Sawah ecotechnology – a trigger for a rice green revolution in Sub-Saharan Africa

Basic concept and policy implications

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Abstract: *The green revolution has yet to be realized in Sub-Saharan Africa (SSA) even 40 years after its success in tropical Asia, suggesting that there was a missing element in the basic principles underlying the Asian green revolution when they were transferred to SSA. The authors argue that this missing element is 'ecotechnology'. Ecotechnology improves the crop growing environment in farmers' fields and enables them to accommodate basic green revolution technologies such as modern varieties, chemical fertilizers and irrigation facilities. The authors focus on sawah ecotechnology, a sustainable rice production technology. The term 'sawah' refers to a levelled, bunded and puddled rice field under controlled submergence, and 'sawah ecotechnology' indicates the technology for designing, developing and managing the sawah system. The sawah system development potential is at least 20 million ha in the West Africa (WA) subregion only. Realizing this potential, WA can sustainably produce food for more than 300 million people, as well as enabling the conservation and restoration of hundreds of millions of hectares of upland forests, contributing to carbon sequestration and global warming mitigation in the future.*

Keywords: *ecotechnology; inland valley; rice farming; green revolution; sawah; Sub-Saharan Africa*

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Sub-Saharan Africa (SSA) is the only remaining region of the world where per capita food production has remained stagnant over the past 40 years (Sanchez, 2002), the prevalence of hunger is over 30% and the number of malnourished people is still increasing (Sanchez and Swaminathan, 2005). In this area, absolute poverty, characterized by an income of less than US$1 per person per day, is associated with an increasingly damaged natural resource base (Sanchez, 2002). This long-lasting trend of stagnation in the agricultural sector in SSA displays a contrasting picture to that in tropical Asia and Latin America, which have benefited from the green revolution. Many economic successes reported in the latter regions provide strong evidence that agricultural productivity growth is vital for stimulating growth in other parts of the economy, and accelerated growth requires a sharp productivity increase in smallholder farming by subsistence farmers in remote areas (World Bank, 2007). There has been little yield increase of most mandated crops in SSA over the past four decades (Hirose and Wakatsuki, 2002; Otsuka and Kalirajan, 2005). For instance, rice is increasingly eaten in SSA, but the rice (paddy) yield has remained stagnant at between 1.2 and 1.5 t ha^{-1} in SSA, while attaining a remarkable increase from 1.8 t ha^{-1} to 4.0 t ha^{-1} in Asia during 1960–2000 (WARDA, 1988, 2004; Otsuka and Kalirajan, 2006). Agricultural productivity in SSA is too low, regardless of its potential, even though natural resource availability (for example, soil fertility and water) is inherently less in SSA than in tropical Asia (Moormann and Veldkamp, 1978; Hirose and Wakatsuki, 2002). It is obvious that the African green revolution is not only far from successful, but that there is no promising roadmap for achieving the green revolution in SSA.

It is widely known that the essential components of green revolution technologies are (1) modern varieties (MVs), (2) chemical fertilizers, and (3) irrigation equipment (Quiñones *et al*, 1997; Evenson and Gollin, 2003; Otsuka and Kalirajan, 2005, 2006). Although institutional and economic aspects such as demographic pressure, market access and labour availability are also important (Otsuka, 2006; World Bank, 2007), these issues are beyond the scope of this paper. After success stories in Asia and Latin America, the same strategy and basic principles of the green revolution have been applied to SSA. National governments have made enormous efforts to introduce, develop and disseminate MVs, to provide subsidies for the import and distribution of fertilizer and to construct large-scale irrigation systems in many countries in SSA.

