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Ecological Engineering for Sustainable Food Production and the Restoration of Degraded Watersheds in Tropics of Low pH Soils: Focus on West Africa

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Since upland rice under shifting cultivation is common, the mean paddy yield in sub-Sahara Africa (SSA), especially West Africa, has been stagnated at 1.3–1.7 t ha^{-1} during the past 30 years of 1970–2000. There exist numerous small inland valley swamps (IVS), of which 10 million ha is capable of being turned into small scale irrigated rice fields, i.e., sawah* by simple and low cost ecological engineering technology with farmer's self-support efforts. The fertility of lowland soils in West Africa was the lowest, particularly available phosphorous status was extremely poor and low pH as well as low exchangeable bases among the three tropics of Asia, Africa and Latin America. However, because of multi-functional mechanisms of soil and water conservation and replenishment of nutrients, sustainable productivity of 1 ha of lowland sawah system can be equivalent more than 10 ha of upland fields. Geological fertilization, nitrogen fixation, neutralization of pH and increase phosphorous availability are the important functions of the sawah system. Sustainable development of sawah systems in IVSs can contribute to increase food production and to restore the degraded watersheds of SSA. *Sawah: The term sawah refers to leveled rice field surrounded by bund with inlet and outlet connecting irrigation and drainage. The term originates from Malayo-Indonesian. The English term, Paddy or Paddi, also originates from the Malayo-Indonesian term, Padi, which means rice plant. The term, Paddy, refers to rice grain with husk in West Africa of SSA. Most of the paddy fields in the Asian countries correspond to the definition of the term sawah. Paddy field is almost equivalent to sawah for Asian scientists. However, the term paddy fields refers to just a rice field including upland rice field in West Africa of SSA. Therefore in order to avoid confusion between the terms rice plant, paddy, and the improved man-made rice growth environment through ecological engineering, the authors propose to use the term sawah.

Key Words: **ecological engineering, inland valleys, multi-functionality of sawah system, restoration of degraded watersheds, sub-Sahara West Africa.**

The distribution characteristics of major soils are quite different among the three major tropics, i.e., tropical Asia, Africa, and America. Table 1 shows the estimated area of each soil order in the three major tropical zones (Sanchez 1976; Okagawa 1984; Wambeke 1992; Eswaran et al. 1992, 1997; Soil Survey Staff 1998, 1999; Kyuma 2001; Hirose and Wakatsuki 2002). In the figures, although Psamments is a suborder belonging to the Entisol order, they are dealt with in an order-equivalent soil category. This is because they are mainly quartzitic sandy soils containing almost no weatherable primary minerals, like Oxisols. In tropical Africa, the combined area of Oxisols and Psamments, the aged, leached, nutrient depleted low pH soils, and Aridisols accounts for 64% of all land. Although very acid low pH Ultisols are widespread, since the geology is much younger, Oxisols, Psamments and Aridisols, unsuitable for agriculture, are little distributed in tropical Asia. In tropical America, Oxisols have wide distribution, 43%, but few distributions of Aridisols and Psamments. Of tropical soil types, Andisols on upland and Inceptisols in lowland have good moisture and fertility in general. While intensive farming is practiced on Andisols in all of the three tropical zones, Inceptisols in lowlands are not very much used in tropical Africa (Windmeijer et al. 1993) and America. In tropical Asia, however, the lowland Inceptisols are utilized for irrigated sawah based rice production systems. The sawah systems produce rice food for more than two billion people on a sustainable basis (Greenland 1997; Kyuma 2003).

