak. Farmers' plots were devastated, but not a single SRI-managed plot was infested. The semi-aquatic larva of the defoliator caseworms strips plants of their leaves, reducing their photosynthetic capacity. After completely defoliating a plant, they swim in the flood waters to the next plant. The absence of standing water in the SRI plots provided an effectively control against the defoliator caseworm. This incident was noticed by farmers and brought to the attention of the researcher. SRI water control method of repeated wetting and drying also helps to control mosquito breeding and thus helps to control against malaria.

High returns associated with SRI management practices thus have been demonstrated to irrigated rice farmers in The Gambia. The prospects are that more and more farmers will adopt some if not all of the components of SRI management practices in their production. The production cost associated with SRI management is initially higher than conventional production cost, but the higher net return compensates for the high production cost (Table 19). Land preparation and putting in place an effective drainage mechanism were identified as the most limiting factors to adoption of SRI management practice, but these could be addressed in the long-term.

It is possible to improve the drainage system in most of the rice fields, and once this is done it will serve for a long period of time without major labor and capital input. Land preparation is much easier and faster in the second and subsequent years after major leveling has been done in the first year of SRI management. This is due in part to improvement of soil physical properties with organic matter built-up and micro-fauna development in plough-layer of the soil.

3.4. Conclusions

SRI management practices produced higher yields than the currently recommended management practices in The Gambia. Yields using SRI management practices are 2 to 3 times higher than national averages in The Gambia and the Sahel. The phenotype of the plant is better expressed with SRI management practice. Lodging incidence was not observed in any of the SRI trials. The major factors that contribute to better plant performance could be attributed in part to high nutrient availability associated with improved soil and water management practices of SRI permitting the soil to be repeatedly wetted and dried as well as using younger seedlings at transplanting.

Younger seedlings are more viable than older ones when uprooted and transplanted. Although older seedlings have a relatively higher bulk root density, they also have a relatively much higher above-ground biomass to supply nutrient and water. For SRI management 7 -10 day old seedlings should be used. At this age they are relatively easy to handle and will not have reached their fourth phyllochron of growth.

Except for plant height and tiller ability, no significant varietal effect was seen. Overall, water management practice did have an effect on plant height. A larger number of tillers per hill was not associated with repeated wetting and drying, as occurred in response to wider spacing.

An increase in SRI yields in subsequent years was observed. Yields in 2002 were higher than in 2001 by 42 % on average for the SRI fertilizer trial. This was probably due to improved soil conditions following 2001 crop, as a result of residual fertilizer and stover incorporation.

Application of compost with 80 kg/ha N as a topdressing gave better yields than compost alone, but was not significantly different from compost with 40 kg/ha N topdressing. In SRI management nitrogen is gradually released from decomposing organic matter during the growing season, so less N fertilization is required as soil organic matter levels increase. A continuously flooded rice field requires more N fertilizer than one that is repeatedly wetted and dried.

Under SRI management practice, the availability of nutrients to support high yields did not seem to be limiting in the soils where the trials were conducted. This may be due to the fact that the rate of mineralization is enhanced by the process of repeated wetting and drying and the enhanced development of microbial populations in the soil.

SRI water control acts a preventive measure against defoliator caseworm outbreak. The caseworms feeds on the rice leaves and in the process some part of the leaves fall in the water. A field infested with caseworms is easily detected by the large number of leaves floating in the water. Caseworms are semi-aquatic and move from one plant to another by swimming in the flood waters or floating on top of rice leaves in water. Draining the field restricts caseworm movement, thereby limiting their spread. Keeping a field drained for 3 days is enough to starve and eliminate any caseworm present.

SRI water management practice address some key policy issues related with water availability and extensification of irrigation schemes. In The Gambia and the semi-arid Sahel, increasing the area under rice irrigation is influenced by the amount of water available to support future expansion. There is a high demand for water in the Sahel, and in some cases, the rivers and distributaries are already failing to support the present irrigation schemes. SRI can reduce water requirements for production by 30-50%, while increasing yield and also the need for use of agrochemicals, often unavailable or beyond the financial reach of small producers.

CHAPTER FOUR:
GENERAL RESEARCH SUMMARY

4.1. General conclusions

The challenge faced by African farmers while managing a fragile natural resource base is to increase food production to feed a still increasing population. To increase rice production, a sustainable production system that optimizes land resource use while economizing on water and agrochemical requirements needs to be available. Apart from maintaining sustainable soil fertility, the complexity of upland rice environment is such that genotypic improvement and management studies to increase and maintain a stable grain yield should take into consideration other components of the upland rice environments such as drought, pest and disease complexes, etc. In the lowland, the major causes of yield reduction are poor water control, nutrient deficiency, water borne-pests, low nutrient use efficiency resulting from continuous flooding, and inconsistent planting calendar.

This study made possible the identification of low-input upland rice cultivars, as well as improved lowland rice management practices that can greatly increase rice yields using small amounts of inorganic fertilizer and/or organic soil conditioners such as compost or green manure.

Although the low-input upland cultivars may have a high NUE, the amount of nutrients available in continuously cultivated lands is not sufficient to support high crop productivity. This study showed that the recommended low-input fertilizer application rate is too low to support optimum rice productivity. However, if the low-input varieties are grown with 80-40-40 kg/ha NPK, not much above the present national recommendation, yields could be tripled even under drought conditions. Application of a relatively higher fertilizer rate than the initially recommended low-input rate is an insurance against crop loss to drought and termites, because of more intensive crop growth with higher fertilizer application rates.

The government of The Gambia and other West African nations need to invest on seed multiplication and dissemination of WARDA's low-input varieties also known an NERICA (New Rice for Africa). Rice productivity in the uplands could be tripled with the introduction of such varieties. With a tripling in yield farmers in the upland will find it more profitable to increase area under cultivation without fear of high risk factors presently associated with upland rice production.

Governments in the Sub-Saharan Africa have in the past invested in rice irrigation schemes to increase production, but output has so far not satisfied demand, and currently there are efforts to increase the area under production. Unfortunately, in the semi-arid Sahel and in most countries in Asia, increase in the area under rice cultivation is presently constrained by the amount of water available to support production. Conflicts over access to irrigation water between the republics of Senegal and Mauritania in the Sahel are still unresolved. Globally, there is a high demand for irrigation water, and in some cases, the rivers and distributaries are already failing to suffice for existing irrigation schemes. Therefore, finding ways to economize on water requirements is an immediate necessity for sustainable agriculture.

The System of Rice Intensification (SRI) management practices are capable of producing higher rice yields than conventional management practices with lower water requirements. Yields with this set of management practices are 2 to 3 times higher than the national rice yield averages in The Gambia and the Sahel generally. SRI offers opportunities to raise production with less water. SRI methodology for growing lowland rice, changes plant, soil, water and nutrient management practices. These changes cause rice genomes to yield more productive phenotypes: ones with more tillers, much larger root systems, and a positive correlation between tillering and grain filling. SRI management practices are capable of producing higher rice yields than conventional management practices. Yields with this set of management practices are 2 to 3 times higher than the national rice yield averages in The Gambia and the Sahel.

Improving the productivity of the soil, water, labor and capital investment, with SRI gives benefits that can spread widely through the economy and contribute to important macroeconomic goals. In fact, improved resource efficiency is in itself a major source of economic growth.

The utilization of the findings in this research work can help lower production costs and increase yields, raising per capita food production while alleviating degradation of land and water resources.

4.2. Prospects

The research findings identify new sources of growth in rice output in The Gambia. These findings are based on scientific approaches different from those on which conventional rice production is based. The findings give scope for great optimism, suggesting that massive growth in rice productivity can be attained through three major sources. Namely, the intensification of production in currently cultivated lands, reduction of production costs as a result of improved water, nutrient, and biological management, and the expansion of area under cultivation as a result of more attractive incentives in the form of higher yields and higher net returns from applied inputs.

