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Toshiyuki Wakatsuki(1), Moro M. Buri(2) and Oladimeji I. Oladele(3)**

Abstract

Even 40 years after the success in tropical Asia and Latin America, the green revolution is yet to be realized in Sub Sahara Africa (SSA). The materialization of rice green revolution is the major target of the millennium development goals of the United Nations. Although the breeding of high yielding varieties (HYV) by biotechnology was the core technology in Asian and Latin American green revolution and which the African Rice Center, WARDA, has innovated in NERICA technologies, the successful path to the green revolution in SSA is still unclear. The paper discussed the Sawah hypothesis (I) and (II). The first Sawah hypothesis (I) explains that the central to the realization of the rice green revolution in SSA is eco-technologies, which can improve farmers rice growing environment, such as lowland sawah eco-technologies. The second Sawah hypothesis (II) explains that sustainable rice productivity of lowland sawah is more than 10times than that of upland rice fields, if appropriate lowlands are selected, developed and managed. Contrary to Asian farmers' fields, the majority of farmers' rice fields in SSA are not ready to accept the three basic components of the green revolution technologies, i.e., (1) irrigation for water supply, (2) fertilizer for soil nutrient supply, and (3) high yielding varieties (HYV). Although researchers have worked seriously on the effect of irrigation, fertilizers and HYV for the last forty years, the researchers have not touched on whether the prerequisite conditions which can accommodate the three basic components of the green revolution are exist or not in SSA. The concept and technologies of Sawah is such an example. The term sawah refers to leveled, bunded, and puddled rice field with water inlet and outlet to control water and manage soil fertility, which may be connecting irrigation and drainage facilities including sawah to sawah irrigation and drainage. The term originates from Malayo-Indonesian. The English and French terms, Paddy or Paddi, also originated from the Malyo- Indonesian term, Padi, which means rice plant. In order to avoid confusion between upland paddy fields and man-made leveled, bunded and puddled rice fields, i.e., typically irrigated rice ecology, which is un-appropriately used as lowland paddy fields, the authors propose to use the term "Sawah" in SSA. Simply speaking the basic infrastructures for the green revolution are

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lacking in the farmers' fields of SSA. Irrigation without farmers' sawah farming technologies has proved inefficient or even damaging because of accelerated erosion and waste of water resources in SSA. In the absence of water control, fertilizers cannot be used efficiently. Consequently, the high yielding varieties perform poorly and soil fertility cannot be sustained, hence the green revolution can not be achieved. The potential of Sawah based rice farming is enormous in SSA, especially in West Africa. Ten to twenty million ha of sawah can produce additional food for more than 300 million people in future. The sawah based rice farming can overcome both low soil fertility and scarce water resources through the enhancement of multi-functionality of sawah type wetlands as well as geological fertilization processes in watersheds. The sawah systems can even enhance the restoration of degraded watershed through the sustainable expansion of afforestation to form a watershed agro-forestry, i.e. the creation of African SATOYAMA systems, which will combat global warming in future. SATO means villagersU habitat and YAMA means multipurpose forest managed by villagers. Both terms are from Japanese. Because of intensive sustainability of lowland sawah systems, the degraded upland fields can be converted to multipurpose forests, which will eventually contribute the global warming.

Introduction

The green revolution has yet taken place in West Africa and Sub Sahara Africa (SSA)(FAOSTAT 2006, Evenson and Gollin 2003). Although food crops are very diverse, per capita total production of major food crops has been stagnating between140-170kg in SSA as seen in Table 1. In tropical Asia, because of the green revolution, the figures increased from 205kg in 1961-1965 more than 280kg in 1996-2000 (Table 1). This is the foundation of high difference of economic growth between SSA and Asia at present. Now Asia is a global center of economic growth thanks to the green revolution that started in 1970s.

Due to high water content (60-70%) of root and tuber crops, such as yam and cassava, the energy per kg is one third of cereals, such as rice, wheat and maize. In addition, the protein and minerals content of yam and cassava are only one fourth to one fourteenth in comparison with cereals. Therefore, the production data of FAO are shown after division by the factor of 8 for cassava and 5 for yam. These factors of 8 or 5 are only tentative, which were used only for reach to the estimation of reasonable cereals' equivalents for comparison in the Table 1 (FAOSTAT 2006, Kiple and Ornelas 2000, Sanchez 1976). Also the following historical observation in Asia adds to the argument. Root and tuber based food had changed to cereals based food, such as rice and wheat. In future, cereals, especially rice, will be more important than now in SSA (FAOSTAT

2006). Although the cereals' equivalents are tentative values, the trend data show the difference of Asia and SSA during 1960-2003. As shown in (Fig. 7) later, mean rice yield has increased from 1.8t/ha to 4.0 t/ha in Asia, but the yield has stagnated between 1.2 to 1.5 t/ha in SSA during 1960 –2005.

As seen in Table 1, West Africa is a core region of SSA in terms of the rice production and importation as well as rice consumption. Therefore the authors discussed mainly West Africa in this strategic paper.

As shown in Table 2, although upland was the major rice ecology 15 years ago, it is no more the largest rice production ecology in West Africa now. If this trend continues, upland rice production ecology will be very small in SSA especially in West Africa in the near future (Table 2: The data were compiled from FAOSTAT 2006, WARDA 1988, 2002, and 2004, JICA 2003). This is however very promising change to realize the green revolution finally in West Africa and SSA. Between 1984 and 1999/2003, annual paddy production increased dramatically from 3.4 to 7.7 million tones in West Africa. Major increases were from the rainfed lowland rice ecology, mainly inland valley, which expanded area from 0.53 to 1.8 million ha and yield increased from 1.4 to 2.0 t/ha. Thus, the annual paddy production increased from 0.75 to 3.4 million tones during the same period. Irrigated lowland was the second contributor. The annual paddy production from irrigated ecologies increased from 0.64 to 1.9 million tones during the same period through the expansion of area from 0.23 to 0.56 million ha and yield increased from 2.8 to 3.4 t/ha. Only very minor contributions came from the upland rice ecology, i.e., the increase of paddy production was from 1.5 to 1.8 million tones and the increase of the cultivated area from 1.5 to 1.8 million ha, but no yield increased during the same period. Although the NERICA technology was released, the upland rice strategy of WARDA for 1993-2003 (WARDA 1988) did not contribute to the rice production during the same period in West Africa.

Table 1. Five years' means of major cereals' production and importation per person last 40 years in Asia and Sub Sahara Africa (FAO STAT 2006). Note: Because of content of water in Cassava and Yam are high (60-70%) and low mineral & protein in comparison with the other cereals, the production data of FAO were divided by 8 for Cassava and 5 for Yam to estimate cereals equivalent (Sanchez 1976, Kiple and Ornelas 2000).

Africa South of Sahara- food production (kg/person)

Year	1961-1965	1966-1970	1971-1975	1976-1980	1981-1985	1986-1990	1991-1995	1996-2000	2001-2003
Rice, Paddy	16.3	17.5	18.2	17.6	17.3	19.2	19.2	19.9	18.1
Wheat	8.1	8.4	7.7	6.8	6.7	6.8	6.2	6.3	6.2
Maize	42.5	44.3	45.0	43.4	40.3	50.6	46.6	46.2	42.2
Cassava (1/8)	18.8	18.6	18.4	18.1	17.6	18.0	20.2	19.5	19.7
Yams (1/5)	7.8	10.8	8.8	6.6	5.6	6.6	11.5	11.9	11.6
Sorghum	44.7	38.3	34.0	31.5	31.1	30.8	31.2	31.3	31.9
Millet	31.7	29.3	27.8	23.3	21.2	23.0	22.1	22.3	21.8
Paddy Rice-Import	3.8	3.8	4.3	7.7	10.3	8.8	9.0	8.3	9.9
Wheat-Import	4.5	6.0	7.4	9.7	11.8	10.2	11.2	13.1	15.7
Total*	169.8	167.2	159.9	147.4	139.5	154.9	157.1	157.3	151.6

Asia- food production (kg/person)

Year	1961-1965	1966-1970	1971-1975	1976-1980	1981-1985	1986-1990	1991-1995	1996-2000	2001-2003
Rice, Paddy	124.5	131.8	134.2	137.4	148.8	149.8	147.1	149.8	141.1
Wheat	41.6	44.2	49.6	57.6	67.0	70.6	79.0	78.4	72.2
Maize	19.6	23.9	26.1	31.3	34.0	38.0	41.8	45.0	43.3
Cassava (1/8)	1.4	1.4	1.5	2.1	2.2	2.1	1.9	1.7	1.8
Yams (1/5)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sorghum	9.6	9.7	8.3	8.2	7.1	5.9	5.0	3.8	3.0
Millet	8.6	9.5	7.8	6.6	6.3	4.9	4.2	3.8	3.6
Paddy Rice-Import	3.7	3.4	3.1	3.0	2.4	2.2	2.3	3.9	3.7
Wheat-Import	10.7	11.4	11.7	12.0	13.7	14.6	15.0	13.5	11.7
Total*	205.3	220.4	227.6	243.1	265.4	271.4	279.0	282.5	265.3

West Africa- food production (kg/person)

Year	1961-1965	1966-1970	1971-1975	1976-1980	1981-1985	1986-1990	1991-1995	1996-2000	2001-2003
Rice, Paddy	18.4	21.1	21.9	22.1	23.8	27.4	29.3	31.4	28.2
Wheat	0.3	0.3	0.2	0.2	0.4	0.6	0.3	0.4	0.3
Maize	27.1	27.2	23.5	18.6	21.9	42.6	48.7	41.4	38.6
Cassava (1/8)	16.6	17.3	16.4	16.7	14.8	16.8	25.3	25.3	24.7
Yams (1/5)	17.8	25.0	20.5	15.2	12.8	15.4	27.4	28.3	27.6
Sorghum	70.6	56.7	47.0	40.3	42.1	46.5	48.6	47.9	47.2
Millet	59.8	54.0	52.7	42.4	41.6	48.0	45.7	45.4	44.6
Paddy Rice-Import	5.3	5.8	6.2	13.2	17.4	15.3	16.7	15.7	19.1
Wheat-Import	4.0	5.8	8.0	13.3	14.3	9.6	11.4	13.8	16.7
Total*	210.7	201.6	182.2	155.5	157.3	197.3	225.3	220.1	211.3

Total*: Excluding the imports of paddy rice and wheat.

These trends clearly show that the improvement of the natural resource management technology, especially through the improvement of water control in rainfed lowland played a major role in increasing rice production during last 15 years. If this trend is supporting by adapting the sawah eco-technology strategy proposed in this paper, the green revolution will be realized in this region by 2015.