In sub-Sahara tropical Africa (SSA), agriculture is mostly upland cultivation by traditional sifting cultivation systems even under rapid population expansion, which destroys forests. In addition lowlands have not yet been widely used. As a result, about 400 million ha of forests have already been lost and turned into degraded land (UNEP/ISRIC 1991; UNEP 1997). West Africa is a core region of sub-Saharan tropical Africa (SSA) and a typical region where food and environmental crises is becoming increasingly serious and the deteriorating environment is threatening human survival (Hirose and Wakatsuki 1997, 2002; Hirano 2002; Sanchez 2002; Conway and Toenniessen 2003). During 1986 to 1998, Wakatsuki conducted various survey trips on the 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, Cameroon and the Dem. Rep. of the Congo. Soil fertility characteristics were evaluated and their fertility was compared with that of soils in tropical Asia and Japan. The results were summarized in Table 2 (Wakatsuki 1988; Hirose and Wakatsuki 1997, 2002; Issaka et al. 1997; Kawaguchi and Kyuma 1977; Buri et al. 1999, 2000). Total carbon and nitrogen content were low for West Africa and tropical Asia. The mean values of available phosphorus 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 addition, some micro-nutrients, such as sulfur and zinc also, are generally very low and about 60–80% of lowland soils, both inland valleys and flood plains, are in deficient level (Buri et al. 2000). Comparison of soil fertility data of tropical America by Tanaka et al. (1984, 1986) revealed that the fertility of lowland soils in West Africa was the lowest (Hirose and Wakatsuki 2002).

In high rainfall zones of West Africa such as equatorial forest in Liberia and Sierra Leone, Oxisols are widespread in upland areas. The typical topsequence of inland valley soils near Makeni in central Sierra Leone was Oxisols in flat upland, Oxisols/Ultisols in slopes and Inceptisols in valley bottom. The eCEC of the topsoils were 1–5 cmol(+) kg^{-1} and exchange acidity percentages were 10–90% throughout the topsequence (Smaling et al. 1985a,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, Bray and Kurtz 1945) 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 5 cmol(+) kg^{-1}. Low activity clay soils are predominated. In addition to the poor soil fertility, the recent shortage of rainfall also further makes it difficult to conduct sustainable upland farming.

Table 1. Major soil distributions in the three tropics based on the Soil Taxonomy (Hirose and Wakatsuki 2002).

	Entisol	Spodosol	Histosol	Ultisol	Inceptisol	Andisol	Oxisol	Psamment	Alfisol	Mollisol	Vertisol	Aridisol	Total
Soil characteristics	Immature parent materials	Sandy, leaching	Peat wetland	Strongly weathered, acid	Young vitality	Volcanic ash, fertile	Aging, leaching	Quartz leaching	Eutrophic low activity	Grasslands, dry season	Black, semi-arid	Dry, desert	(excluding no-soil surface)
Tropical Africa	50	3	2	190	240	5	440	340	320	4	100	810	2,504
Tropical America	90	0.5	5	330	130	90	660	20	120	15	20	50	1,531
Tropical 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

Table 2. Mean values of fertility properties of inland valleys (IVS) and flood plains (FLP) of West Africa in comparison with lowland topsoils of tropical Asia and Japan (Hirose and Wakatsuki 2002).

Location	pH	Total C (%)	Total N (%)	Available P (ppm)[b]	Exchangeable cation ($cmol\ kg^{-1}$)				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[a]	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

[a]Kawaguchi and Kyuma 1977, [b]Bray II.

Recent report by Annan et al. (2004a, b) described the soil fertility characteristics of upland to lowland topsequence in watersheds in forest savannah transitional zone, Ashanti region of Ghana. They reported that the upland soils were rather more fertile than lowland soils. These general fertility trends along upland to lowland topsequence were quite different to those of monsoon Asia and Japan (Kamidohzono et al. 2002a, b), where the sustainable sawah based lowland rice farming has more than thousand of years' history.

Although organic matter management through agroforestry and cover crop systems are possible options for 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 poor soils must be developed. For in terms of sustainability, re-evaluation of traditional technology is important (Barrera-Bassols and Zinck 2000; Ishida et al. 2001; Kamidohzono et al. 2002a, b). For sustainable increase to cope with present population expansion, however, only re-evaluation of traditional farming is not enough (Wakatsuki et al. 1998; Hayashi and Wakatsuki 2002; Hirose and Wakatsuki 2002). As discussed in this paper new concept of ecological engineering technology is necessary. The African adaptive sawah-based lowland farming with small-scale irrigation scheme for the integrated watershed management will be the most promising strategy to increase sustainable food production and the same time to restore degraded watersheds in tropical areas, especially in SSA.