Plant growth is enhanced by the amount of available nutrients in the soil, which depends to a great extent on management practices, the amount of added fertilizer, soil microbiology, and the interaction synergy among these factors and dynamics. Management is the single most important production factor and the most sustainable input toward optimization of crop yields.

Adoption of low-input varieties will facilitate greater production on the same land with the addition of reasonable amounts of inorganic or organic fertilizer. This will reduce pressure for deforestation and land degradation caused by shifting cultivation. However, the current blanket fertilizer recommendation rate will have to be replaced with site-specific recommendations using the NuMaSS or other recommendation domains. There is a critical need for a soil testing system that can be used by farmers across SSA. Future research in the upland will also have to look at limitations posed by other nutrients apart from N. In The Gambia, one current need is to classify both upland and lowland soils into fertility level classes. This will help researchers and extension agents to determine soil amendment needs and give quick responses to soil fertility needs in the different rice growing ecosystems.

The adoption of SRI technological practices could greatly affect agricultural policies in the Sahel regarding possibilities to extend the present area under irrigation in the face of water shortage and salinization.

Much emphasis in optimizing lowland rice yield prior to this study was on the introduction of new cultivars and increasing the amount of fertilizer application. This study has proven that in fact the yields of current cultivars could be doubled or even tripled with simple changes in management practices such as transplanting younger seedlings, better water control, and spacing.

The next step in this research is to disseminate the improved technologies and to define ways for introducing and facilitating adoption of the technologies. For SRI to be effectively introduced, some community-based interventions such as formation of irrigation water user groups to synchronize irrigation and drainage should be established among other things.

Adoption of low-input varieties in the upland and SRI in the lowland both has the potential to triple yields in each of these rice ecologies; upland to 3 t/ha and lowland to 6 t/ha or even 8 t/ha. If by 2005 low-input varieties are adopted in the 10,000 ha cultivated of upland rice in 2000, and SRI is adopted in the 8,000 ha of cultivated lowland rice area, independent of projected population growth, the rice deficit will be reduced from 83% to 45%. However, if the area under cultivation in the upland and lowland are increased by just 50%, with the benefits derived from the improved technologies, a deficit of only 20% will need to be provided with importations. This will require only 20% of the projected US$20.3 million (US$4 million) needed to import rice in 2005.

Despite the importance of these findings, implementation and adoption of the identified technologies by farmers will remain the weak link unless future activities are designed to disseminate and promote the technologies. The knowledge gap that exists in SSA as a result of insufficient attention attached to the dissemination and extension of improved research technologies needs to be bridged through research and extension efforts.

4.3. Future Research Needs

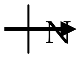
Although during the 3 years of field investigation several research findings were made, there are still some areas that require further investigation. In the upland ecology, future rice research needs are in the following areas:

1). To study the short and long-term effects of legumes rotations
2). The effect of mulching
3). The effect of P and K as well as N management
4). Develop a soil testing and calibration system for the upland rice fields in The Gambia

In the lowland, future SRI research should focus on the following:

1). Quantifying microbial development with SRI management
2). The impact of compost use over time
3). Long term experiments with the following:
    a). Water control
    b). P and K as well as micronutrients
    c). Organic matter inputs such legumes
4). Quantifying rate mineralization over time

APPENDIX 1: FIELD LAYOUT



V. High-Input

V3	V4	V2	V1
V4	V3	V1	V2
V2	V1	V4	V3

High-Input

V2	V3	V1	V4
V3	V2	V4	V1
V1	V4	V3	V2

Low-Input

V2	V4	V1	V3
V4	V1	V3	V2
V3	V2	V4	V1

Control

V1	V2	V3	V4
V2	V3	V4	V1
V3	V4	V1	V2

Main-plots: Fertilizer application rates

1. Control 0-0-0 kg/ha NPK
2. Low-Input 40-40-40 kg/ha NPK
3. High-Input 80-40-40 Kg/ha NPK
4. Very High-Input 160-80-80 Kg/ha NPK

Sub-plots: Varieties

V1	WAB 56-125
V2	WAB 377-B-16-L3-LB
V3	WAB 56-50
V4	Peking (local check)

Four blocks were established separated by 2 m wide foot-paths. Each block is planted with the 4 test varieties using a randomized complete block design. Each block is then allocated a fertilizer application rate. There were 12 plots 2.7 x 4.0 m in each block.

APPENDIX 2: SOIL ANALYSIS DATA

Table 24. Soil Sample Analysis at Time of Planting, Upland Rice Trial, Brikama, The Gambia, 2000

Texture	**Soil pH Water 1:2**	**EC mmhos/cm 1:2**	**Bray-1 Avl. P ppm**	**Organic matter (%)**	**Total N (%)**
Sandy loam	5.4	0.07	3.13	1.56	0.41

Table 25. Soil Sample Analysis at Tillering, Upland Rice Trial, Brikama, The Gambia, 2000

Treatment	**Soil pH Water 1:2**	**EC mmhos/cm 1:2**	**Bray-1 Avl. P ppm**	**Organic matter (%)**	**Total N (%)**
Control	5.3	0.1	7.3	1.1	0.3
Low-Input	5.5	0.1	12.5	2.1	0.3
High-Input	5.6	0.1	2.3	1.2	0.3
V. High-Input	5.2	0.1	3.6	1.1	0.1

Table 26. Soil Sample Analysis at Harvest, Upland Rice Trial, Brikama, The Gambia, 2000

Treatment	Soil pH Water 1:2	EC mmhos/cm 1:2	Bray-1 Avl. P ppm	Organic matter (%)	Total N (%)
Control	5.5	0.07	5.1	1.7	0.08
Low-Input	5.5	0.05	6.9	1.7	0.08
High-Input	5.2	0.06	7.6	1.5	0.07
V. High-Input	5.0	0.06	8.4	1.4	0.06

Table 27. Soil Sample Analysis at Planting, Upland Rice Trial, Brikama, The Gambia, 2001

Treatment	Soil pH Water 1:2	EC mmhos/cm 1:2	Bray-1 Avl. P ppm	Organic matter (%)	Total N (%)
Control	5.8	0.09	3.0	1.4	0.04
Low-Input	5.6	0.09	10.0	1.1	0.06
High-Input	5.7	0.09	5.1	0.9	0.08
V. High-Input	5.4	0.09	5.0	1.2	0.04

Table 28. Soil Sample Analysis at Tillering, Upland Rice Trial, Brikama, The Gambia, 2001

Treatment	**Soil pH Water 1:2**	**EC mmhos/cm 1:2**	**Bray-1 Avl. P ppm**	**Organic matter (%)**	**Total N (%)**
Control	6.0	0.12	2.6	1.3	0.07
Low-Input	5.6	0.24	5.3	3.6	0.06
High-Input	5.6	0.12	8.2	4.6	0.06
V. High-Input	5.1	0.11	5.3	1.0	0.07

Table 29. Soil Sample Analysis at Harvest, Upland Rice Trial, Brikama, The Gambia, 2001

Treatment	**Soil pH Water 1:2**	**EC mmhos/cm 1:2**	**Bray-1 Avl. P ppm**	**Organic matter (%)**	**Total N (%)**
Control	5.7	0.09	2.7	8.2	0.06
Low-Input	6.1	0.14	3.7	5.6	0.06
High-Input	6.0	0.17	2.2	5.6	0.08
V. High-Input	5.9	0.21	4.9	5.8	0.06