International organizations and donors of developed countries have not only enthusiastically supported these national programmes, but have themselves conducted a number of relevant projects. However, the impact of these efforts has been considerably less than expected (World Bank, 2007). What is more, the adoption of green revolution technologies has sometimes resulted in adverse events such as waste of natural resources, environmental pollution and biodiversity degradation (Shiva, 1991; Hirose and Wakatsuki, 2002). The authors hypothesized that ecotechnology was the missing piece to the basic principles underlying the Asian green revolution when these principles were transferred to SSA. Ecotechnology is ecologically sound technology that modifies ecosystem functions and the environment and can improve agricultural fields on a sustainable basis. In this paper, we focus on *sawah* ecotechnology as the most promising technology for realizing the rice green revolution in SSA.

The term *sawah* indicates a man-made intensified rice field with levelling, bunding and puddling (Wakatsuki *et al*, 1998). The *sawah* system is a highly productive and sustainable rice production system that prevails in monsoon Asia (Kyuma and Wakatsuki, 1995).

Rice production trends in Sub-Saharan Africa

West Africa (WA) is the most important region in SSA in terms of rice production (share: 63%) and consumption (share: 67%), followed by East Africa (production share: 32%; consumption share: 21%) and Central and South Africa (production share: 5%; consumption share: 12%) (WARDA, 2008). Annual paddy production in West Africa dramatically increased from 3.4 to 7.7 million tons in the period 1984–1999/2003 (Table 1). This production increase was due mainly to rainfed lowland rice ecology, which expanded considerably from 0.53 to 1.8 million ha during this period and showed a yield increase from 1.4 to 2.0 t ha^{-1}.

The derived paddy production augmented from 0.75 to 3.4 million tons during the given period. Irrigated lowland rice ecology was the second major contributor to regional rice production, with 1.9 million tons being produced, an increase from 0.64 million tons with the area expansion from 0.23 to 0.56 million ha, and a yield increase from 2.8 to 3.4 t ha^{-1}. Upland rice ecology exhibited only a slight increase from 1.5 to 1.8 million tons and from 1.5 to 1.8 million ha for annual rice production and the cultivated area respectively. There was practically no yield growth in this ecology in the same period. Rice yield stagnation as a whole indicates that the rice production increase achieved by SSA during 1960–2000 predominantly arose from expansion of the rice cultivation area (JICA, 2003).

Rice was predominantly produced in (rainfed) upland ecology in WA 20 years ago, while its contribution to the production and cultivation area had sharply decreased by 2000 (Table 1). Upland cropping systems, which are mostly characterized by slash-and-burn agricultural practices, is increasingly facing such threats as (i) soil degradation under shortened fallow periods, exploitation of other food crops due to the ever-increasing human population (Sakurai, 2006), (ii) agronomically and economically fragile upland farming systems due to soil degradation and water resource scarcity (for example, unstable rainfall and groundwater depletion) (Hirose and Wakatsuki, 2002) and (iii) widespread distribution of unexploited lowlands over SSA and better potential for rice cultivation due to higher water availability than in the surrounding uplands (Windmeijer and Andriesse, 1993). In fact, over the past 20 years, the authors have witnessed voluntary efforts made by farmers to become self-supporting through land reclamation and water control improvement by field bunding as well as canal construction in inland valleys in WA, even though the farmers were provided with little assistance from national programmes and international projects (Baba, 1993; Fu *et al*, 2010). This is in good agreement with the macro data, which show a steady increase in the contribution of the lowland ecology (WARDA, 2008).

Ecotechnology supports green revolution technology transfer

Genetic improvement

Genetic improvement is a core technology of the green revolution (Evenson and Gollin, 2003; Otsuka and Kalirajan, 2005, 2006). The first generation of MVs had dwarfing genes and a good response to fertilizers, while the second generation targeted genes displaying tolerance against local constraints such as salinity, drought, disease and pests (Otsuka and Kalirajan, 2005, 2006). Most MVs

Table 1. Rice production trends in West Africa, 1984–1999/2003.