Conceptual Frameworks for the Restoration of Degraded Inland Valley Watersheds in West Africa of SSA

Sawah hypothesis: Sawah system and integrated watershed approach

Why has the green revolution not yet occurred in SSA and in West Africa in spite of its success in Asia in the 1960s? The green revolution laid the foundation for the rapidly growing economies of Asia today. The layouts of groups of sawahs in the lowlands in a watershed were adapted to the local topography for efficient irrigation and drainage. The main cause of the present agricultural and environmental crises in SSA and in West Africa is the general under development of lowland agriculture. Environmentally creative technology, or ecological engineering technology, such as sawah farming is not traditionally practiced in sub-Saharan Africa. Sawah is multifunctional constructed wetland, which is the prerequisite for realizing the green revolution as well as for preserving and even restoring ecological environments. Irrigation and drainage without sawah farming technologies has proved inefficient or even dangerous because of accelerating erosion. Thus, the development of irrigation has been slow. In the absence of water control, fertilizers cannot be used efficiently. Consequently, the high yielding varieties are useless and soil fertility cannot be sustained. Hence, the green revolution cannot take place (Wakatsuki et al. 1998).

As shown in Fig. 1, soil formed and nutrients released during weathering in upland are accumulated in lowlands (geological fertilization). If sawah system exists in lowlands, it can store and effectively use these nutrient rich water and fertile topsoils. This is an eco-environmental basis for long-term sustainability of high productivity of Sawah based rice farming in Asia.

Suppose the soil formation rate in uplands, which make up 95% of the total area in the example of a watershed shown in Fig. 1, to be 1 $t\ ha^{-1}\ y^{-1}$. In a stable ecosystem in a watershed, the rate of soil formation and erosion should be well balanced; therefore, the topsoils formed in uplands—which account for 95%—and the nutrients produced in the process will be concentrated in lowlands, which make up 5% of the area. Thus the soil formation rate in the lowlands equals to 20 $t\ ha^{-1}\ y^{-1}$. Though it will be impossible to use all of the rich soils and nutrient rich water from the uplands effectively, sawah will be the best system for making an effective use of them. A sawah system in lowlands is, as it were, the one for effectively using the interest accrued from the huge stocks named "uplands." This farming system could artificially reinforce the geological fertilization processes, which are 1) Lowland soil formation and 2) Regeneration of the soils. The quantitative scientific evaluation of the geological fertilization process in a watershed will be important future research subject.

The sustainability under intensive cultivation of upland can be possible through the integration with stock raisings. Animals can accumulate nutrients on upland farms and lowlands. However as shown in the Fig. 2, since natural and artificial water flows can accu-

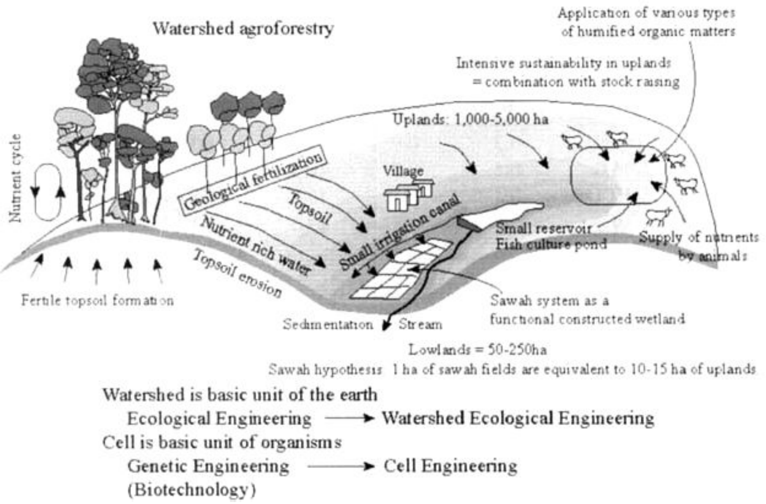

Fig. 1. The concept of watershed ecological engineering. Cell is the basic unit of organisms and biotechnology, or genetic engineering, is practiced by cell engineering. If we apply the progress of the biotechnology to ecotechnology or ecological engineering, the watershed ecological engineering will be the key component. Watershed agroforestry through the integration of upland forestry and lowland sawah systems in a unit watershed is a possible typical model of the watershed ecological engineering.