APPENDIX 3: LOW-INPUT UPLAND RICE TRIAL PARAMETERS

Table 30. Low-Input Upland Rice Trial, Phenotypic Parameters, Brikama, The Gambia, 2001

Fertilizer Level	**Variety**	**Plant Ht (cm)**	**Tiller per m²**	**Panicle per m²**
Zero Application 0-0-0	WAB56-50	64.7	273	148
	WAB56-125	63.4	177	121
	WAB377-B	63.2	223	105
	Peking	50.7	196	156
Low-Input 40-40-40	WAB56-50	74.0	199	145
	WAB56-125	82.7	203	117
	WAB377-B	81.1	231	143
	Peking	48.1	292	177
High-Input 80-40-40	WAB56-50	68.0	260	185
	WAB56-125	88.4	279	187
	WAB377-B	82.3	260	239
	Peking	54.1	292	241
Very High Input 160-80-80	WAB56-50	73.2	264	188
	WAB56-125	93.7	203	175
	WAB377-B	99.8	231	175
	Peking	57.8	267	200
$Lsd_{.05}$		17.4	101	92
Cv(%)		14.7	24.4	32.9
P_{Fert}		0.0005	0.0033	0.0048
$P_{Variety}$		<0.0001	0.0468	ns
$P_{Fert*Variety}$		<0.0001	0.0145	0.169

Table 31. Low-Input Upland Rice Trial, Grain and Panicle Quality,
Brikama, The Gambia, 2001

Fertilizer Level	**Variety**	**Panicle Length (cm)**	**Grains per Panicle**	**Spikelet Fertility (%)**
Zero Application 0-0-0	WAB56-50	13.6	426	87
	WAB56-125	14.4	411	78
	WAB377-B	12.5	220	66
	Peking	14.3	362	82
Low-Input 40-40-40	WAB56-50	12.8	352	84
	WAB56-125	15.1	501	81
	WAB377-B	12.8	354	83
	Peking	12.8	330	87
High-Input 80-40-40	WAB56-50	13.6	455	87
	WAB56-125	15.5	431	81
	WAB377-B	13.1	369	85
	Peking	12.8	298	85
Very High Input 160-80-80	WAB56-50	16.3	718	88
	WAB56-125	16.2	740	90
	WAB377-B	13.8	484	95
	Peking	15.3	398	79
$Lsd_{.05}$		2.8	189	
Cv(%)		12.1	26.6	
P_{Fert}		0.0277	<0.0001	
$P_{Variety}$		0.0249	0.0007	
$P_{Fert*Variety}$		0.1035	0.0002	

Table 32. Low-Input Upland Rice Trial, Phenotypic Parameters, Brikama, The Gambia, 2002

Fertilizer Level	**Variety**	**Plant Ht (cm)**	**Tiller per m²**	**Panicle per m²**
Zero Application 0-0-0	WAB56-50	84.7	57	41
	WAB56-125	83.6	56	41
	WAB377-B	78.8	63	45
	Peking	82.7	44	31
Low-Input 40-40-40	WAB56-50	91.3	48	39
	WAB56-125	94.8	51	35
	WAB377-B	96.0	50	36
	Peking	96.0	53	39
High-Input 80-40-40	WAB56-50	98.8	83	52
	WAB56-125	104.3	89	57
	WAB377-B	111.7	70	42
	Peking	103.4	79	51
Very High Input 160-80-80	WAB56-50	109.3	77	52
	WAB56-125	111.7	65	49
	WAB377-B	110.7	100	69
	Peking	106.9	75	44
$\text{Lsd}_{.05}$		13.4	24	16
Cv(%)		8.26	22.1	22.3
P_{Fert}		<0.0001	<0.0001	0.0006
P_{Variety}		ns	ns	ns
$P_{\text{Fert*Variety}}$		<0.0001	0.0008	0.0095

Table 33. Low-Input Upland Rice Trial, Grain and Panicle Quality,

Brikama, The Gambia, 2002

Fertilizer Level	**Variety**	**Panicle Length (cm)**	**Grains per Panicle**	**1000 Grain Wt (g)**
Zero Application 0-0-0	WAB56-50	17.4	368	27.2
	WAB56-125	21.2	447	27.3
	WAB377-B	19.1	468	27.3
	Peking	16.1	348	23.8
Low-Input 40-40-40	WAB56-50	22.1	596	30.2
	WAB56-125	21.9	576	30.6
	WAB377-B	19.7	448	29.9
	Peking	22.9	644	29.3
High-Input 80-40-40	WAB56-50	20.6	569	28.5
	WAB56-125	20.6	520	28.1
	WAB377-B	18.1	376	27.3
	Peking	20.2	603	29.6
Very High Input 160-80-80	WAB56-50	19.5	438	29.4
	WAB56-125	23.3	571	34.8
	WAB377-B	22.3	547	34.1
	Peking	21.3	485	31.8
$Lsd_{.05}$		3	159	8
Cv(%)		8.9	19.1	18.1
P_{Fert}		0.0009	0.0029	0.0518
$P_{Variety}$		0.0853	ns	ns
$P_{Fert*Variety}$		0.0010	0.0084	ns

Table 34. Harvest Index of Rice Varieties in 2000, 2001, 2002, Brikama, The Gambia

Fertilizer Level	**Variety**	**Harvest Index**		
		2000	**2001**	**2002**
Zero Application **0-0-0**	WAB56-50	0.523^{a}	0.439^{ab}	0.345^{abc}
	WAB56-125	0.438^{ab}	0.235^{c}	0.269^{c}
	WAB377-B	0.475^{ab}	0.322^{abc}	0.409^{abc}
	Peking	0.551^{a}	0.379^{abc}	0.317^{bc}
Low-Input **40-40-40**	WAB56-50	0.561^{a}	0.364^{abc}	0.399^{abc}
	WAB56-125	0.484^{ab}	0.298^{bc}	0.359^{abc}
	WAB377-B	0.470^{ab}	0.416^{ab}	0.258^{c}
	Peking	0.568^{a}	0.288^{bc}	0.440^{abc}
High-Input **80-40-40**	WAB56-50	0.432^{ab}	0.418^{ab}	0.529^{ab}
	WAB56-125	0.460^{ab}	0.293^{bc}	0.567^{a}
	WAB377-B	0.444^{ab}	0.479^{a}	0.478^{abc}
	Peking	0.519^{a}	0.392^{abc}	0.451^{abc}
Very High Input **160-80-80**	WAB56-50	0.423^{ab}	0.402^{abc}	0.306^{bc}
	WAB56-125	0.403^{ab}	0.366^{abc}	0.274^{c}
	WAB377-B	0.462^{ab}	0.392^{abc}	0.307^{bc}
	Peking	0.319^{b}	0.293^{bc}	0.333^{abc}
Lsd$_{.05}$		0.147	0.149	0.201
Cv(%)		18.29	24.9	32.1

Table 35. Straw Nitrogen Content of Rice Varieties at Harvest in 2000, 2001, 2002, Brikama, The Gambia

Fertilizer Level	**Variety**	**Straw N(%)**		
		2000	**2001**	**2002**
Zero Application 0-0-0	WAB56-50	0.30	0.61	0.97
	WAB56-125	0.48	0.53	0.80
	WAB377-B	0.69	0.92	0.82
	Peking	0.64	0.69	1.03
Low-Input 40-40-40	WAB56-50	0.33	0.53	1.25
	WAB56-125	0.49	0.53	1.14
	WAB377-B	0.61	0.73	1.47
	Peking	0.54	0.54	1.56
High-Input 80-40-40	WAB56-50	0.40	0.65	1.25
	WAB56-125	0.49	0.89	1.00
	WAB377-B	0.61	0.64	1.01
	Peking	0.55	0.91	1.15
Very High Input 160-80-80	WAB56-50	0.60	0.68	1.44
	WAB56-125	1.01	0.69	1.17
	WAB377-B	0.74	0.71	1.15
	Peking	0.96	0.78	1.52
$Lsd_{.05}$		0.45	0.42	0.60
Cv(%)		42.9	36.5	31.1