Table 2. Estimation of rice production trend by rice ecology in West Africa during 1984-1999/2003 and 2015 estimation by the author (JICA 2003, WARDA 1988, 2002, 2004, FAOSTAT 2006)

	Area (million ha)			Production (million ton/y)			Yield (t/ha)		
	1984	1999/03	2015	1984	1999/03	2015	1984	1999/03	2015
Upland	1.5	1.8	2.0	1.5	1.8	2.0	1.0	1.0	1.0
Contribution (%)	57%	40%	30%	42%	23%	13%	No yield increase		
Rainfed lowland	0.53	1.8	3.0	0.75	3.4	7.0	1.4	2.0	2.4
Irrigated lowland	0.23	0.56	0.80	0.64	1.9	3.0	2.8	3.4	3.8
Total	2.6	4.7	6.0	3.4	7.7	14	1.3	1.6	2.4

Table 3. Major soil distributions in the three tropics based on the Soil Taxnomy (Hirose and Wakatsuki 2002)

	Entisol	Spodosol	Histosol	Ultisol	Inceptisol	Andisol	Oxisol	Psamment	Alfisol	Mollisol	Vertisol	Aridisol	Total
Soil Characterristics	Immature parent materials	Sandy, leaching	Peat wetland	Strongly weathered, acid	Young vitality	Volcanic ash, fertile	Aging, leaching	Quartz leaching	Eutrohpic, low activity	Grasslands, dry season	Black, semi-arid	Dry, desert	(excluding no-soil surface)
Toropical Africa	50	3	2	190	240	5	440	340	320	4	100	810	2,504
Toropical America	90	0.5	5	330	130	90	660	20	120	15	20	50	1,531
Toropical Asia	250	3	22	300	200	50	tr	tr	80	tr	100	10	1,015
Total tropics (million ha)	620	7	30	820	570	145	1,100	360	520	19	220	890	5,050
Total (ratio in %)	11.7	0.1	0.6	15.5	10.8	2.7	20.8	6.8	9.8	0.4	4.2	16.6	100
Japan (ratio in %)	4	3.5	1.0	2.5	58	16	0	tr	tr	0	0	0	100

Soil Distribution Characteristics of SSA and Soil Fertility of West African Lowland in comparison with Tropical Asia (Wakatsuki and Masunaga 2005)

Table 3 shows the estimated area of soil order in three major tropical zones in the world, i.e., tropical Asia, Africa, and America (Sanchez 1976, Kyuma 2004, Eswaran et al 1992 and 1997, Soil Survey Staff 1998, 1999, Hirose and Wakatsuki 2002). The combined area of the nutrients depleted Oxisols and Psamments as well as water deficient Aridisols accounts for 64% of SSA. In tropical Asia, although acid Ultisols are widespread, since the geology is much younger, Oxisols, Psamments and Aridisols are minor distribution. These soils are unsuitable for agriculture. In tropical America, Oxisols have wide distribution, 43%, but few distributions of Aridisols and Psammnets. Among the soil orders in the tropics, Andisols on upland and Inceptisols as well as Entisols in lowland have good moisture and fertility in general. While intensive and relatively sustainable farming systems are practiced on Andisol areas in all of the three tropical zones, the Inceptisols and Entisols in lowlands are not very much used in both tropical Africa and America. In tropical Asia, however, the lowland Inceptisols and

Entisols are utilized more intensively for sawah based rice production systems. The sawah systems, total area of about 100million ha, are producing rice food for more than two billion people in sustainable basis (Greenland 1997, Kyuma 2004).

During 1986 to 2007, the senior author conducted various surveys on the West African rice based farming systems in flood plains, inland valleys and various uplands. Those soils, mainly lowlands, were collected from most West African countries, including Senegal, Guinea, Sierra Leone, Liberia, Cote d'Ivoire, Mali, Burkina Faso, Ghana, Togo, Benin, Niger, Nigeria, and Cameroon as well as the Dem. Rep. of the Congo in central Africa. Soil fertility characteristics were evaluated and their fertility were compared with that of soils in tropical Asia and Japan. The results were summarized in Table 4 (Wakatsuki et al 1998, Issaka et al. 1997, Buri et al. 1999 and 2000, Kawaguchi and Kyuma 1977, Hirose and Wakatsuki 2002). Total carbon and nitrogen content were low both for West Africa and tropical Asia. The mean values of available phosphorous and pH suggest that the phosphorous status of West Africa is very critical. Base status such as exchangeable calcium and potassium and effective cation exchange capacity were also very low in comparison with the tropical Asia. In addition, some micronutrients, such as sulfur and zinc are also generally very low and about 60-80% of lowland soils, both inland valleys and flood plains were in deficient level (Buri et al 2000). Comparison of soil fertility data of tropical America also revealed that the fertility of lowland soils in West Africa was the lowest among the three tropics (Hirose and Wakatsuki 2002).

Table 4. Means values of fertility properties of inland valleys (IVS, about 200 sites) and flood plains (FLP, about 70 sites) of West Africa in comparison with lowland topsoils of tropical Asia (about 500 sites) and Japan (about 150 sites) (Hirose and Wakatsuki 2002)

Location	pH	Total C (%)	Total N (%)	Available P (ppm)**	Exchangeable Cations (cmol/kg)				Sand (%)	Clay (%)	CEC /Clay
					Ca	K	Mg	eCEC			
IVS	5.3	1.3	0.11	9	1.9	0.3	0.9	4.2	60	17	25
FLP	5.4	1.1	0.10	7	5.6	0.5	2.7	10.3	48	29	36
T. Asia*	6.0	1.4	0.13	18	10.4	0.4	5.5	17.8	34	38	47
Japan*	5.4	3.3	0.29	57	9.3	0.4	2.8	12.9	49	21	61

*Kawaguchi and Kyuma 1977, ** Bray 2

In high rainfall zones of West Africa such as equatorial forest in Liberia and Sierra Leone, Oxisols are widespread in upland areas. The typical toposequnce of inland valley soils near Makeni in central Sierra Leone was Oxisols in flat upland, Oxisols/Ultisols in gentle slopes and Inceptisols in valley bottom. The eCEC of the topsoils were 1-5 cmol(+) /kg and exchange acidity percentages were 10-90% throughout the topesequnce (Smaling et al 1985 a and b, Hirose and Wakatsuki 2002). The upland soils have especially low carbon and nitrogen contents, less than 1% and 0.1% respectively. Available phosphorus (Bray II) was also lower than that of lowland soils. Exchangeable bases are also generally lower than those of soils in inland valleys and flood plains. In Savannah zones, such as Sudan and Guinea, although the upland soils are mainly Alfisols but the eCEC of these soils is also very low, normally less than 5Cmol(+)/Kg. Low activity clay soils are predominant. In addition to the poor soil fertility, the recent shortage of rainfall also further makes it difficult to conduct sustainable upland rice cultivation.

Although organic matter management through agroforestry and cover crop systems are possible options to sustain soil fertility (Tian et al 2001), in order to overcome such difficulties and for effective and sustainable crop production in SSA, new farming systems that can restore and enrich these poor soils must be developed. In terms of sustainability, re-evaluation of traditional farming technology is important (Barrera-Bassols and Zinck, 2000). However, for the sustainable increase to cope with recent population expansion, only re-evaluation of traditional farming is not enough (Hirose and Wakatsuki 2002). As discussed in this paper, the new concept of ecological engineering technology is necessary. The African adaptive lowland sawah-based farming with adjunct small-scale irrigation scheme for the integrated watershed management will be the most promising strategy to increase sustainable and intensive food production and at the same time to restore the degraded watersheds in SSA.

Concept of Sawah Ecotechnology

The concept and the term “sawah” refers to man-made improved rice fields with demarcated, leveled, bunded and puddled rice fields with water inlet and water outlet, which, if possible, can be connecting various irrigation facilities, such as irrigation canals, pond, spring, pump, water harvesting, and flooded sawah, etc (Fig.1-6). Just sawah to sawah irrigation as well as drainage are possible. Rainfed sawahs without any irrigation facilities are also far better than rainfed fields for rice growth and for rice green revolution because of the improvement of water and soil management. Drainage facilities are also useful in over flooded area. The term “sawah” originates from Malayo-Indonesian. The English and French terms, Paddy or Paddi, also originated from the Malayo-Indonesian term, Padi, which means rice plant. In order to avoid confusion between upland paddy fields and man-made leveled, bunded and puddle rice fields, i.e., typically irrigated rice growing environment, which is often un-appropriately used as lowland paddy fields, the authors propose to use the term “Sawah” in SSA (Wakatsuki et al 1998).

For the sustainable increase of rice yield and production, farmers have to control water on rice fields. If the degree of water control improves, sustainable rice yields will increase (Hiose and Wakatsuki 2002, Table 5 by Ofori et al 2005). In order to control water, sawah system has to be developed, improved and managed (Fig. 1). Taiwan team has played a pioneering role in technical cooperation for the introduction of the sawah based rice cultivation in Africa during 1965 to 1975 (Hsieh 2003). However as this technical cooperation continued only for some 10 years because of political reason, confusion and stagnation occurred on the technology transfer of the sawah based rice framings in the 1980s (Buddenhagen and Persley 1978 and IITA 1989/1990).

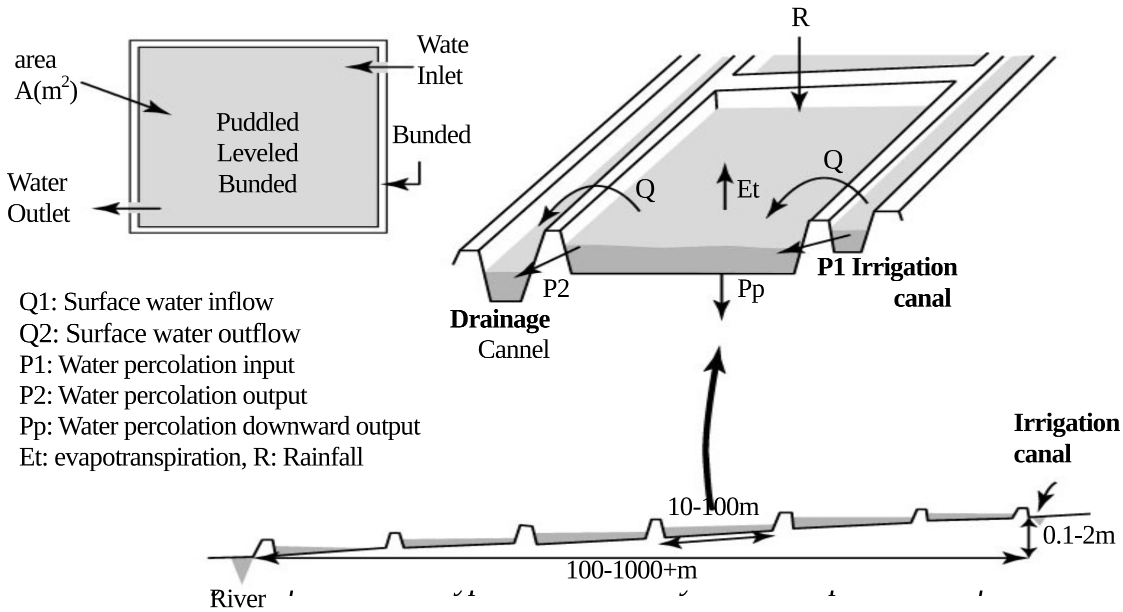


Fig. 1. What is a sawah? A sawah is a leveled, bunded and puddled rice field with inlets and outlets to control water.