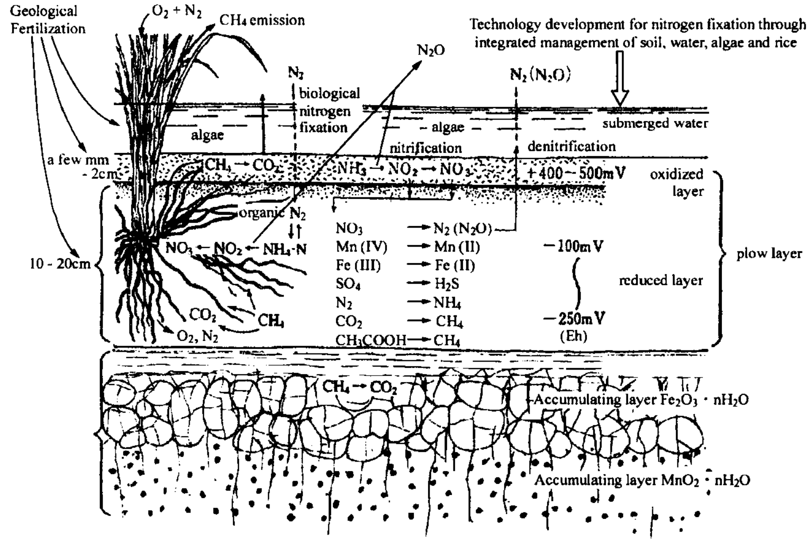

Fig. 2. Sawah system: functional constructed wetland. Estimated nitrogen fixation is 20–200 kg N ha^{-1} y^{-1}. Morphology of sawah soil profile and various redox reactions to increase soil fertility (Modification based on Wada in 1984 and Minami in 1994 which were cited by Wakatsuki in 1997).

mulate the nutrients in lowland sawah, the advantage of sawah to upland is clear. The excessive decomposition of organic matter in tropical soils is another problem. Because of wetland, sawah system can control such excessive organic matter decomposition (Kyuma 2001). Another possibility to restore the upland soil fertility is the application of refractory humified organic matters to soil (Wakatsuki et al. 2003). However except for lowland sawah farming, these options are not so successful to make the tropical upland farming sustainable under intensive cultivation.

When the unit yields of upland slash and burn rice cultivation is compared to that of lowland sawah rice cultivation, the latter (2.5 t ha^{-1}) is approximately 2.5 times higher than the former (1 t ha^{-1}) under the condition of no fertilizer application. With standard fertilizer application, the unit yield of sawah rice increases to 5–6 t ha^{-1}. In contrast, fertilizer application is not a viable option for rainfed upland rice cultivation because of its low efficiency unless soil conservation measures and infrastructures, such as terracing, are provided. In addition, the planting of rice in rainfed upland areas based on the slash and burn method of farming must be followed by a fallow period of at least 4–5 years to allow restoration of the soil fertility, i.e., for the sustainable 1 ha of upland rice cultivation based on slash and burn, 4–5 ha of upland are necessary. In comparison, continuous cultivation is possible with sawah fields as they have various mechanisms to restore the soil fertility by geological fertilization (Fig. 1) in the watershed and cultivation under submerged water condition (Fig. 2). When these two types of cultivation are compared for a long period of 10-plus years, which are necessary for sustaining a complete cycle of slash and burn cultivation, taking the above facts into consideration, the difference in sustainable unit productivity can be more than tenfold, i.e., yield difference (2.5) times difference of required area (4–5 times) for sustainable production. Accordingly, the development of 1 ha of sawah field enables the conservation or regeneration of 10 ha or more of forest area. Sawah fields can, therefore, contribute to not only increased food production but also conservation of the forest environment as well as soil and water conservation in the catchment area, resulting in the enhanced sustainability of an intensive lowland sawah field system. Furthermore, they can contribute to the alleviation of global warming and other global environmental problems through the fixation of carbon to forests and forest soil.

Sawah system as multi-functional constructed wetland: High sustainability

Figures 1 and 2 show the various mechanisms of intensive and long terms ecological sustainability of sawah fields. It is well-known that weeds can be controlled by means of water control. But it is not well evaluated that the nitrogen fixation amount of soil microbes under a submerged sawah systems reach to 20–100 kg ha^{-1} y^{-1} in Japan and 20–200 kg ha^{-1} y^{-1} in the tropics depending on the level of soil fertility and water management (Hirose and Wakatsuki 2002; Kyuma 2003). This amount is comparable with the nitrogen fixation amount of leguminous plants. Rainfed upland farming has no such option but to rely on the use of leguminous plants, animal dung, other organic fertilizer, and or chemical fertilizers. The above-mentioned advantage of the sawah field system in lowland areas through water management is not properly understood.