Table 36. Nitrogen-Use Efficiency for Grain Production (NUEg)of Rice Varieties in 2000, 2001, 2002, Brikama, The Gambia

Fertilizer Level	**Variety**	**NUEg**		
		2000	**2001**	**2002**
Zero Application **0-0-0**	WAB56-50	87.2^{a}	49.1^{ab}	13.5^{abc}
	WAB56-125	81.1^{a}	66.1^{a}	12.2^{abc}
	WAB377-B	63.1^{abcd}	31.2^{b}	9.4^{bc}
	Peking	75.1^{ab}	51.7^{ab}	9.5^{bc}
Low-Input **40-40-40**	WAB56-50	83.5^{a}	63.8^{a}	6.7^{c}
	WAB56-125	83.9^{a}	59.9^{ab}	10.7^{bc}
	WAB377-B	68.9^{abc}	40.2^{ab}	7.5^{c}
	Peking	81.2^{a}	47.6^{ab}	10.2^{bc}
High-Input **80-40-40**	WAB56-50	91.4^{a}	65.9^{a}	14.0^{abc}
	WAB56-125	64.9^{abcd}	48.8^{ab}	19.2^{ab}
	WAB377-B	68.5^{abc}	44.0^{ab}	22.3^{a}
	Peking	75.2^{ab}	46.4^{ab}	15.1^{abc}
Very High Input **160-80-80**	WAB56-50	65.7^{abcd}	53.8^{ab}	7.4^{c}
	WAB56-125	45.7^{cd}	54.9^{ab}	7.2^{c}
	WAB377-B	51.7^{bcd}	49.1^{ab}	6.5^{c}
	Peking	39.2^{d}	37.3^{ab}	8.8^{bc}
Lsd$_{.05}$		20.1	25.0	9.2
Cv(%)		24.5	29.7	49.3

APPENDIX 4: SYSTEM OF RICE INTENSIFICATION PARAMETERS

Table 37. Seedling Root Re-Growth Count and Bulk Root Length

	Seedling Age (days)	**Variety**	
		ITA 306	**IET 3137**
Number of New Root Re-growth	7	4.2^{e} ± 0.241	3.7^{e} ± 0.223
	14	5.6^{d} ± 0.259	4.4^{ed} ± 0.204
	21	7.3^{c} ± 0.331	4.5^{ed} ± 0.247
	28	12.4^{a} ± 1.179	9.1^{b} ± 0.522
LSD **CV(%)**	1.4 45.5		
Bulk Root Length (cm)	7	6.9^{d} ± 0.743	7.1^{d} ± 0.733
	14	8.5^{d} ± 0.675	6.3^{d} ± 0.483
	21	15.4^{c} ± 1.135	5.7^{d} ± 0.656
	28	18.9^{b} ± 2.818	24.6^{a} ± 2.271
LSD CV(%)	3.4 62.2		

Table 38. SRI vs Conventional Practice using Different Varieties and Plant Spacing, Sapu, The Gambia, 2000

Spacing	**Variety**	**Yield T/Ha**	
		Local Practice	**SRI Practice**
20x20	ITA 306	2.4^{de}	7.4^{a}
20x20	IET 3137	2.6^{d}	5.8^{b}
30x30	ITA 306	1.4^{fg}	5.5^{b}
30x30	IET 3137	1.9^{ef}	4.6^{c}
40x40	ITA 306	0.9^{g}	4.4^{c}
40x40	IET 3137	1.7^{ef}	4.1^{c}
$LSD_{.05}$			0.7
CV(%)			13.8

Table 39. SRI Practice Using *cv* IET3137 and Different Plant Spacings, Sapu, The Gambia, 2001

Variety	**Inter Space**	**Plant Ht (cm)**	**Tiller per hill**	**Panicle per hill**
IET 3137	20x20	81.0	53	26
	30x30	79.5	82	40
	40x40	80.5	99	42
$LSD_{.05}$		ns	ns	ns
CV(%)		4.3	23.4	18.2

Table 40. Grain Yield from SRI Practice Using var. IET 3137 with Different Planting Density, Sapu, The Gambia, 2000, 2001, 2002

Inter Space	**Grain Yield T/Ha**			
	2000	**2001**	**2002**	**Average**
20x20	5.8	5.3	8.9	6.7
30x30	4.6	3.2	8.4	5.4
40x40	4.0	1.8	6.4	4.1

Table 41. SRI Fertilizer Management Trial with Different Varieties, Sapu, The Gambia, 2001

Fertilizer Level	Variety	1000 Grain wt (g)	Harvest Index	Stover T/Ha	Yield T/Ha
Normal	ITA 306	24.2	0.39	10.6	6.6
(70-30-30)	IET 3137	23.8	0.41	8.6	6.0
High	ITA 306	27.1	0.42	8.4	6.2
(140-30-30)	IET 3137	22.1	0.42	8.5	6.0
Very High	ITA 306	25.1	0.44	9.1	7.3
(280-30-30)	IET 3137	22.2	0.45	8.5	6.8
$D_{.05}$		ns	0.06	ns	ns
CV(%)		11.4	8.6	18.6	12.1
P_{Var}		ns	0.05	ns	0.17
P_{Fert}		ns	ns	ns	0.05
$P_{Var*Fert}$		ns	ns	ns	ns

Table 42. SRI Fertilizer Management Trial with Different Varieties, Sapu, The Gambia, 2002

Fertilizer Level	**Variety**	**Plant Ht (cm)**	**Tiller per hill**	**Panicle per hill**	**Panicle Setting Ratio (%)**
Normal	ITA 306	101.3	21	19	92.8
(70-30-30)	IET 3137	87.8	26	21	81.1
High	ITA 306	103.4	24	23	95.2
(140-30-30)	IET 3137	93.9	28	24	86.4
Very High	ITA 306	107.6	25	22	86.1
(280-30-30)	IET 3137	97.5	41	35	84.8
$LSD_{.05}$		6.7	13	11	ns
CV(%)		3.9	24.9	24.6	7.8
P_{Var}		<0.0001	0.024	0.067	0.04
P_{Fert}		0.0123	0.066	0.0868	ns
$P_{Var*Fert}$		ns	ns	0.18	ns

Table 43. SRI Fertilizer Management Trial with Different Varieties, Sapu, The Gambia, 2002

Fertilizer Level	**Variety**	**Yield T/Ha**
Normal	ITA 306	9.0
(70-30-30)	IET 3137	8.8
High	ITA 306	10.4
(140-30-30)	IET 3137	9.0
Very High	ITA 306	8.9
(280-30-30)	IET 3137	9.1
$LSD_{.05}$		ns
CV(%)		12.2
P_{Var}		ns
P_{Fert}		ns
$P_{Var*Fert}$		ns

Table 44. SRI Fertilizer Management Trial with Different Varieties, Sapu, The Gambia, 2001, 2002

Fertilizer Level	**Variety**	**Yield T/Ha**	
		2001	**2002**
Normal	ITA 306	6.6	9.0
(70-30-30)	IET 3137	6.0	8.8
High	ITA 306	6.2	10.4
(140-30-30)	IET 3137	6.0	9.0
Very High	ITA 306	7.3	8.9
(280-30-30)	IET 3137	6.8	9.1
$LSD_{.05}$		ns	ns
CV(%)		12.1	12.2