It is now very difficult to build new irrigation project through the conventional ways of Official Development Assistance (ODA) because of the high cost of irrigation and its apparent low return in SSA. Especially, the large-scale irrigation projects are very costly. Even in the small irrigation schemes, the construction cost becomes comparable to large schemes as far as their development depends mainly on engineering works by construction companies. Although the total sale of produce is between 1,000 –2,000 dollars per ha, the running cost including maintenance of such systems, machinery for operation, agrochemicals become very high. Due to the high construction cost, the economic return has been negligible or rather negative for a long period of time, 20-30 years.

In addition to the construction cost of irrigation schemes, the management of the schemes has been a problem in SSA. Water use efficiency was very low because of the confusion between irrigation scheme and the sawah systems in SSA. The irrigation schemes are constructed and managed by government and/or communities, but the water condition in each irrigated rice field, i.e., sawah, has to be managed by each rice farmers. Actually water use efficiency in the whole irrigation schemes is dependent on the management skill of sawah fields of each rice farmer. The lack of eco-technologies of sawah in SSA, majority of irrigation schemes have never been sustainable for the last four decades. Therefore the official development of irrigation schemes, large and small, by governments is very slow.

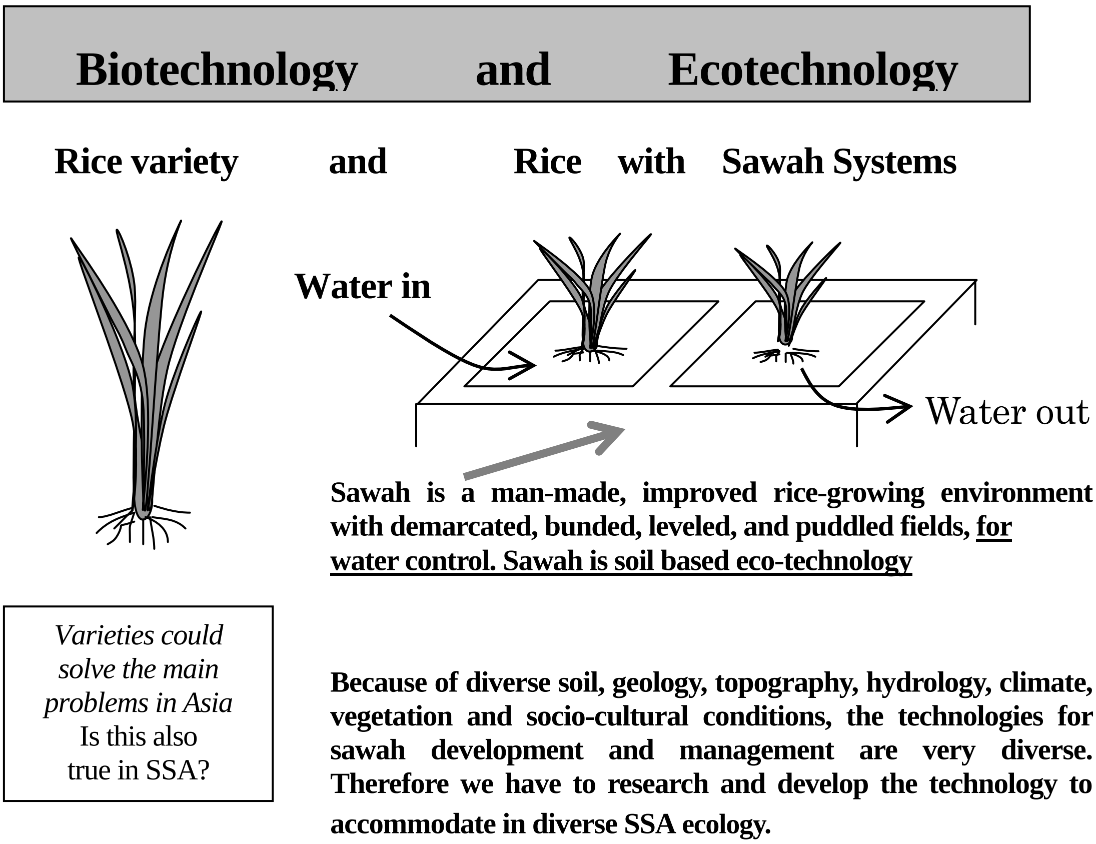


Fig. 2. Rice (variety) and environment (Sawah) improvement. Both Bio & Eco-technologies must be developed in balance

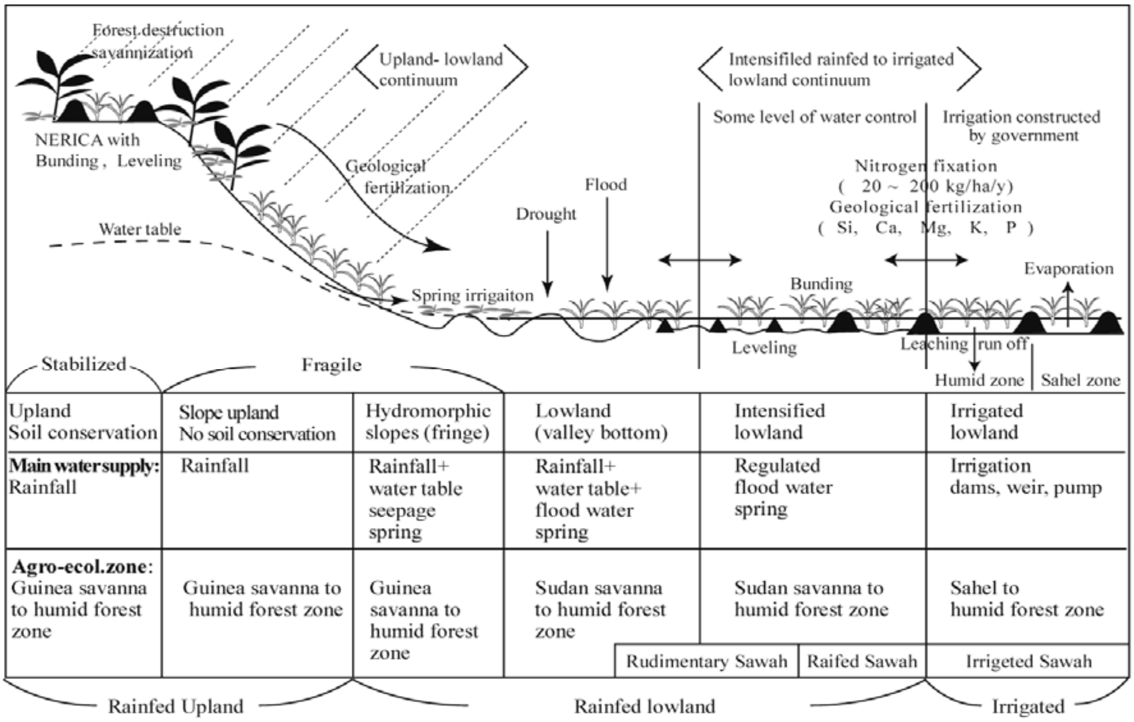
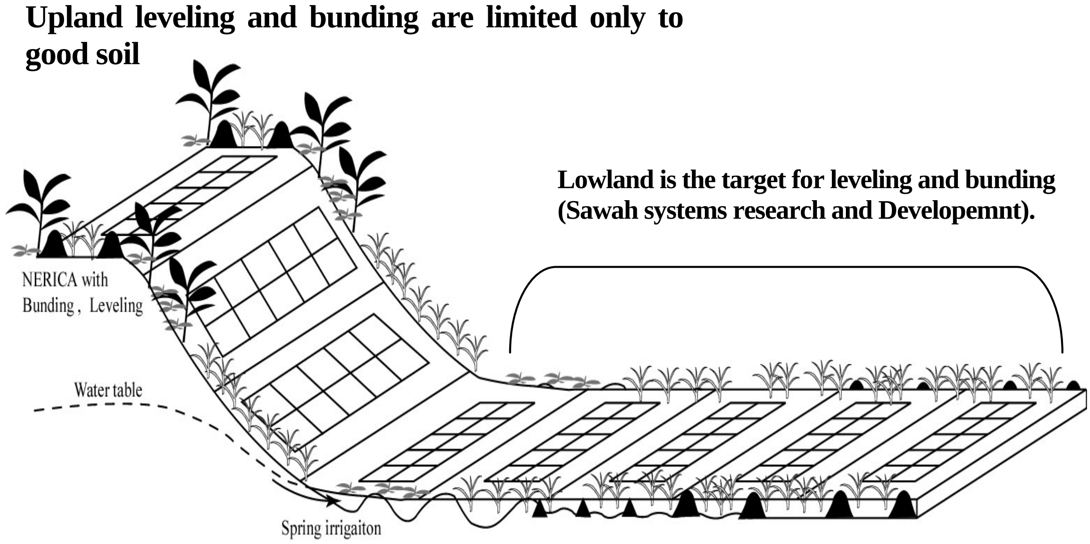
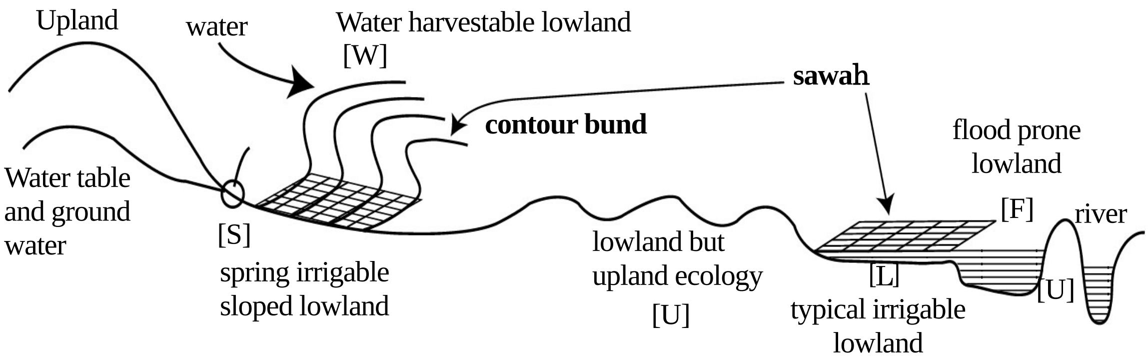


Fig. 3. Rice ecologies along upland-lowland continuum in West Africa (JICA 2003, WARDA 2004)



Water table and water management continuum (WARDA 2004).