Rice ecology	Area (million ha)		Production (million tons)		Yield (ton h^{-1})	
	1984	1999/2003	1984	1999/2003	1984	1999/2003
Rainfed upland	1.5	1.8	1.5	1.8	1.0	1.0
Growth rate	–	1.2	–	1.2	–	1.0
Contribution (%)	57	40	42	23	–	–
Rainfed lowland	0.5	1.8	0.8	3.4	1.4	2.0
Growth rate	–	3.6	–	4.3	–	1.4
Contribution (%)	20	38	22	44	–	–
Irrigated lowland	0.2	0.6	0.6	1.9	2.8	3.4
Growth rate	–	3.0	–	3.2	–	1.2
Contribution (%)	9	12	19	25	–	–
Total rice ecology	2.6	4.7	3.4	7.7	1.3	1.6
Growth rate	–	1.8	–	2.3	–	1.2

Source: WARDA (1988); FAOSTAT (2005).

were fertilizer-responsive and their growth was optimized by irrigation equipment.

African farmers began introducing rice MVs in the 1960s (Otsuka and Kalirajan, 2006). The MV adoption rate, however, is still lower in SSA than in Asia (Evenson and Gollin, 2003). The lack of functionality of national agricultural research and extension services in SSA is often blamed for this (Otsuka and Kalirajan, 2005, 2006; Balasubramanian *et al*, 2007). However, with regard to rice production in WA, the impact of genetic improvement has occurred disproportionately over rice ecologies: high MV adoption rates in irrigated wetlands (close to 100%) and the rainfed lowlands (about 62%), but low MV adoption rates in the upland ecology (less than 30% in most countries) (Dalton and Guei, 2003). In addition, most MVs that were adopted in farmers' fields had poorer performance than expected (Hirose and Wakatsuki, 2002; Becker *et al*, 2003). Many farmers in SSA have perceived that MVs perform well only in a favourable growing environment with fertilizer application, whereas local (farmers') varieties often show better growth than MVs under unfavourable conditions without fertilizers.

Fertilizer use

African farmers often apply fertilizer to cash crops only, and the application rate is usually low. In fact, the average intensity of fertilizer use in SSA has been less than 10 kilograms per hectare of cultivated land over the past 40 years; this application rate is much lower than in other developing regions (Quiñones *et al*, 1997; JICA, 2003; Morris *et al*, 2007; World Bank, 2007). Farmers in SSA are generally reluctant to use fertilizer because they often suffer from shortages of initial investment and little economic benefit from using it. African farmers have to pay higher prices for fertilizers – relative to the price they receive for their output – than their Asian counterparts because of low subsidies and high costs of transportation (Otsuka and Kalirajan, 2005, 2006; Morris *et al*, 2007). Another problem is the very low agronomic fertilizer use efficiency in farmers' fields, due to poor field management under the diverse rice farming systems and growing environments in SSA (Hirose and Wakatsuki, 2002). The low fertilizer use efficiency also implies that environmental pollution, as well as economic loss and resource waste, is occurring. Eco-environmental (biophysical) improvement of rice fields would be essential to enhancing both economic and agronomic fertilizer use efficiency.

Irrigation equipment

A number of large-scale irrigation facilities have been constructed over the last 40 years, but most were poorly managed and their potential economic benefits were often unable to outweigh the real economic costs (Adams, 1993). Currently, some irrigation schemes have completely collapsed due mainly to lack of proper maintenance, and many others are functioning far below full capacity. In fact, most irrigation facilities are constructed and managed by governments and/or communities, while the water control at each irrigated field is the responsibility of individual farmers. This has lowered the irrigation capacity on a regional scale and reduced its efficiency even further because water use efficiency is often very low in farmers' fields due to inappropriate land preparation and poor field management. On the other hand, traditional small-scale irrigation systems developed by farmers to support themselves are of growing economic significance in some regions (for example, Baba, 1993; Fu *et al*, 2010).