Table 45. Panicle Development SRI Fertilizer Management Trial with Compost and Urea, Sapu, The Gambia, 2002

Fertilizer Level	**Variety**	**1000 Grain wt (g)**	**Panicle Setting Ratio (%)**
Compost	ITA 306	22.0	78.8
Compost	IET 3137	21.7	79.7
Compost + 40N	ITA 306	25.7	76.7
Compost + 40N	IET 3137	22.0	83.3
Compost + 80N	ITA 306	23.5	80.8
Compost + 80N	IET 3137	19.0	74.6
70N+30P+30K	ITA 306	21.0	90.6
70N+30P+30K	IET 3137	22.0	76.6
$LSD_{.05}$		ns	ns
CV(%)		15.8	11.5
P_{Var}		0.14	ns
P_{Fert}		ns	ns
$P_{Var*Fert}$		ns	ns

Table 46. Yield Parameters SRI Fertilizer Management Trial with Compost and Urea, Sapu, The Gambia, 2002

Fertilizer Level	**Variety**	**Plant Ht (cm)**	**Tiller per hill**	**Yield T/Ha**
Compost	ITA 306	84.0	17	3.9^{d}
Compost	IET 3137	76.7	24	5.3^{cd}
Compost + 40N	ITA 306	89.7	25	5.3^{cd}
Compost + 40N	IET 3137	81.0	22	6.2^{bc}
Compost + 80N	ITA 306	93.0	26	4.3^{cd}
Compost + 80N	IET 3137	89.3	27	5.8^{cd}
70N+30P+30K	ITA 306	97.4	19	8.1^{ab}
70N+30P+30K	IET 3137	86.79	23	8.3^{a}
$LSD_{.05}$		14.6	7.7	1.9
CV(%)		8.2	16.6	19.1
P_{Var}		0.01	0.15	0.0475
P_{Fert}		0.03	0.04	0.0002
$P_{Var*Fert}$		ns	ns	ns

BIBLIOGRAGPHY

Alagarswamy, G., J.C. Gardner, J.W. Maransville, and R.B. Clark. 1988. Measurement of instantaneous nitrogen use efficiency among pearl millet genotypes. Crop Sci. J. 28:681-685.

Amano, T., Q. Zhu, Y. Wang, N. Inoue, and H. Tanaka. 1993. Case studies on high yields of paddy rice in Jiangsu Province, China: I. Characteristics of grain production. Jpn. J. Crop Sci. 65(1):16-21.

Batten G.D. 2002. Relating minerals in rice shoots and grain to soil tests, yield and grain quality. Rural Industries Research and Development Corporation. Australia. No 02/101.

Begg, J.E and N.C. Turner. 1976. Crop water deficits. Adv. Agron. J. 28:181-217.

Bhattacharjee, D.P., R. Krishnayya, and A.K. Ghosh. 1973. Analysis of yield components and productive efficiency of rice varieties under soil moisture deficit. Oryza, vol.10, No.2.

Birch, H.F. 1958. The Effect of soil drying on humus decomposition and nitrogen. Plant Soil 10:9-31.

Black, C.A. 1993. Soil fertility evaluation and control. p.66-67. CRC Press, Boca Raton, FL.

Boonjung, H., and S. Fukai. 1996. Effects of soil water defict at different growth stages on rice growth and yield under upland conditions. 2. Phenology, biomass production and yield. Field Crops Res. 48:47-55.

Broadbent, F.E. 1979. Mineralization of organic nitrogen in paddy soils. *In*: IRRI (ed). Nitrogen and rice. Los Banos, Phillipines, pp. 105-118.

Bufogle, A., Jr., P.K. Bollich, J.L. Kovar, R.E. Macchiavelli, and C.W. Lindau. 1997. Rice variety differences in dry matter and nitrogen accumulation as related to plant stature and maturity group. J. Plant Nutr. 20:1203-1224.

Cabrera, M.L. 1993. Modeling the flush of nitrogen mineralization caused by drying and rewetting soils. Soil Society of America J. 57:63-66.

Campbell, C.A., R.J.K. Myers, and D. Curtin. 1995. Managing nitrogen for sustainable crop production. Fert. Res. 42:277-296.

Carter, M.R. and Macleod J.A. 1987. Biological properties of some Prince Edward Island Soils: Relationship between microbial biomass nitrogen and mineralizable nitrogen. Canadian Journal of Soil Science. 67:333-340.

Cassman, K.G., and R.R. Harwood. 1995. The nature of agricultural systems: food security and environmental balance. Food Policy 20, 439-454.

Ceesay, M. 1997. The national rice policy review: Working towards an increased food security. National Agricultural Research Institute (NARI), Brikama, The Gambia.

Chang, T.T., G.C. Loresto, J.C. O'Toole, J.L. Armenta-Soto. 1982. Strategy and methodology of breeding rice for drought-prone areas. p. 217-244. In: IRRI (ed) Drought resistance in crops with emphasis on rice. IRRI Publication, Manila, Philippines.

Chapin, F.S. III. 1991. Integrated responses of plants to stress: A centralized system of physiological responses. Bioscience J. 4(1):29-36.

Chevalier, P and L.E. Schrader. 1977. Genotypic differences in nitrate absorption and partioning of N among plant parts in maize. Crop Sci. 17:897-901.

Cicerone, R.J., J.D. Shetter, and C.C. Delwiche. 1983. Seasonal variation of methane flux from a California rice paddy. Journal of Geophysic Research. 88:7203-7209.

Conrad, R. 1989. Control of methane production in terrestial ecosystems, *In*: Andreae M.O. and Schimel D.S. (eds) Exchange of trace gases between terrestial ecosystems and the atmosphere, pp 39-58. John Wiley & Sons Ltd., Chichester, U.K.

Consultative Group on Agricultural Research (CGIAR). 1989. Sustainable agricultural production: Report of the CGIAR committee. CGIAR Document no. MT/89/14.

Cornell International Institute for Food, Agriculture and Development. Annual Report, 2000-2001. CIIFAD, Cornell University Ithaca, NY.

Cox, M.C., C.O. Qualset, and D.W. Rains. 1985. Genetic variation for nitrogen assimilation and translocation in wheat. Crop Sci. 25:430-435.

Das, K.A., Boral, L., Tripathi, R.S. and Pandey H.N. 1997. Nitrogen mineralization and microbial biomass-N in a subtropical humid forest of Meghalaya, India. Soil Biology & Biochemistry. 29:1609-1612.

De Boer, J. 1993. Building sustainable agricultural systems: economic and policy dimensions. Winrock International inst. for Ag. Dev. Studies Paper Series. Arkansas.

De Datta S.K., and F.E. Broadbent. 1988. Methodology for evaluating nitrogen utilization efficiency by rice genotypes. Agron. J. 80:793-798.

Dingkuhn, M., Cruz, T.R., O'Toole, J.C., Dorffling, K. 1989. Net photosynthesis, water use efficiency, leaf water potential and leaf rolling as affected by water deficit in tropical upland rice. Aus. J. Agric. Res. 40:1171-1181.

Dobermann, A., and T.H. Fairhurst. 2002. Rice straw management. Better Crops International. Vol. 16.

Drew, M.C. 1990. Root function, development, growth and mineral nutrition. p.35-57. In: J.M. Lynch (ed.) The rhizosphere. Wiley Series in ecological and applied microbiology. J. Wiley, Interscience, NY.

Dubey, S.K., and J.S. Singh. 2001. Plant-induced spatial variations in the size of methanotrophic population in dryland and flooded rice ecosystems. Nutrient Cycling in Agroecosystems. 59:161-167.