Fig.4. Rice farmer's field demarcation based on soil, water and topography, such as sawah development, are the starting point for scientific observation, technology generation and application



Irrigation options: Sawah to sawah/ contour bund water harvesting, spring, dyke,
river, point, peripheral canal
Interceptor canal, tank, pump
Lowland sawah development priority
[S] > [L] > [F] > [W] > [U]

Fig. 5. Strategy for sawah and irrigation development. Various sawah (bunded, leveled, puddled rice land) development with various irrigation options depending on the characteristics of valley bottom diversity in each agroecological zone.

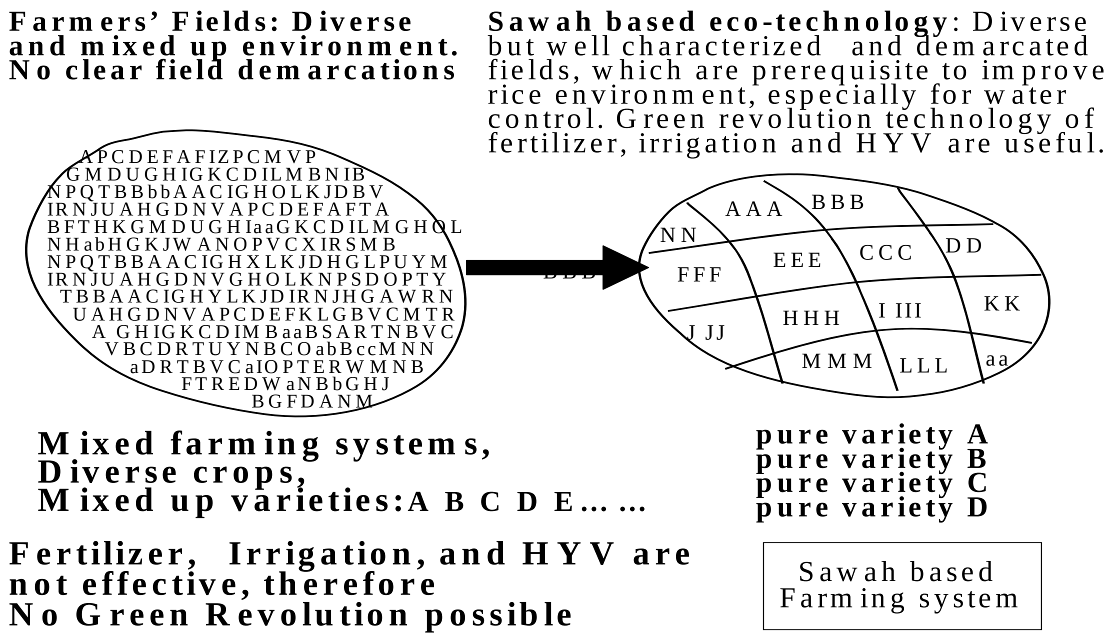


Fig. 6. Sawah Hypotehsis (I) : Successful Integrated Genetic and Natural Resource Management (IGNRM) Needs Classified Demarcated Land Eco-technologically

However, the most impressive achievements observed by the senior author in the past 15 years were that inland valley development for improving water control of the rice-growing environment through bunding and leveling, which are ongoing in West Africa despite the major negligence of the research in this area and scarce official funding (Table 2). These are based mainly on farmers' self-support efforts. Decreasing trend of rainfall in recent years might persuade farmers to shift partly from upland to lowland. The senior author observed that there were many upland rice fields around Bouake in 1987. In 2002, however, almost no upland rice fields were observed around the Bouake area.

These lowland development activities are called "intensified lowland", "partial water control", just "lowland development", "amenagement" or "system du Chinois" after the activities by Taiwan team" in some Francophone SSA, or "contour bund system". Although the quality of these systems is quite diverse, these are all covered by the "sawah concept and sawah technology and development" (Wakatsuki et al 1998). Some rice farmers as well as some West African and donor countries have realized the importance of soil and water management, especially the water management, through various sawah based rice cultivation technologies are not defined clearly (Figs. 1 and Table 2). WARDA's inland valley consortium (IVC) also contributed to encourage these developments partly. A USD$ 23 million inland valley rice development project (IVRDP, 2004-2009) is based on the sawah approach in Ghana financed by African Development Bank, is a good example, if it becomes successful (Wakatsuki et al 2001, Hirose and Wakatsuki 2002, Ministry of Food and Agriculture, Ghana, 2007 a and b). Massive irrigation scheme by office du Niger in Mali has been performing and now to reach the level of green revolution, 4-5ton/ha, in their full scheme of 50,000ha in last ten years after thirty years of very poor performance during 1960-1990 (JICA 2003).

Balanced Approach between Biotechnology and Ecotecnology

In order to strengthen these trend, the way for rapid expansion of ecotechnology based low cost and self-support sawah fields have to be researched and developed in the rainfed lowland, especially in inland valleys (Wakatsuki et al 1998, 2001, Hirose and Wakatsuki 2002). SSA needs eco-technologies that can improve farmers' rice fields similar to the biotechnologies that can improve rice varieties (Fig. 2, Table 5 by Ofori et al 2005). Table 5 clearly shows that eco-technological improvement of farmers rice fields are critical compared to the biotechnological variety improvement in SSA.

Table 5. Mean gain yield of 23 rice cultivars in low land ecologies at low (LIL) and high input levels (HIL), Ashanti, Ghana (Ofori et al 2005)

	Entry No.	Cultivar	← ECOTECHNOLOGICAL YIELD IMPROVEMENT Irrigated Sawah HIL (t/ha)	Irrigated Sawah LIL (t/ha)	Rainfed sawah HIL (t/ha)	Rainfed sawah LIL (t/ha)	Upland like fields HIL (t/ha)	Upland like fields LIL (t/ha)
BIOTECHNOLOGICAL IMPROVEMENT	1	WAB	4.6	2.9	2.8	1.6	2.1	0.6
	2	EMOK	4.0	2.8	2.9	1.3	1.4	0.5
	3	PSBRC34	7.7	3.5	3.0	2.1	2.0	0.4
	4	PSBRC54	8.0	3.7	3.8	2.1	1.7	0.4
	5	PSBRC66	5.7	3.3	3.8	2.0	1.8	0.4
	6	BOAK189	7.0	3.8	3.7	2.0	1.4	0.3
	7	WITA 8	7.8	4.2	4.4	2.1	1.8	0.5
	8	Tox3108	7.1	4.1	4.0	2.3	2.3	0.6
	9	IR5558	7.9	4.0	3.8	2.0	1.8	0.5
	10	IR58088	7.7	4.0	3.7	1.8	1.4	0.3
	11	IR54742	7.7	4.3	4.0	2.2	1.9	0.4
	12	C123CU	6.9	4.1	4.2	1.9	2.0	0.4
	13	CT9737	6.5	4.0	4.0	1.7	1.9	0.6
	14	CT8003	7.3	3.8	3.8	1.7	2.0	0.5
	15	CT9737-P	8.2	4.0	4.3	1.8	1.2	0.5
	16	WITA1	7.6	3.6	3.3	1.8	0.9	0.3
	17	WITA3	7.6	3.5	4.1	2.0	1.3	0.5
	18	WITA4	8.0	4.1	3.7	2.1	1.5	0.3
	19	WITA6	8.0	3.5	4.0	2.3	1.4	0.3
	20	WITA7	7.3	3.7	3.8	2.2	2.0	0.4
	21	WITA9	7.6	4.4	4.5	2.8	2.0	0.6
	22	WITA12	7.6	4.0	3.8	1.9	1.8	0.4
	23	GK88	7.5	3.8	3.5	2.0	1.8	0.5
	Mean (n=23)		7.2	3.8	3.8	2.0	1.7	0.4
	Range		(4.0-8.2)	(2.8-4.4)	(2.8-4.5)	(1.3-2.8)	(0.9-2.3)	(0.3-0.6)
	SD		1.51	0.81	0.81	0.45	0.44	0.12

Because of various costs of green revolution technology, yield must be higher than 4t/ha for sustainable adoption of green revolution technologies

The technologies of genetic improvement of rice (variety) and the rice growing environment (sawah) must be researched and developed in good balance for integrated genetic and natural resources management (IGNRM) (Fig. 2 and Fig. 8). Because of the success story of the green revolution by HYV in Asia and Latin America by CG centers, our research activities have been too much one sided focusing on HYV only for the last forty years in SSA.

Table 6 summarized the possible eco-technology options to improve rice yields in comparison with biotechnology options. The table shows that sawah eco-technology can give wide range of the improvement of rice yield, rice quality and ecological environment including carbon sequestration (Darmawan et al 2006a and b) through the improvement of water shortage, poor nutrient conditions, acidity, alkalinity, weed control, pest and diseases control, and food quality (Hirose and Wakatsuki 2002, Kyuma 2004). Therefore, in addition to the improvement of variety through biotechnology, the improvement of rice growing environment has to be done through eco-technology. Balanced research and technology development of biotechnology and eco-eco-technology is very important.

Table 6. Comparison between Biotechnology and Ecotechnology Options for the improvement of Rice Production in various ecological constraints

Eco-technology and Bio-technology Options in Rice Based Farming

(1) For Water shortage and Flooding

Biotechnology: Genes for deep rooting, tolerance in submergence, C4-nature, Osmotic regulation genes,

Eco-technology of Sawah based soil and water management, bunding, leveling, puddling, well, weir,tank irrigation, and System rice intensification. Dyke construction and drainage

(2) For Poor nutrition, acidity and alkalinity

Biotechnology: Gene of Phosphate and micronutrient transporter

Eco-technology of Sawah based N fixation, increase P availability and micro- as well as macronutrient. Geological fertilization, Watershed agroforestry, organic matter and fertilization. Use of birds feculent for the enrichment of P.

(3) For Weed control

Biotechnology: Gene of weed competition, rapid growth.

Eco-technology of Sawah based weed management through water control and trans-planting. Leveling quality of sawah is important. Duck and rice farming.

(4) For Pest and disease control

Biotechnology: Resistance genes.

Eco-technology of Sawah based silica and other nutrients supply to enhance immune mechanisms of rice. Mixed cropping.

(5) For Food quality

Biotechnology: Vitamine rice gene.

Eco-technology of Sawah based nutrition control. Fish, duck and rice in sawah systems

(6) For Carbon Sequestration

Biotechnology: Breeding of high biomass productive genes

Ecotechnology: Soil organic matter accumulation in Sawah soil in Satoyama watersheds

Rice growing ecologies are extremely diverse in West Africa and SSA (Fig.3, JICA 2003, WARDA 2004). The appropriate bund layout, bunding and leveling quality, and size and shapes of sawah as well as appropriate site selection are different depending on the characteristics of targeted inland valleys and on the targeting farming systems. Because of obvious benefits of geological fertilizations (Fig. 11) as described later, lowland is the priority target for sawah development (Fig.4). Water harvesting and various simple irrigation technologies have to be integrated with the various sawah developments in diverse characteristics of the valley bottoms (Fig.5). Small machinery, such as power tiller, has to be examined to accelerate the sawah development. Tropical Asian experiments in collaboration for sawah development and for animal traction and power tiller operation for sawah based rice farming will be very useful (Fashola et al 2007 a and b, Hsieh 2003).