Under submerged condition, because of reduction of ferric iron to ferrous iron, phosphorous availability is increased and acid pH is neutralized, hence micro-nutrients availability is also increased (Kyuma 2003). These are the other benefit of sawah systems. These eutrophication mechanisms are not only encourage the growth of rice plant but also encourage the growth of various algae that increase the nitrogen fixation. The quantitative evaluation of nitrogen fixation in sawah systems including the role of algae will be also important future research topics.

Under nitrate rich submerged water condition, sawah systems encourage the denitrification. Easily decomposable organic matters become substrate of various denitrifyers. This is another function of sawah system for purify the nitrate polluted water (Wakatsuki 2002; Kyuma 2003).

Eco-Technology Approach to Low-Cost and Self-Support Sustainable Sawah Development in Sub-Saharan West Africa

State of rice cultivation in West Africa

In West Africa of SSA rice production increased 280% last 30 years, which is far bigger than the increase of other cereals, such as maize 170%, sorghum 170% and millet 150% (FAOSTAT 2005). Nevertheless, the amount of rice import has increased. This increase of rice production basically came from the expansion of upland rice cultivation that causes destruction of forest. Sustainable and intensive lowland rice systems are what is needed and not the ecology-destructive upland rice systems. However it is now very difficult to build new irrigation project because of the high cost of irrigation and its apparent low net return. The eco-technology approach to sustainable sawah development will be a promising new method. Rice cultivation in West Africa has traditionally been an extension of upland farming. The topography of West Africa is dominated by peneplains that are very flat with few undulations. There are many areas where the natural topography provides dipped areas which are ideal for the collection of water and the cultivation of rice without the deliberate development of sawah fields. Typical examples are a rice growing area near Abakaliki in southeast Nigeria and rainfed lowland areas in Sierra Leone. In areas like these, rice has long been cultivated without clear distinction between lowland sawah based rice cultivation and upland rice cultivation. However, following the pioneering technical cooperation activities of Taiwanese teams regarding to wide spread and intensive sawah based farming for some 10 years in the 1960's and 1970's, the number of rice farmers who are consciously conducting water management has been steadily increasing throughout the subsequent 30–40 years (WARDA 1988, 2002; Toon et al. 2002; Nagumo 2003; Hsieh 2001). Such management involves the introduction of bunding, leveling, construction of dams, dykes and weir and extension of water canals. Consequently, there are now many types of rice cultivation in terms of water control, ranging from upland rice cultivation to irrigated lowland sawah.

Constraints for sustainable development of irrigation systems

It is now very difficult to build new irrigation project through traditional way of Official Development Assistance (ODA) because of the high cost of irrigation and its apparent low net return. A large-scale irrigation project is very costly. Although the total sales of produces is between 1,000–1,500 dollars per ha, the running cost including maintenance of the systems, machinery for operation, agrochemicals for rice cultivation is 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). Owing to various problems in large scheme, small irrigation schemes are considered more suitable to develop at present. However, with the present small irrigation schemes, the construction cost is comparable to large schemes as far as their development depends mainly on engineering work by experts. Therefore the project ownership still belongs to the government (engineers) rather than the farmers. The production level of rice farmers could not compensate for the high construction cost. As described below, the eco-technology approach to sustainable sawah development proposed by the joint study between JICA/Ghana will be a promising new method (Wakatsuki et al. 2001; Hirose and Wakatsuki 2002).

Restoration of Degraded Inland Valley Watersheds in West Africa: A Case Study of Ecological Engineering Project

The term, Ecological Engineering Technology (Eco-Technology), is defined here as an ecology-based sustainable farming technology viable to local socio-cultural systems to increase farming productivity and to improve the environment. The ecotechnology can be developed and managed by local farmers to control water and to conserve water and soil. Leveling, bunding, and construction of canal and head dyke are the example of such ecotechnologies, which can be practiced as an extension of agronomic practices using locally available tools and materials. Forestry technology, such as nursery preparation and management, contour bund planting of the useful trees, regeneration of the water and soil conservation forest, and to establish carbon sequestration against global warming are the examples of the ecotechnology which this project are going to develop. The ecotechnology will be the key technology to attract local farmers' active participation for the improvement of basic agricultural infrastructure, such as irrigation and soil conservation measure. The ecotechnology will be able to integrate partly between agronomy and agricultural engineering as well as ecological sciences and various engineering.