Dunsmore, J.R., A.B. Rains, G.D.N. Lowe, D.J. Mofatt, I.P. Anderson, and J.B. Williams. 1976. The agricultural development of the Gambia: An agricultural, environmental, and socioeconomic analysis. Land Resources Study 22. Land Resources Development Center, Ministry of Overseas Development, Surrey, England.

Eghball, B., and J.W. Maranville. 1991. Interactive effects of water and nitrogen stresses on nitrogen utilization efficiency, leaf water status and yield of corn genotypes. Commun. Soil Sci. Plant Anal. 22:1367-1382.

Ekanayake, I.J., D.P. Garrity, and J.C. O'Toole. 1986. Influence of deep root density on root pulling resistance in rice. Crop Sci. J. 26:1181-1186.

Elliot, E.T. 1986. Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Science Society of America J. 50:627-633.

Erlandsson, G. 1979. Efflux of potassium from wheat roots induce by changes in the water potential of the root medium. Plant Physiology. 47: 1-6.

Evans, L.T. 1993. Crop evolution, adaptation and yield. Cambridge Univ. Press, Cambridge. 500pp.

Evans, L.T., R.M. Visperas, B.S. Vergara. 1984. Morphological and physiological changes among rice varieties used in the Philippines over the last seventy years. Field Crops Res. 8:105-125.

Food and Agriculture Organization. 2002. The state of food insecurity in the world. Published by the Food and Agriculture Organization (FAO) of the United Nations Viale delle Terme di Caracalla, 00100 Rome, Italy.

Fukai, S. 1999. Phenology in rainfed lowland rice. Field Crop Res. 64:51-60.

Fukai, S. and M. Cooper. 1995. Development of drought-resistant cultivars using physio-morphological traits in rice. Field Crops Res. 40:67-86.

Garrity, D.P. 1982. A rainfed lowland yield nursery for drought-prone areas: testing genetic materials for unfavorable shallow rainfed rice environments. Philippines Crop Sci. J. 7(1):37-43.

Garrity, D.P. 1984. Asian upland rice environments: An overview of upland rice research. P.161-183. In Proceedings of the 1982 Bouake, Ivory Coast Upland Rice Workshop. IRRI Publication, Manila, Philippines.

Gijsman, A.J., Oberson, A., Friesen, D.K., Sanz, J.I. and Thomas, R.J. 1997. Nutrient cycling through microbial biomass under rice-pasture rotations replacing native savanna. Soil Biology & Biochemistry. 29:1433-1441.

Gladwin, C.H., A.M. Thomsom, J.S. Peterson and A.S. Anderson. 2001. Addressing food security in Africa via multiple livelihood strategies of women farmers. Food Policy J. 26(2):177-207.

Goh, K.M., and R.J. Haynes. 1986. *In*: T.T. Kozlowski (ed) Mineral nitrogen in the plant-soil system. p.379-442. Physiological ecology series. Academic Press Inc. NY.

Graham, R.D., and R.M. Welch, 1996. Breeding for stable crops with high micronutrient density. Working papers on agricultural strategies for micronutrients No. 3. International Food Policy Research Institute, Washington DC, p.79.

Greenland, D.J. 1997. The sustainability of rice farming. CAB Int., NY.

Greenway, H. and B. Klepper. 1969. Relation between anion transport and water flow in tomato plants. Physiology of Plants J. 22:208-219.

Gregory, P.J. 1989. The role of root characteristics in moderating the effects of drought. P. 141-150. In F.W.G. Baker (ed.) Drought resistance in Cereals. CAB Int., NY.

Guerra L.C., S.I. Bhuiyan, T.P. Tuong, and R. Barker. 1998. Producing more rice with less water from irrigated systems. IRRI, System-Wide Initiative on Water Management. Manila, Philippines.

Gutierrez, J.R., and W.G. Whitford. 1987. Chihuahuan desert annuals: importance of water and nitrogen. Ecology J. 68(6):2032-2045.

Hassink, J., Lebbink, G. and Van Veen, J.A. 1991. Microbial biomass and activity of a reclaimed-polder Soil under a Conventional or a Reduced-Input Farming System. Soil Biology & Biochemistry. 23:207-513.

Hoogerbrugge, I.D., and L.O. Fresco. 1993. Homegarden systems: agricultural characteristics and challenges. International Institute for environment and development Gatekeeper series. No. SA39.

Hubbell, D.H. 1995. Extension of symbiotic biological nitrogen fixation technology in developing countries. Fert. Res. 42:231-239.

Ichwantori et al., Growth response of rice (Oryza Sativa L.) Japanese Journal of Crop Science, 58(4):740-747.

Ingram, K.T., F.D. Bueno, O.S. Namuco, E.B. Yambao, C.A. Beyrouty. 1994. Rice root traits for drought resistance and their genetic variation. p. 67-77. *In*: G.J.D. Kirk (ed.) Rice Roots: Nutrient and water use. Selected paper from the Internationaln Rice Research Conference. IRRI Publication, Manila, Philippines.

Inthapan, P., Fukai, S. 1988. Growth and yield of rice cultivars under sprinkler

irrigation in South-Eastern Queensland. 2. Comparison with maize and grain sorghum under wet and dry conditions. Aust. J. Exp. Agric. 28:243-248.

Inthapanya, P. Sipaseuth, P. Sihavong, V. Sihathep, M. Chanphengsay, S. Fukai, and J. Basnayake. 2000. Genotype differences in nutrient uptake and utilisation for grain yield production of rainfed lowland rice under fertilised and non-fertilized conditions. Field Crops Research. 65:57-68.

Inubushi, K., and H. Wada. 1987. Easily decomposable organic matter in paddy soils: VII. Effect of various pretreatments on N mineralization in submerged soils. Soil Science & Plant Nutrition. Tokyo 33:567-576.

IRRI Standard evaluation system. 1996. IRRI Publication, Manila, Philippines.

Kaimowitz, D. and, A. Angelsen. 1998. Economic model of tropical deforestation. A review. CIFOR. Bogor, Indonesia.

Kanampiu, F.K., W.R. Raun, and G.V. Johnson. 1997. Effect of nitrogen rate on plant nitrogen loss in winter wheat varieties. J. Plant Nutr. 20:389-404.

Karrou, M., and J.W. Maranville. 1993. Seedling vigor and nitrogen fertilizer nitrogen deficiencies in winter wheat. Commun. Soil Sci. Plant Anal. 24:1153–1163.

Kropff, M.J., K.G. Cassman, S. Peng, R.B. Matthews, and T.L. Setter. 1994. Quantitative understanding of yield potential. p. 21-38. In: K.G. Cassman (ed.) Breaking the yield barrier. IRRI, Los Banos, Philippines

Jongdee, B., S. Fukai, and M. Cooper. 1997. Genotypic variation for water relations and growth during the vegetative stage among six rice lines contrasting in maintenance of high leaf water potential. p.180-191. In Proceeding of an International Workshop held at Ubon Ratchathani, Thailand, 5-8 November 1996. ACIAR Proceedings No. 77.

Kaimowitz, D. and, A. Angelsen. 1998. Economic model of tropical deforestation. A review. CIFOR. Bogor, Indonesia.

Legg,J.P. 1999. Emergence, spread and strategies for controlling the pandemic of cassava mosaic virus disease in East and Central Africa. Crop Protection. Oxford, U.K. Elsevier Science Ltd. 18(10):627-637.

Lilley, J.M., Fukai, S. 1994. Effect of timing and severity of water deficit on four diverse rice cultivars. II. Physiological response to soil water deficit. Field Crops Res. 37:225-234.