The Sawah Hypothesis (I) for the Green Revolution

On December 26, 2004, the concept of and the term "TSUNAMI" were lacking in the vocabulary of people in Indian Ocean locations such as Sumatra, Indonesia, Sri Lanka, India and Thailand. This seriously exaggerated the tsunami disaster. The lack of the concept and appropriate technical term for improving and managing the rice growth environment, such as "sawah" creates confusion in the research and sustainable development of rice cultivation in West Africa. As seen from the success of publicity of NERICA by WARDA, a clear concept and key technical term are very important for integrated genetic and natural resource management (IGNRM). As discussed already, unlike in Asian rice farmers' fields, Sub Sahara African farmers' fields, and therefore the farming technologies, are not ready to accept various IGNRM technologies, such as irrigation, fertilizers, integrated pest management (IPM), and high yielding varieties (HYV) (Fig. 6 and 7). Rice farmers' field demarcation based on topography, hydrology and soil is the starting point for scientific observation, technology generation and application, including the green revolution technologies (Fig.6). For efficient uses of fertilizers and irrigation water, rice farmers' fields have to be demarcated based on topography, hydrology and soils (Fig. 5 and 6). Although there have been discussions on researches and developments on irrigation, fertilizers and HYV for the last forty years, the discussions have not touched on whether the prerequisite conditions are lacking in SSA (Fig.6 and 7). The concept and technologies of Sawah is such an example. Simply speaking the basic infrastructures for the green revolution, such as sawahs, are lacking in SSA (Fig. 1, 2, 6, and 7). Irrigation without farmers' sawah farming technologies has proved inefficient or even damaging because of accelerated erosion and waste of water resources. In the absence of water control, fertilizers cannot be used efficiently. Consequently, the high yielding varieties perform poorly and soil fertility cannot be sustained hence the green revolution cannot take place. These are the Sawah hypothesis (I).

As shown in Fig.7, majority of Asian rice farmers' fields were already quality sawah fields in 1960s when the green revolution technologies were introduced. Therefore the three major components of the green revolution technologies were quickly adapted. However, majority of rice farmers' fields of SSA are lacking such sawah fields, therefore the three green revolution technologies have not been effective for the last forty years. The HYVs have never been performed successfully without sawah fields. Irrigation and other agronomic technologies also never performed well without sawah fields. But if the sawah ecotechnolgy is adapted to majority of rice farmers in SSA, the green revolution will be realized quickly as in the case of Asia. Contrary to Asian farmers' fields, the farmers' rice fields in SSA are not ready to accept the three basic components of the green revolution technologies, i.e., (1) irrigation for water supply, (2) fertilizer for soil nutrient supply, and (3) high yielding varieties (HYV).

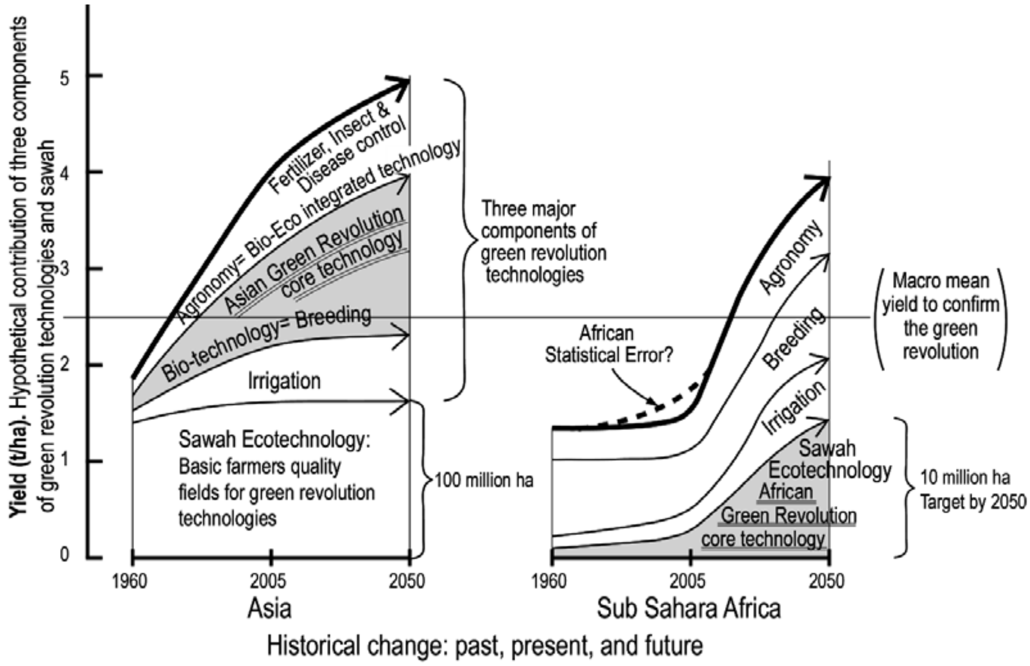


Fig.7. Sawah hypothesis (I): hypothetical contribution of three green revolution technologies and sawah eco-technology during 1960-2005 and during 2005-2050 in Sub Sahara Africa and Asia. Bold lines during 1960-2005 are based on mean rice yields based on FAOSTAT 2006. Bold lines during 2005-2050 are the expected or target trend based on the sawah hypothesis (I) by the authors.

As described " African Statistical Error" in the yield trend of Sub Sahara Africa during 1960-2005 in the Fig. 7, agricultural statistics are also not so reliable in SSA. There are many reasons, but lack of sawah as demarcated rice fields makes itdifficult to estimate the yield too. Without reliable statistical data, appropriate rice development policy can not be established.

The sawah system development and management are the technologies that should be transferred to farmers. Since bunding, leveling and puddling need very hard, skilled and careful works as well as obvious additional benefits of geological fertilization, rainfed lowland will be the primary target for sawah development (Fig. 4 and 11). The ecology of the majority of rice farmers' fields is extremely diverse in naturally and farming systematically (Fig. 3), therefore even the good quality seeds cannot be evaluated properly without sawah systems (Fig.6). Sawah is also a means by which such ecologically diversified rice fields bringing into relatively homogenous and classified fields to evaluate appropriate variety. The successful IGNRM needs classified demarcated lands such as sawahs. The technology of rice variety improvement and dissemination has a clear concept and target such as high yield, pest, draught and poor nutrient tolerant, and high nutritive and quality varieties. The remarkable achievement of the breeding program at WARDA is clear. However there were no such clear concepts and targets in the researches of natural resource management in West Africa for the last 20 years.

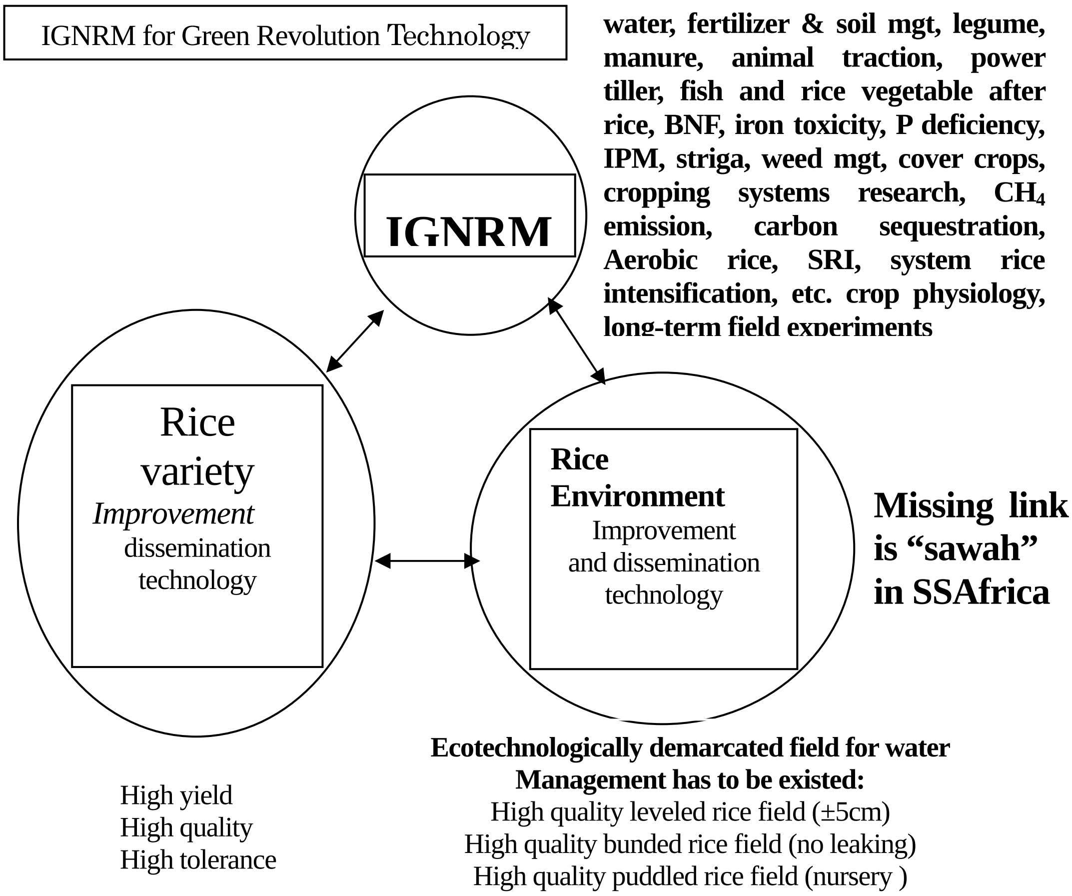


Fig. 8. Concept of Integrated Genetic and Natural Resources Management (IGNRM) for green revolution technology: Missing link is Sawah which is lacking in majority of famers' fields

The missing link for the green revolution is a sawah concept and technology, targeting the expansion of high quality but with low cost. If sawah systems are successfully introduced to farmers' rice fields, the integrated genetic and natural resources management (IGNRM) technology generations to deal with water, soil, and fertilizer management, low P availability problem, weed and striga management, IPM, control of CH_4 emission and carbon sequestration, animal traction and small machinery operation, fish and rice, vegetable after rice, and so on, will have clear target fields to apply and will therefore be accelerated (Fig.7 and 8). Long term experiments on the effect of cropping system investigations such as legume, biological nitrogen fertilizer (BNF) and organic manure will be possible. Iron toxicity has been often cited in West Africa that can be tackled only properly in sawah based IGNRM. Some pest and disease such as African rice gall midge (AfRGM) and rice yellow mottle virus (RYMV) problems may even be partly mitigated through enhancing the healthy growth of rice through the sawah type eco-technology. Water saving aerobic rice cultivation and Systems Rice Intensification (SRI) methods become only possible on sawah fields (Fig. 6 and 8).