Biotechnology and ecotechnology

The failure of the green revolution technology transfer in SSA for the reasons described above shares a commonality: the transferred technologies have failed due to unfavourable conditions in farmers' fields. In tropical Asia, however, rice farmers ecotechnologically developed their farms to be favourable for rice cultivation when green revolution technologies were first introduced in the 1960s. In contrast, the rice fields of the major farmers in SSA have been poorly developed for rice growing and for green revolution technologies. In fact, eco environmental (biophysical) improvement of the crop growing environment is often superior to crop genetic improvement in SSA (Table 2). It is therefore necessary for African farmers to improve the crop growing environment in their own fields before applying the green revolution technologies. Ecotechnology can help African farmers improve their farms and enable them to become prepared

Table 2. Fertilization and eco-environmental impact on grain productivity of 23 rice varieties, including *Oryza glaberrima* Stud. and traditional and improved *O. sativa* L.

Fertilization level	**Irrigated *sawah***		**Rainfed *sawah***		**Traditional (upland-like)[b]**	
	High-input	*Low-input*	*High-input*	*Low-input*	*High-input*	*Low-input*
Average	7.2	3.8	3.8	2.0	1.7	0.4
Maximum	8.2	4.4	4.5	2.8	2.3	0.6
Minimum	4.0	2.8	2.8	1.3	0.9	0.3
SD	1.5	0.8	0.8	0.5	0.4	0.1

Notes: [a] Fertilization: high-input, 90–45–45; low-input, 20–0–0. [b] Traditional system is lacking in bunding, levelling and puddling.
Source: Ofori *et al* (2005).

for the green revolution technologies. Hence, ecotechnology transfer is a prerequisite for realizing the green revolution in SSA.

What is *sawah* ecotechnology, and why is it needed?

Sawah ecotechnology is possibly the most promising rice production method because the *sawah* system is already a highly productive and sustainable rice production system (Kyuma and Wakatsuki, 1995; Greenland, 1997). Asian rice farmers were already very familiar with *sawah* ecotechnology and the majority of them had developed a *sawah* system in their fields before green revolution technologies were introduced, and thus the Asian green revolution took place immediately after the introduction of the green revolution technologies (Wakatsuki *et al*, 1998; Wakatsuki and Masunaga, 2005). In contrast, African farmers have not traditionally practised *sawah* rice farming and thus have not been able to accommodate the green revolution technologies effectively and efficiently over the last 40 years. *Sawah* ecotechnology transfer and *sawah* system development are prerequisites for realizing the rice green revolution in SSA.

Terminological confusion: sawah fields or paddy fields?

The authors have been concerned about the lack of appropriate terminology for describing the rice growth environment. Lowland rice fields are generally called 'paddy fields' in English. The term 'paddy' originates from a Malayo-Indonesian term 'padi', which means rice plant. In tropical Asia, the world's largest rice granary, 'paddy field' commonly indicates a bunded, levelled and puddled rice field with controlled and continuous flooding. Although the term 'paddy field' was supposed to be inherently ambiguous, due to the long-established history of wet rice cultivation under a monsoon climate in Asia, the term has come to mean a man-made enhanced wetland system for rice cultivation. On the other hand, in many SSA countries, rice is just one of the mandated food crops and is of less importance than other cereals and root and tuber crops such as maize, sorghum, millet, cassava and yam (JICA, 2003). Moreover, rice is grown in diverse biophysical environments along a toposequence (Andriesse and Fresco, 1991; WARDA, 2004), and thus the words 'paddy field' may signify upland rice fields as well as lowland ones. In fact, there is no consensus about the specific rice growing environment even in the lowland areas because the words given above provide little information on land condition and environment – for example, whether the lowland 'paddy field' has bunds or not and whether it is levelled or not. These terminological uncertainties have been a considerable obstacle to the sharing of ideas and strategies among researchers, policy makers and stakeholders about rice field development. We therefore propose the term '*sawah*', which originates from Malayo-Indonesian, to describe specifically man-made intensified rice fields with levelling, bunding and puddling, in order to avoid any further terminological confusion when describing the rice growing environment. The *sawah* has a levelled and puddled basin surrounded and thus demarcated by bunds. It is often connected with irrigation and drainage facilities including a plot-to-plot irrigation/drainage scheme and is submerged most of the time during the rice growth period. Note that the *sawah* does not represent any special system such as the System for Rice Intensification (SRI), but a common system often regarded as an Asian-type lowland rice field.