Lindau, C.W., W.H. Patrick Jr, and R.D. DeLaune. 1993. Factors affecting methane production in flooded rice soils. In: Harper L.A., Duxbury, J.M., and D.E. Rolston (eds) Agricultural ecosystem effects on trace gases and global climate change. ASA Special Publication, No. 50, pp157-165.

Loomis, R.S., and D.J. Connor. 1992. Crop ecology: productivity and management in agricultural systems. Cambridge Univ. Press, Cambridge, 538pp.

Maire, N., Besson, J.M., Sutter, H., Hasinger, G., and Palasthy, A. 1990. Influence of cultural practices on the equilibrium of physico-chemistry and biology of agricultural soils. Swiss Agricultural Research (Schweizerische Landwirtschaftliche Forschung. 29:61-74.

Maranville, J.W., R.B. Clark, W.M. Ross. 1980. Nitrogen efficiency in grain sorghum. Plant Nut. J. 2(5):577-589.

Marong, A. et al. 2001. Towards self-sufficiency: strategies for enhancing sustainable rice development. Dept of State for Agric. The Gambia.

Marumoto, T., H. Akai, T. Yoshida, and T. Harada. 1977. Drying effect on mineralization of microbial cells and their cell walls in soil and contribution of microbial cell walls as a source of decomposable soil organic matter due to drying. Soil Science & Plant Nutrition. Tokyo. 23:9-19.

Matlon, P., Randolph, T.F., Guei, R., 1996. Impact of rice research in West Africa. International conference on the impact of rice research, Bangkok, Thailand, 3-5 June 1996. WARDA, Bouake, Cote d'Ivoire, 28pp.

Min H., Y.H. Zhao, M.C. Chen, and Y. Zhao. 1997. Methanogens in paddy rice soil. Nutrient Cycling in Agroecosystems. 49:163-169.

Minami, K. 1997. Atmospheric methane and nitrous oxide: Sources, sinks and strategies for reducing agricultural emissions. Kluwer Academic Publishers. Nutrient Cycling in Agroecosystems. 49:203-211.

Misra, G.N. 1994. Nitrogen management in upland rice. Indian Farming Journal. 43(10):5-7.

Mitchell, J.H. et al. 1998. The use of Seedling leaf death score for evaluation of drought resistant of rice. Field Crops Res. 55:129-139.

National Agricultural Sample Survey. 1995. Statistical yearbook of Gambian agriculture. Dept. Of Planning, State Dept. for Agriculture, Banjul, The Gambia.

Neue, H.V. and Lantin K.S. 1994. Micronutrient toxicities and deficincies in rice. In: Xeo A.R. and Flowers, T.J. (eds) Monographic Theories of Applied Genetics. 21:175-200.

Nguyen, H.T., J.D. Ray, Long-Xi Yu. 1994. Nutrient and water use. *In*: G.J.D. Kirk (ed.) Rice roots: Selected papers from the International Rice Research Conferences. p.79-86. IRRI Publication, Manila, Philippines.

Novoa, R., and R.S. Loomis. 1981. Nitrogen and plant production. Plant Soil. 58:177-204.

Nye, P.H., and P.B. Tinker. 1977. Solute movement in the soil-root system. Studies in ecology series. Vol.4. Blackwell scientific publications. Oxford, England.

Oldeman L.R. and T. Woodhead. 1986. Physical aspects of upland rice environments. p.3-10. In: IRRI (ed) Progress in Upland Rice Research,Proceeding of the 1985 Jakarta conference. IRRI publication, Manila, Philippines.

Osmond, D.L., T.J. Smyth, R.S. Yost, D. L. Hoag, W.S. Reid, W. Branch, X. Wang and H. Li. 2002. Nutrient Management Support System (NuMaSS), v. 2.0. Soil Management Collaborative Research Support System, North Carolina State University, Raleigh, NC.

Otoo, E., R. Ishii, and A. Kumura. 1989. Interaction of nitrogen supply and soil water stress on photosynthesis and transpiration in rice. Japan J. of Crop Sci. 58(3):424-429.

O'Toole, J.C. 1981. Seedling stage drought response in rice. IRRI publication, Manila, Philippines.

O,Toole, J.C., Chang, T.T. 1979. Drought resistance in cereals - rice: A case study. p. 374-405. In: Mussel, H. and R.C. Staples (eds.) Stress physiology of crop plants. Wiley-Interscience, New York.

Pantuwan, G., Fukai, S., Cooper, M., O'Toole, and J.C., Sarkarung, S. 1997.

Root traits to increase drought resistance in rainfed lowland rice in drought-prone environments, Proceedings of an International Workshop, Ubon Ratchatani, Thailand, 5-8 November 1996. ACIAR, Canberra, pp. 170-179.

Parr, J.F. 1973. Chemical and biological considerations for maximizing the efficiency of fertilizer nitrogen. J. of Environ. Qual. 2:75-84.

Peng, S. and K.G. Cassman. 1998. Upper thresholds of nitrogen uptake rates associated nitrogen fertilizer efficiencies in irrigated rice. Agronomy J.

Penning de Vries, F.W.T., and R. Rabbinge. 1995. Model in research and education, planning and practice. P. 1-18. In: A.J. Haverkort and D.K.L. MacKerron (eds.) Potato ecology and modelling of crops under conditions limiting growth. Current Issues in Production Ecology, Vol.3. Kluwer, Dordrecht.

Peters, J.B., and E.E. Schulte. 1996. Using plant analysis to guide research and extension programs in The Gambia. Commun. Soil Sci. Plant Anal., 27(5-8):1311-1329.

Pillai, K.G. Rice. 1992. *In*: A. Finck (ed.) World Fertilizer Use Manual. Institute for Plant Nutrition and Soil. Christian-Albrechts University, Kiel, Germany. http://WWW.fertilizer.org/ifa/publicat/html/pubman/rice.htm

Ponnamperuma, F.N. 1984. Straw as source of nutrients for wetland rice. Organic matter and rice. IRRI publication, Manila, Philipines.

Prasertsak, A., and S. Fukai. 1997. Nitrogen availability and water-stress interaction on rice growth and yield. Field Crops Res. 52:249-260.

Pretty, J.N., J. Thompson, and F. Hinchcliffe. 1997. Sustainable agriculture: Impacts on food production and challenges for food security. International Institute for Environment and Development Gatekeeper series No. SA60.

Rice Intensification. Sanya, China. April 1-4, 2002. CIIFAD publication. Ithaca, NY.

Rafey, A., P.A. Khan, and V.C. Srivastava. 1989. Effect of N on growth, yield and nutrient uptake of upland rice. Indian J. Agron. 34(1):133-135.

Raun, W.R. et al. 2002. Improving Nitrogen Use Efficiency in Cereal Grain Production with Optical Sensing and Variable Rate Application. Agronomy Journal. 94:815-820.

Reddy, K.R. and W.H. Patrick,Jr. 1980. Uptake of fertilizer nitrogen and soil nitrogen by rice using ^{15}N-labelled nitrogen fertilizer. Plant and Soil. Vol.57, No. 2/3.

Runge, M. 1983. Physiology and ecology of nitrogen nutrition. In: O.L. Lange, P.S. Noble, C.B. Osmond, H. Ziegler (eds.) Physiological Plant Ecology III. Responses to the chemical and biological environment. 12C. pp163-200. Springer, Berlin, Germany.

Saikia, M. and S.P. Palniappan. 1994. Nitrogen management in direct seeded upland rice-A review. Agric. Rev., 15(2):78-86.

Saleh, A.F.M. 1995. Crop and rain water management strategies for increasing productivity of rainfed lowland rice systems. Agricultural systems. 49:259-276.

Sanchez, P.A. 2002. Soil fertility and hunger in Africa. Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA 94720. www.sciencemag.org. Science 295:2019-2020.