African Lowlands Characterization in Comparison with Asian Lowlands in Watersheds

Because of diversity in soils, hydrology, climate, vegetation, topography, and geology as well as socio economic, cultural and historical conditions, the technologies for sawah development and management must fit such diverse conditions. This is an important research and development target for sustainable rice production (Fig. 4-8). There is information on the potential area of lowland sawah development, such as 330,000 ha in Benin, 230,000 ha in Burkina Faso, 200,000 ha in Togo, one million ha in Ghana, 20 million ha in whole SSA (Hirose and Wakatsuki 2002) and so on. This area estimation is, however, still at the preliminary stage. Details survey and characterization targeting sawah type lowland development are necessary (Table 7, Fig. 3-5).

As shown in Table 7, the lowland area in SSA is enormous (Windmaijer and Andriesse 1993), but because of characteristics of natural environment, particularly scarce water resources, the potential area for sustainable sawah development cannot cover all the lowland of SSA. Lowland soil formation in SSA is much smaller than in tropical Asia (Fig 9 by Walling 1983, Wakatsuki 2002). This will be a basic ecological limiting factor to develop sawah systems in SSA. One of the reasons why the ecology of inland valleys in West Africa is so diverse (Jamin and Windmeijer 1995) can be explained partly from this (Fig.3, 5 and 9). Inland valleys have various micro-topographies as shown in Fig. 5, of which spring irrigable sloped land and typical irrigable lowland that can be easily irrigated using pump, simple weir and dyke have the highest priority for sawah development in SSA. The relative area distribution of these kinds of lowlands in various inland valleys is yet to be determined. Flood prone areas need the control measures. Many areas of inland valley bottoms that have upland hydrology have the lowest priority for sawah development. However upland NERICA may fit into such upland like ecology in lowland. Water harvestable lowland along the foot slopes can be developed as contour-bunded sawah systems with partially water controllable rice fields as seen in northern Ghana and Burkina Faso. The low cost technology to develop these systems has to be researched based on the field trials and errors approach. The lowland demarcation and area estimation can be done with help of geographical information system (GIS) technology.

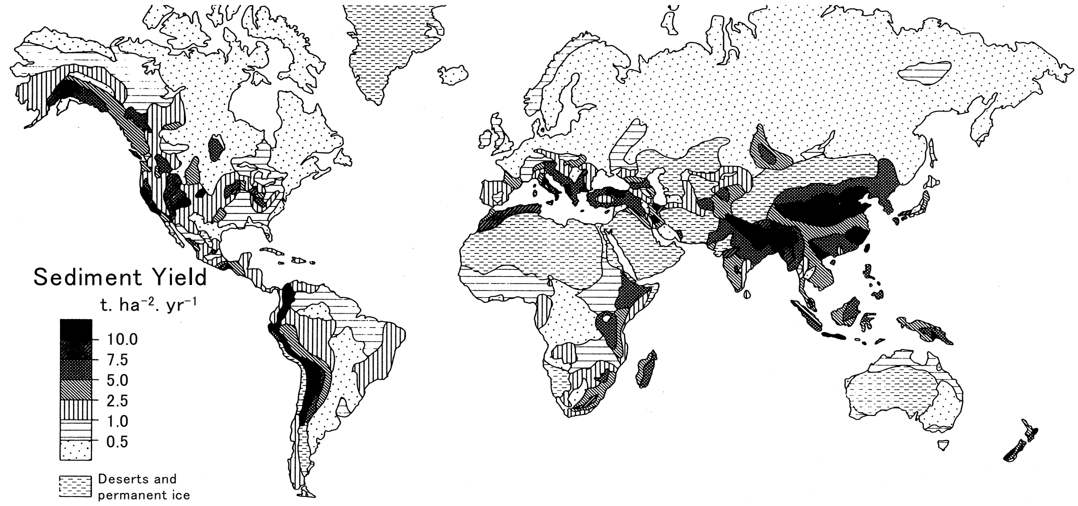
Asian region has about 60-75% of global monsoon rainfall, while SSA has about 10-15%, which is about one fifth of Asia (Trenberth et al 2000, Qian et al 2001, Levinson 2004). Based of this amount of water cycling in the monsoon climate in comparison with Asia, where it has about 100 million ha of irrigated sawah, the total potential irrigated sawah may be about 20 million ha in SSA (Table 7). Immediate target will be 10 million ha in SSA by 2050 (Fig. 7). However more appropriate estimation has to be researched in detail coupled with real development through field trials and errors approach in each agro-ecology.

Table 7. Distribution of lowlands in Sub Sahara Africa
Windmeijer and Andriesse (1993); Sawah area estimation by Wakatsuki (2002)

Classification	Area (million ha)	Percentage (%)
Coastal swamps	16.5 (3-5)	7 (17)
Inland basins	107.5 (1-4)	45 (10)
Flood plains	30.0 (5-10)	12 (31)
Inland valleys	85.0 (5-15)	36 (42)

Figures in parentheses are the potential area of sawah development (million ha): *Maximum total area in SSA may be 20 million ha. This estimation is based on the data that the relative amount of rain fall in Asia Pacific monsoon is five times bigger than that of SSA and sawah area in Asia is 100 million ha currently*

Can watersheds of SSA sustain Sawah system? High rate of soil erosion and lowland sawah soil formation can be compensated by high rate of soil formation in Asia. However soil formation, soil erosion and hence lowland soil formation are very low in comparison with Asian watersheds: Ecological Balance studies are necessary



Rate of soils erosion in the world (Walling1983)

Fig. 9. Rates of Soil Erosion in the Worlds (Walling 1983)

Historical and Geographical Consideration for Sawah Development

Undoubtedly natural environmental conditions, such as hot temperature and enough water during rice growing season and lowland soil sedimentation are the important factors for sustainable development of sawah system. As seen in Fig. 9 (Walling 1983), soil erosion and hence lowland soil formation in West Africa are very low in comparison with Asian watersheds. High rates of soil erosion and lowland sawah soil formation can be compensated by high rate of soil formation in Asia because of active geological formation and ample monsoon rainfall (Hirose and Wakatsuki 2002). Paradoxically, extreme diversity of lowland in West Africa (Fig. 5) may relate to the low rate of soil erosion and weak lowland soil formation.

As shown in Fig. 10, before the green revolution, there were long continued efforts to expand lowland sawah systems in the history of Japanese rice cultivation during the 6th to 20th centuries. The Fig.10 shows the trends of rice yields, sawah area, and population of historical path in Japan in comparison with rice yields in major Asian and African countries. Because of farmers' sawah fields had been developed and sawah-based eco-technology was traditional, Japan's green revolution happened immediately after the introduction of Euro-American's fertilizer technology at the end of

19th century. The green revolution in turn encouraged the rapid expansion of sawah area more than one million ha within 50 years when population was less than 60 million (Fig.10). Although after world war II, because of the expansion of the economy, industrialization, and urbanization, the sawah area had decreased rapidly, more than 1.5 million ha within 40 years, 1960 to 2000. The Japanese population is estimated to decrease almost 50% during 21st century. These are the crises in current Japan and near future. On the other hand, SSA and the world are expecting rapid population explosion during the 21st century, the green revolution and the expansion of sawah area are necessary to cope with the forthcoming peak population.

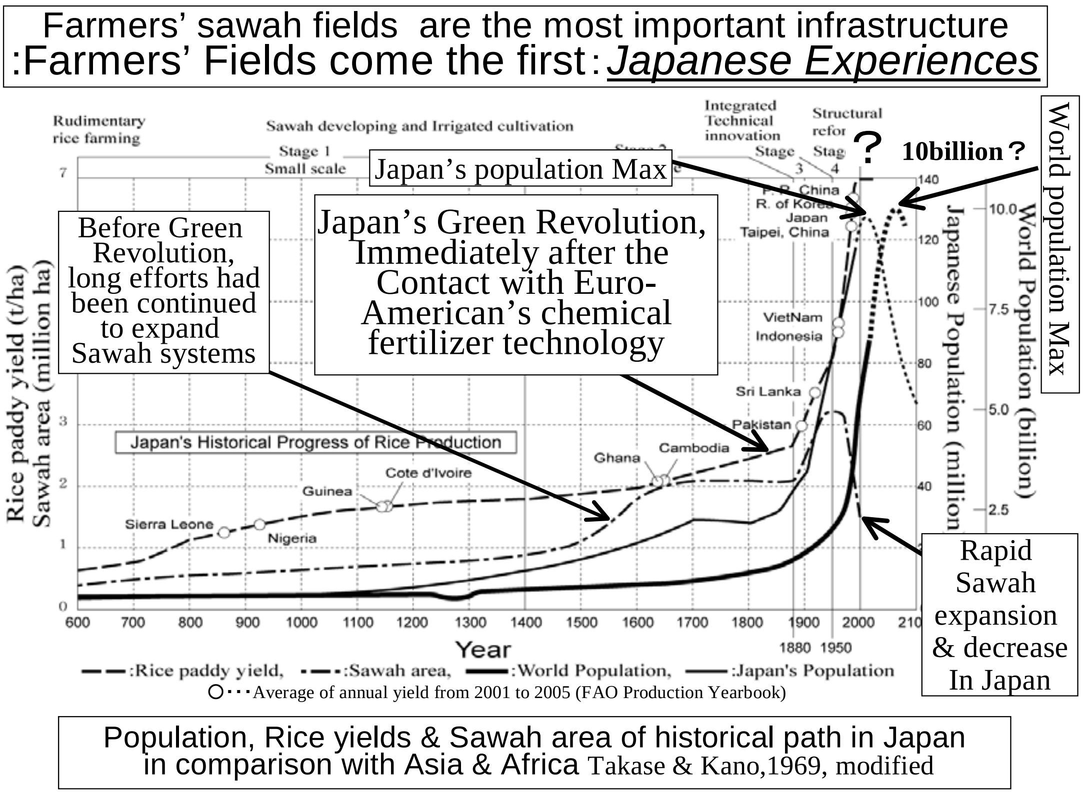


Fig. 10. Rice yields & sawah area of historical path in Japan in comparison with rice yields in Asia & Africa. Japanese and world population trend in past and near future are also shown.(JICA 2003, modified)

Apart from the above natural geographical reasons, the background of the cause of lack of the prerequisite for the green revolution can be found in the tragedies many years ago. The slave trade by European countries for as long as 400 years, 16th to 19th centuries, destroyed African communities. Young Africans had to work for the nation building of the new worlds not for SSA. Subsequent colonization continued for additional 150 years until 1960. These are probably the main reasons why the basic nation building, i.e., typically the farmers' fields, is still stagnating. Thus the farmers' fields lack basic infrastructures to accept the green revolution technologies in SSA (Wakatsuki 2002).