Advantages of the sawah system

Bunded and levelled fields are advantageous for water control and harvesting and thus are submerged almost throughout the rice growth period. Controlled submergence reduces weed growth and labour for weeding as well as replenishing various macro- and micronutrients in the soil. Soil phosphorus availability increases while the soil reaction neutralizes because of the reduction process of iron from ferric to ferrous iron under prolonged submergence. These chemical mechanisms of nutrient replenishment encourage not only rice growth, but also the breeding of various microbes such as aquatic algae that commit biological nitrogen fixation through increased photosynthesis. The amount of nitrogen fixed by microbes varies from 20 to 100 kg ha^{-1} $year^{-1}$, and sometimes reaches up to 200 kg ha^{-1} $year^{-1}$, depending on soil and water management and climatic conditions (Kyuma and Wakatsuki, 1995; Greenland, 1997). These natural soil fertility replenishment mechanisms are essential for enhancing the sustainability and productivity of lowland rice farming systems in inherently unfertile soils in WA and SSA (Eswaran *et al*, 1997; Abe *et al*, 2010). Moreover, there are generally few concerns about soil erosion in the lowlands. More importantly, the *sawah* system is even advantageous for collecting eroded sediments from adjacent uplands through enhanced capacity of water harvesting. The essence of the *sawah* system is water control, not only on a field scale but also on a watershed scale (Abe and Wakatsuki, forthcoming). The *sawah* system is the only practical option that allows rice farmers to enjoy optimal water management in their fields. Improved performance of field water management can sustainably increase rice yields (Becker and Johnson, 2001; Ofori *et al*, 2005; Touré *et al*, 2009).

Sawah system development can improve rice productivity in the lowlands to a great extent when applied in combination with improved varieties and fertilizers (Table 2), and a certain amount of improvement can even be expected by bund construction only (one of the *sawah* system components) (Becker and Johnson, 2001; Sakurai, 2006; Touré *et al*, 2009).

Productivity and sustainability of sawah system

As has been demonstrated by many long-term field trials, the *sawah* system is a highly productive and sustainable rice farming method due to its natural nutrient-replenishing mechanisms (Kyuma and Wakatsuki, 1995; Greenland, 1997). Moreover, this is endorsed by the fact that the total *sawah* area of about 100 million ha has fed over two billion people in Asia, the most densely populated area in the world, over hundreds of years. Furthermore, it has been empirically revealed that sustainable rice productivity in the *sawah* system is much higher than in the upland system. Centuries of successful rice cultivation in monsoon Asia demonstrate the invaluable productivity and sustainability of the *sawah* rice production system (Kyuma and Wakatsuki, 1995; Greenland, 1997). Rice yield in the *sawah* system is usually about 2–3 $t\ ha^{-1}$ without any fertilizer application, and this yield is continuously attainable at least for several decades without any fallow period. In contrast, the slash-and-burn upland farming system prevailing in SSA produces only 1–2 $t\ ha^{-1}$ or less rice, but often requires a natural fallow period of 5–10 years after 2 or 3 harvests. This implies that sustainable productivity of the *sawah* system is roughly 10–20 times as high as that of the upland slash-and-burn system (Wakatsuki *et al*, 1998). In fact, there have been an increasing number of reports that the slash-and-burn farming system is no longer sustainable under high demographic pressure and cannot meet domestic/regional rice food demand (Hirose and Wakatsuki, 2002; Wakatsuki and Masunaga, 2005). In contrast, the *sawah* system is capable of providing food for a much larger population than the upland cropping system (Kyuma and Wakatsuki, 1995). See Figure 1 for comparative photographs of *sawah* and traditional fields in Ghana. As estimated above, one ha of *sawah* development can conserve or regenerate 10–20 ha of forest, because its sustainable productivity is 10–20 times higher than the upland farming system. *Sawah* ecotechnology can, therefore, contribute not only to food security and poverty reduction, but also to forest conservation and regeneration (Hirose and Wakatsuki, 2002). Forest regeneration in the uplands would further enhance sustainability of the *sawah* system at the bottom of the watershed due to the enhanced geological fertilization processes (Abe and Wakatsuki, forthcoming). This watershed design would be advantageous for alleviating global warming by the fixation of atmospheric carbon in forest trees and *sawah* soils (Abe and Wakatsuki, forthcoming).