Sanchez, P.A., R. J. Buresh, and R. R. B. Leakey. 1998. Trees, soils, and food security. In: R. J. Buresh et al., (Eds.) Replenishing soil fertility in Africa. Spec. Publ. No. 51, SSSA, Madison, WI.

Sass, R.L., F.M. Fisher, Y.B. Wang, F.T. Turner, and M.F. Jund. 1992. Methane emission from rice fields: The effect of floodwater management. Global Biogeochem Cycles. 6:249-262.

Savithri, p., R. Perumal and R. Nagarajan. 1999. Soil and Crop Management Technoloies for Enhancing Rice Production under Micronutrient Constraints. Nutrient Cycling in Agroecosystems. 53:83-93.

Schneiders, M., Scherer, H.W. 1998. Fixation and release of ammonium in flooded rice soils as affected by redox potential. European J. of Agronomy. 8:181-189.

Seneviratne R., and A. Wild. 1985. Effect of mild drying on the mineralization of soil nitrogen. Plant Soil. 84:175-179.

Sharma, P.K., G. Pantuwan, K.T. Ingram, S.K. De Datta. 1994. Rainfed lowland rice roots: soil and hydrological effect. *In*: G.J.D. Kirk (ed.) Rice Roots: nutrient and water use. p.55-66. IRRI, Manila, Philippines.

Sinha, N.P and B. Prasad. 1980. Influence of different fertilizers nett gain or loss of soil nitrogen in long-term manure and fertilizer applications. Plant and soil journal, vol.57. N0.2/3.

Slafer, G.A., D.F. Calderini, and D.J. Miralles. 1996. Generation of yield components and compensation in wheat: opportunities for further increasing yield potential. *In*: M.P. Reynolds, S. Rajaram, A. McNab (ed.). Increasing yield potential in wheat: breaking the barriers. p.110-133. International Maize and Wheat Improvement Center, Mexico.

Smith J.L. 1993. Cycling of Nitrogen through microbial activity. *In*: J.I. Hatfield and B.A. Stewart (eds)Soil Biology: Effects on Soil Quality. p.91-120, Advances in Soil Science. CRC Press. Boca Raton, FL.

Smith,L.C. and L.J. Haddad. 1999. Explaining child malnutrition in developing countries: A cross-country analysis. *In*: Research report, International Food Policy Research Institute 111. Washington, DC : International Food Policy Research Institute, xiii, 112 p.

Soulides, D.A., and F.E. Allison. 1961. Effect of drying and freezing of soils on carbon dioxide production, available mineral nutrients, aggregation, and bacterial population. Soil Science. 91:291-298.

Special panel on impact assessment, contributions made bythe CGIAR and its partners to agricultural development in Sub-Saharan Africa. 2001. CGIAR, Washington, DC.

Sta Cruz, P.C., and G. Wada. 1994. Genetic variation in nitrogen uptake by rice and the effects of management and fertility. P.29-40. *In*: G.J.D. Kirk (ed.) Rice roots: nutrient and water use. IRRI publication, Manila, Philipines.

Stoop, W.A., N. Uphoff, and A. Kassam. 2003. A review of agricultural research issues raised by the system of rice intensification (SRI) from Madagascar: opportunities for improving farming systems for resource-poor farmers. Agricultural systems. 71:249-274.

Tanaka, A., S.A.Navasero, C.V. Garciaq, F.T. Parao, E. Ramirez. 1964. Growth habit of the rice plant in the tropics and its effect on nitrogen response. IRRI Technical bulletin 3. IRRI publication, Manila, Philipines.

Tanaka, A., J. Yamaguchi, S. Miura, and H. Tamaru. 1984. Comparison of fertilizer nitrogen efficiency among field crops. Soil Sci. Plant Nutr., 30(2):199-208.

Tandon, H.L.S. 1974. Fertilizer News, 19(8):24.

The Potash Corporation Letter. Sept. 1995. Saskatchewan Inc.

Uphoff, N. 1999. Agroecological implications of the system of rice intensification (SRI) in Madagasgar. Environment, Development and Sustainability. 1:297-313.

Uphoff, N. 2002. The system of rice intensification developed in Madagascar. A presentation for conference on raising agricultural productivity in the tropics: Biophysical challenges for technology and policy, Harvard University, Oct. 16-17. 8pp.

Viets, F. 1972. Water deficits and nutrient availability. Academic Press, NY.

Vlek, P.L.G., Craswell, E.T., 1979. Effect of nitrogen source and management on ammonia volatilization losses from flooded rice soil systems. Soil Science Society of America J. 43:352-358.

Vose, P.B., 1990. Screening Techniques for plant nutrient efficiency. Philosophy and methods. In: El Bassam, N. et al. (Eds) Genetic Aspects of Plant Mineral Nutrition. Kluwer Academic Publishers, Dordrecht, pp. 283-289.

Wada, G., D.V. Aragones, R.C. Aragones. 1989. Nitrogen absorption pattern of rice plants in the tropics. Japanese Journal of Crop Science. 58(2):225-231.

Wailes, E.J., G.L. Cramer, E.C. Chavez, and J.M. Hansen. 1997. Arkansas global rice model: International baseline projections for 1997–2010. Arkansas Agric. Exp. Stn. Special Report 177.

WARDA annual report. 1993. West African Rice Development Association. M'be, Cote D'Ivoire.

WARDA annual report. 1996. West African Rice Development Association. M'be, Cote D'Ivoire.

Wopereis, M.C.S., Donovan, C., Nebie, B., Guindo, and N'Diaye, M.K. 1999. Field Crop Science. 61:125-145.

World Bank. 2002. World development indicators CD-ROM.

Yagi, K., K. Minami, and Y. Ogawa. 1990. Effects of water percolation on methane from paddy fields. NIAES Research Report Division of Environment and Planning6:105-112.

Yamagata, M. and A.E. Noriharu. 1999. Direct acquisition of organic nitrogen by crops. Jpn. Agric. Res. Quarterly. 33:15-21.

Yamauchi, M. 1994. Physiological bases of higher potential in F1 hybrids. p.71-80. In: S.S. Virmani (ed). Hybrid rice technology: New development and future prospects. IRRI, Los Banos, Philippines.

Yamboa, E.B. and J.C. O'Toole. 1984. Effects of nitrogen nutrition and root medium water potential on growth, nitrogen uptake and osmotic adjustment of rice. Physiology of Plant. 60:507-515.

Ying, J. et al. 1998. Comparison of high-yield rice in tropical and subtropical environments. I. Determinants of grain and dry matter yields. Field Crops Research. 57:71-84.

Ying, J. et al. 1998. Comparison of high-yield rice in tropical and subtropical environments. II. Nitrogen accumulation and utilization efficiency. Field Crops Research. 57:85-93.

Yoshida, S. 1975. Factors that limit the growth and yields of upland rice. p.46-71. In: International Rice Research Institute, 1975. Major research in upland rice. IRRI publication, Manila, Philippines.

Yoshida, S. 1981. Fundamentals of rice crop science. IRRI, Los Banos, Philippines, 269pp.

Yoshida, S. 1983. Rice. p.103-127. In: W.H. Smith, and S.J. Banta (eds.) Potential productivity of field crops under different environments. IRRI, Los Banos, Philippines.

Yoshida, S., and S. Hagegawa. 1982. The rice root system: its development and function. p. 97-114. In International Rice Research Institute, 1982. Drought resistance in crops with emphasis on rice. IRRI publication, Manila, Philippines.

http://www.worldbank.org/data/wdi2002/environment.pdf. March 12, 2003.

http://www.cgiar.org/areas/rice.htm April 14, 2003.