Sawah Hypothesis (II) for Intensive Sustainability

Sustainable yield of lowland sawah system is very high. Although this is based on long history and experiences (not experiments) of sawah based rice farming in Asia, there is no scientific quantitative confirmation yet. Lowland sawah can produce about 2t/ha without any chemical fertilizer application (Fig 10 and Table. 8). In addition the lowland sawah based farming can support rice cultivation continuously for decades or more without any fallow. However sustainable upland slush and burn rice yield without fertilizer never exceed 1t/ha. In addition to the lower yield, the upland rice fields need a fallow period to restore soil fertility, such as two years of upland cultivation and eight, sometime more than 15 years, of fallow. This means 1 ha of sustainable upland rice cultivation need at least 5 ha of additional land. Therefore sustainable upland rice yield is actually not 1t/ha but less than 0.2t/ha. Therefore as shown in the Table 8, sustainable productivity of sawah based rice farming is more than ten times higher than that of the upland slush and burn rice farming (Sawah Hypothesis II). This hypothesis II has to be examined quantitatively under SSA conditions. This is the reason why the upland rice cultivation destroys forest and degrades the land in SSA. Accordingly, the development of 1 ha of lowland sawah field enables the conservation or regeneration of more than 10 ha of forest area. Sawah fields can, therefore contribute to not only increased food production but also to conserve forest, which in turn enhances sustainability of intensive lowland sawah systems through nutrient cycling and geological fertilization processes. Furthermore, they can contribute to the alleviation of global warming problems through the fixation of carbon in forest trees and sawah soils (Wakatsuki and Masunaga 2005, Darmawan 2006a).

(1) Concept of “Watershed Ecological Engineering” and “Watershed Agroforestry” :

The optimum landuse pattern and landscape management practices optimize the geological fertilization through the control of optimum hydrology in watershed. Because of geological fertilization, lowland can receive water, nutirents, and fertile topsoils from upland. Sawah system enhances to utilize such geological fertilization flows.

(2) Sawah systems as multi-functional constructed wetlands for enhanced supply of N, P, Si and other nutrients. Technology development for enhance the multi-functionality of wetland sawah in diverse SSA agro-ecologies is a key in IGNRM.

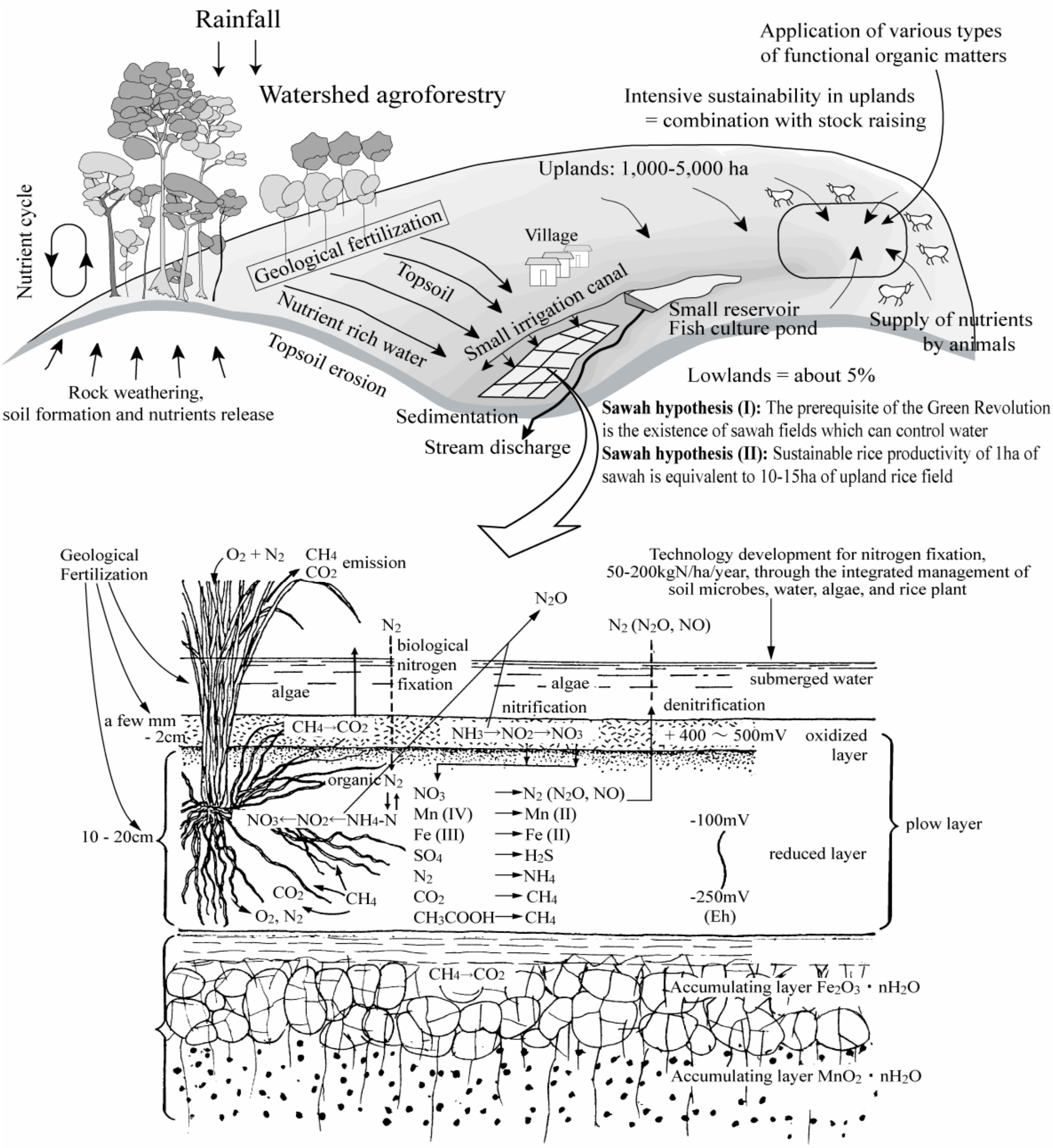


Fig. 11. (1) Macro- and (2) micro-scale ecological mechanisms of intensive sustainability of lowland sawah systems

Mechanisms of Intensive Sustainability of Lowland Sawah Systems

(1) Geological Fertilization Theory

The upper part of Fig. 11 explains what is the geological fertilization. Although this is a kind of axiom process, quantitative data confirmation is lacking. West African conditions are quite different from Asia, therefore the watershed characterization in terms of upland and lowland connected sequences is important in relation to the geological fertilization as shown in Fig.3 and 11. The upper part of Fig. 11 shows a concept of macro-scale ecological engineering, i.e., watershed ecological engineering and watershed agroforestry. The soils formed and nutrients released during rock weathering and soil formation processes in upland are accumulated at least partly in lowland through geological fertilization processes, such as soil erosion and sedimentation as well as surface and ground water movements or colluvial processes. The sustainable integration of upland forestry, upland farming and lowland sawah systems in a watershed composed of a watershed agroforestry, can be a typical model of watershed ecological engineering. The optimum land use pattern and landscape management practices optimize the geological fertilization processes through the control of optimum hydrology. Irrigation, surface and subsurface water also contributes the increase of the supply nutrients, such as Si, Ca, Mg and K as well as sulfate. This is an eco-environmental basis for long-term intensive sustainability of sawah-based rice farming in Asia.

World scale sediment delivery data from various river basins in tones per ha per year were reported by Walling (1983). The Asian monsoon area, which has the major distribution of sawah based rice farming, has the highest delivery of sediments by soil erosion as shown in Fig.9. For the upland based farming, such soil erosion destroys biological productivity. For sawah-based rice farming, however, such eroded topsoil, although the amounts should be appropriate, from the upland is a source of fertile parent materials for lowland sawah soils. The appropriate soil erosion can be compensated by new soil formation in healthy sustainable ecosystem in a watershed. Major problem in terms of sustainability of the sawah systems in West Africa may be very limited rates of soil formation and erosion in comparison with Asian watersheds (Fig. 9, Wakatsuki 2002). The rates of both soil erosion and soil formation in West Africa may be one fifth to one tenth of those of Asia watersheds. There is, however, no simple appropriate scientific method to evaluate such geological nutrients flows in a given watershed, except a few examples (Wakatsuki et al 1992, 1993, Rasyidin et al 1994). Ecological engineering researches to evaluate the geological fertilization processes and to develop the technology to enhance and control the processes are important in future.

(2) Multi-functionality of Sawah systems as Constructed Wetland

The lower half of the Fig. 11 shows the micro scale mechanisms of the intensive sustainability of the sawah system. The sawah system can be managed as multi-functional constructed wetland. Submerged water can control weeds. Under submerged conditions, because of reduction of ferric iron to ferrous iron, phosphorous availability is increased and both acid as well as alkaline soil pH is neutralized or mitigated. Hence, micronutrients availability is also increased. These mechanisms encourage not only the growth of rice plant but also the growth of various aquatic algae and other aerobic and anaerobic microbes, which increase nitrogen fixation in the sawah system through increase of photosynthesis as a functional wetlands. The technology development and quantitative evaluation of nitrogen fixation in sawah including the role of algae will be important future research topics. Although the amounts of nitrogen fixation under the submerged sawah systems are not well evaluated, the amounts could be 20-100kg/ha/year in Japan and 20-200kg/ha/y in tropics depending on the level of soil fertility and water management (De Datta and Buresh 1986, Kyuma 2004, Greenland 1997). The technology development of the nitrogen fixation by sawah systems, such as 50-200kg N/ha/y, through the integrated management of water, soil microbes, algae and rice plant is the very challenging research subject in SSA. Because of general very poor fertility of lowland soils in West Africa (Abe et al 2006, Buri et al 1999, 2000, Issaka et al 1997, Kyuma et al 1986), these various multi-functional mechanisms to enhance nutrient availability of lowland sawah systems are particularly important for intensive sustainability. The sawah systems are the field laboratory for research and technology generation and the factory for dissemination the technology developed. Rice green revolution will only be realized in the farmers' sawah fields (Fig. 7).

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References

Abe, S. S., Masunaga, T. Yamamoto, S., Honna, T. and Wakatsuki, T. 2006. Comprehensive assessment of the clay mineralogical composition of lowland soils in West Africa. *Soil Sci. Plant Nutr.* **52**: 479-488.

Barrera-Bassols N. and Zinck, J.A. 2000. *Ethnopedology in a Worldwide perspective, An annotated bibiliography,* ITC Publication No. 77, Enschede, the Netherlands,

Buddenhagen, I.W. and Persley, G.J. 1978. *Rice in Africa*, Academic Press , 355pp

Buri, M. M., Ishida, F., Kubota, D., Masunaga, T., and Wakatsuki, T. 1999. Soils of flood plains of West Africa: general fertility status. *Soil Sci. Plant Nutr.* **45**: 37-50.