Figure 1. Comparative photograph of *sawah* fields (top) and traditional fields (bottom) in Sokwae, Kumasi, Ashanti, Ghana. Mean grain yield during 2008–2009 was 4–5 t/ha and 1–2 t/ha in the upper and lower respectively.

Photos by T. Wakatsuki.

Conclusions and policy implications

The green revolution in Asia and Latin America was triggered by such biotechnological innovations as crop genetic improvement (Evenson and Gollin, 2003; Dalton and Guei, 2003; Otsuka and Kalirajan, 2005, 2006). After the success in these two regions, many SSA countries, donor countries and international organizations have predominantly committed to the development and dissemination of MVs. The green revolution has not occurred in SSA, however, and SSA is still struggling with food shortage. What we have learned in SSA over the past 40 years is that there are substantial limitations to the biotechnological options that can be applied, as indicated by limited performance of MVs in farmers' fields, while ecotechnological improvement of the crop growing environment often results in crop productivity enhancement to a much greater extent than the adoption of biotechnology options. Moreover, ecotechnology helps smallholder farmers adopt biotechnology options. Nevertheless, the current strategies and policies for agricultural development in SSA are still predominantly oriented towards biotechnology. The lessons that have been learned are that both ecotechnology and biotechnology must be addressed in order to establish integrated genetic and natural resource management.

On the other hand, rice production trends clearly show the increased importance of lowland ecologies – whether irrigated or rainfed lowlands – in the face of increased food demand, population expansion and environmental degradation. This is in fact a welcome sign to fill the production-consumption gap of rice grains in WA and SSA. Among major wetland ecosystems, a priority target should be 85 million ha of widely unexploited inland valleys because water control is relatively easier with less investment than in other wetland ecosystems (Windmeijer and Andriesse, 1993; Hirose and Wakatsuki, 2002).

Despite this potential for rice cultivation, only 15–20% of inland valleys are currently reclaimed for agriculture, and rice productivity there is usually low (IITA, 1990; WARDA, 1998; Gumma *et al*, 2009). A major policy issue is how inland valleys can be sustainably and intensively utilized.

Sawah ecotechnology is the key for sustainable enhancement of rice productivity in SSA. The *sawah* ecotechnology spontaneously evolved under the Asian monsoon climate and became a cornerstone of the green revolution in Asia, whereas rice fields in SSA have been largely undeveloped in terms of the *sawah* system, creating a bottleneck in the green revolution technology transfer. An African adaptive *sawah*-based farming system using supplemental small-scale irrigation could be the most promising strategy for sustainably and intensively increasing rice production in SSA. The *sawah* development potential is considerable – as much as 20 million ha in WA alone (Hirose and Wakatsuki, 2002) – which can produce additional food for more than 300 million people while generating the opportunity to conserve or regenerate hundreds of millions of hectares of upland forests as the estimated sustainable productivity of the *sawah* rice farming system is more than 10 times higher than that of an upland (slash-and-burn) rice cultivation system (Hirose and Wakatsuki, 2002). The *sawah*-based rice farming system also has advantages in soil fertility management and water harvesting. Furthermore, accelerated organic matter accumulation in soils under the *sawah* system and in tree biomass and upland forest soils would contribute to carbon sequestration and global warming mitigation in the future.

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