Buri, M. M., Masunaga, T., Wakatsuki, T. 2000. Sulfur and zinc levels as limiting factors to rice production in West Africa lowlands. *Geoderma* **94**: 23-42.

Darmawan, Kyuma, K., Saleh, H. Subagjo, Masunaga, T., and Wakatsuki, T. 2006a.

Effect of green revolution technology from 1970 to 2003 on Sawah soil properties in Java, Indonesia: I. Carbon and nitrogen distribution under different land management and soil types, Soil Sci. Plant Nutr., 52(5): 634-644

Darmawan, Kyuma, K., Saleh, H. Subagjo, Masunaga, T., and Wakatsuki, T. 2006b.

Effect of green revolution technology from 1970 to 2003 on Sawah soil properties in Java, Indonesia: II. Changes in the chemical properties of soils, Soil Sci. Plant Nutr., 52(5): 645-653

De Datta, S.K. and Buresh, R. J. 1986. Integrated nitrogen management in irrigated rice, *Adv. Soil Sci.*, 10:143-169

Eswaran, H., Kimble, J., Cook, T., and Beinroth, F.H. 1992: Soil Diversity in the Tropics: Implications for Agricultural Development. *In* Lal R and Sanchez P ed., "*Myths and Science of Soils of the Tropics*", 1-16, SSSA Special Publication Number 29, Wisconsin, USA

Eswaran, H., Almaraz, R., van den Berg, E. and Reich, P. 1997. An assessment of the soil resources of Africa in relation to productivity. *Geoderma*, **77**, 1-18

Evenson, R.E. and Gollin, D. 2003. Assessing the impact of the Green Revolution, 1960 to 2000, *Science*, **300**:758-762

FAOSTAT 2006

Fashola, O.O., Oladele. O., Alabi, M.O., Tologbone, D. and Wakatsuki, T. 2007a. Socio-economic factors influencing the adoption of Sawah rice production technology in Nigeria. *J. Food, Agriculture & Enivironment-JFAE*, 5:239-242

Fashola, O.O., Ademiluyi, Faleye, T, James, D. and Wakatsuki, T. 2007b. Machinery systems management of walking tractors (power tillers) for rice production (Sawah) in Nigeria, . *J. Food, Agriculture & Enivironment-JFAE*, 5:284-287

Greenland, D.J. 1997. *Sustainability of Rice Farming*, CAB Int'l, U.K. and IRRI, Los Banos, 273pp

Hirose, H. and Wakatsuki, T. 2002. *Restoration of Inalnd Valley Ecosystems in West Africa*, Nourin Tokei Kyoukai, Tokyo. 600pp

Hsieh, S.C. 2003. *Agricultural Technology Transfer to Developing Countries*, National Pintung University of

Science and Technology Press, Taipei, 310pp

IITA 1989/1990. *Annual Report 1989/1990* International Institute of Tropical Agriculture, Ibadan, 20-21pp

Issaka, R. N., Ishida, F., Kubota, D., and Wakatsuki, T. 1997. Geographical distribution of selected soil fertility parameters of inland valleys in West Africa. *Geoderma* **75**: 99-116.

Jamin, J.Y. and Widmeijer, P.N. 1995. *Characterization of Inland Valley Agro-ecosystems: a Tool for their Sustainable Use*. Proceedings of the 1st Scientific Workshop of the Inland Valley Consortium, WARDA, Boauke, November 6-10, 1995, 325pp

JICA, 2003. *Study on international cooperation in rice farming in West Africa*, Japan International Cooperation Agency, JICA, Tokyo, 92pp+ Apendixes

Kawaguchi, K. and Kyuma, K. 1977. *Paddy Soils in Tropical Asia, Their Materials, Nature and Fertility*, University Hawaii Press, pp258,

Kiple, K.F and Ornelas, K.C. 2000. *The Cambridge World History of Food*, Cambridge Univ. Press, Cambridge. 2153pp.

Kyuma, K. 2004. *Paddy Soil Science*, Kyoto University Press, Kyoto, 280pp

Kyuma, K., Kosaki, T., and Juo, A.S.R. 1986. Evaluation of the fertility of the soils. In: *The Wetlands and Rice in Subsaharan Africa* Juo, A. S. R. and J. A. Lowe (Eds) , 43-58pp, Inter. Inst. Trop. Agric. , Ibadan

Levinson, D.H. 2005. *State of the Climate in 2004*. BAMS, American Meteorological Society, 1-89pp

Ministry of Food and Agriculture, Ghana 2007a. Inland valley rice development project, IVRDP, Consultancy Services for Surveys, Design and Construction

Supervision of Water Management Structures (LOT 1) PHASE 1, FINAL DESIGN REPORT, 96pp

Ministry of Food and Agriculture, Ghana 2007b. Inland valley rice development project, IVRDP, Consultancy Services for Surveys, Design and Construction

Supervision of Water Management Structures (LOT 5) PHASE 1, FINAL DESIGN REPORT, 55pp

Moormann, F. R., and Veldcamp, W.J. 1978. Land and rice in Africa: constraints and potentials. In: *Rice in Africa* Buddenhagen, I. W. and G. J. Persley (Eds), pp29-43 Academic Press, London

Ofori, J., Hisatomi, Y., Kamidouzono, A., Masunaga, T., and Wakatsuki, T. 2005. Performance of Rice Cultivars in Various Sawah Ecosystems Developed in Inland Valleys, Ashanti Region, Ghana, *Soil Sci. Plant Nutr.,* 51:469-476

Okigbo, B.N. 1990. Sustainable Agricultural Systems in Tropical Africa, In: *Sustainable Agricultural Systems*. Edwards, A., Lal, R., Madden, P., Miller, R.H., and House. G. (Eds), pp323-352, SWCS, Iowa

Qian, W., Debg, Y., Zhu, Y. and Dong, W. 2002. Demarcating the worldwide monsoon, *Theor. Appl. Climatol*. 71:1-16

Rasyidin, A. and Wakatsuki, T. 1994. Characterization of Precipitation and River Water Chemistry for Measuring Rates of Weathering and Soil Formation in Iu-River Watersheds, Southwestern Japan. *Soil Sci. Plant Nutr.,* 40:319-332

Ruthenberg, H. 1980. *Farming Systems in the Tropics*, Oxford Univ. Press, London, 424pp

Sanchez, P. 1976. *Properties and Management of Soils in Tropics,* Wiley & Sons, New York, 619pp

Smaling, E. M. A., Dyfan, T., and Andriesse, W. 1985 a. *Detailed Soil Survey and Quantitative Land Evaluation of the Rogbom-Makene and Matam-Romangoro Benchmark Sites, Makeni, Sierra Leone*, Wetland Utilization Research Project, Phase II, ILRI, Wageningen, The Netherlands

Smaling, E. M. A., Kiestra, E., and Andriesse, W. 1985 b. *Detailed Soil Survey nd Quantitative Land Evaluation of the Echin-Woye and Kunko Benchmark Sites, Bida, Niger State, Nigeria*, Wetland Utilization Research Project, Phase II, ILRI, Wageningen, The Netherlands

Soil Survey Staff, 1998. *Keys to Soil Taxonomy*, 6th ed., SMSS of USDA, Washington DC, 306pp

Soil Survey Staff, 1999. *Soil Taxonomy, A Basic System of Soil Classification for Making and Interpreting Soil Surveys,* Natural Resources Conservation Service of USDA, Washington D C, 869pp

Takase, K. and Kano, T., 1969. "Development Strategies on Irrigation and Drainage" in Asian Agriculture Survey, Asian Development Bank, 520pp

Tian, G., Ishiada, F., and Keatinge, D. 2001. *Sustaining Soil Fertility in West Africa*, SSSA Special Pub. No.58, 321pp

Trenberth, K.E., Stepaniak, D.P., Caron, J.M. 2000. The Global Monsoon as Seen through the Divergent Atmospheric Circulation. *Journal of Climate*, 13:3969-3993

Wakatsuki, T. 2002. Sustainable agricultura development of West Africa during global environmental crises, In : *Restoration of Inland Valley Ecosystems in West Africa*. Hirose, S. and Wakatsuki, T. (Eds), pp1-82, Nourin Tokei Kyoukai, Tokyo

Wakatsuki, T. 2009. http://www.kinki-ecotech.jp/

Wakatsuki, T. and Rasyidin, A. 1992. Rates of Weathering and Soil Formation, *Geoderma* 52:251-261

Wakatsuki, T., Rasyidin, A., and Naganawa, T. 1993. Multiple Regression Method for Estimating Rates of Weathering and Soil Formation in Watersheds. *Soil Sci. Plant Nutr.*, 39:153-159

Wakatsuki, T., Shinmura, Y., Otoo, E., and Olaniyan. 1998. Sawah system for integrated watershed management of small inland valleys in West Africa. In FAO ed., Water Report N0.17, *Institutional and Technical Options in the Development and Management of Small Scale Irrigation*, pp45-60, FAO, Rome

Wakatsuki, T., Otoo, E., Andah, W.E.I., Cobbina, J., Buri, M.M., and Kubota, D. (eds). 2001. *Integrated Watershed Management of Inland Valley in Ghana and West Africa: Ecotechnology Approach*, Final Report on JICA/CRI joint study project, CRI, Kumasi, Ghana and JICA, Tokyo, 337pp

Wakatsuki, T. and Masuanga, T. 2005. Ecological Engineering for Sustainabel Food Production and the Restoration of Degraded Waterheds in Tropics of low pH Soils: Focus on West Africa. *Soil Sci. Plant Nutr.*, 51:629-636

Wakatsuki, T., Buri, M.M., and Fashola, O.O. 2005. Ecological Engineering for sustainable rice production and the restoration of degraded watersheds in West Africa. In: *Rice is life: Scientific Perspectives for the 21st Century*. Toriyama, K., Heong, K.L., and Hardey, B.(Eds), pp363-366, IRRI, JIRCAS, NARO, NIAS, NIAES, NIRE, APO, MAFF, Tsukuba

Walling, D.H. 1983. The sediment delivery problem. *J. Hydrological Sci*., 65:209-237

WARDA 1988. *WARDA's Strategic Plan: 1990-2000*. Bouake. 66pp.

WARDA, 2002. The African Rice Initiative (ARI): NERICA Consortium Security in Sub Saharan Africa. 40pp.

WARDA, 2004. *Strategic Plan: 2003-2012*, WARAD-The Africa Rice Center, Bouake. 58pp

Windmeijer, P.N. and Andriesse, W. 1993. Inland Valley in West Africa: An Agroecological Characterization of Rice-Growing Environment, ILRI, Wageningen, 160pp.