The focus of research activities is to develop suitable Ecological Engineering Technologies (Eco-Technologies) for integrated watershed/rural development through increasing sustainable productivity and at the same time through improving the total water cycling in a given watershed. Eco-technologies should be adaptive to Indigenous Farming Systems and rural village society. Various area of benchmark watersheds, from 100 to 10,000 ha, which is located 40–50 km northwest from Kumasi, has been selected for basic agroecological survey. Among and surrounding watersheds, various sized watersheds including Adujama, Potrikrom, Biemtetrete, and Biemso No. 1 and No. 2 villages were selected for detailed survey and intensive field testing for participatory low cost sustainable sawah under the JICA project with collaboration of Ghana (Fig. 3; Wakatsuki et al. 2001; Hirose and Wakatsuki 2002).

During JICA/Ghana joint study, the project tested various types of sawah systems including rainfed, pump, spring, weir and canal and integrated types, adapting in diverse reliefs, soils and water conditions. Participated farmers groups played major role for the on-farm testing of various types of eco-technologies. Based on the various participatory on-farm experiments and evaluations on various sawah eco-technologies, the project could propose the following new eco-technology and loan

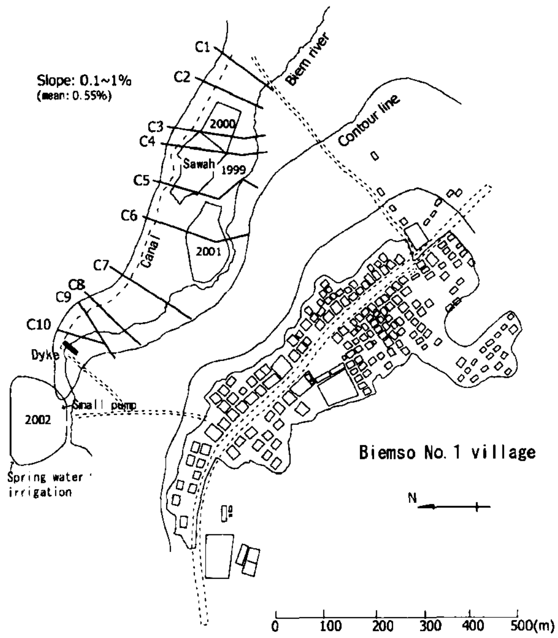

Fig. 3. Proceedings of self-support development of Biemso No. 1 sawah system with cross section lines (C1–10) for details topographical survey (Wakatsuki 2002).

based sustainable small scale sawah development for integrated watershed management of inland valley in Ghana and West Africa. Although following proposal is a draft, it can be improved and consolidated through continuous field practices and dialog with participating farmers (Wakatsuki 2002; Takase et al. 2003).

Possible funding for sawah development to make the eco-technology approach sustainable in Ghana and West Africa

1. Call for sawah group formation of about 10 farmers
2. $6,000 loan for one group: breakdown
   $4,000 for power tiller
   $500 for tools for development and rice cultivation
   $500 for small pump
   $1,000 for annual running cost including fuel, spare parts, fertilizer, sand bags and pesticides
3. Provision of free technical advice, on the job training and education. Institutional backstopping to facilitate such technical advice. The development of sawah system for rice cultivation by sawah group without external assistance.
4. 1 ha of sawah development; 5 ha per 5 years during the 5 years of no loan payment. During 6–11 years, loan payment with 5% interest (Note: in the case of African bank loan, no interest is necessary to pay). Total payment will be $7,050 and annual mean payment will be $1,175.
5. 1st year income will be $1,350, assuming a rice sale of $1,100 from 3.5 t ha^{-1} and dry season vegetable of $200.

6. 2–5th year: total sales will be \$2,600–\$6,500 and running cost, \$600–\$1,000 annually.
7. 6th year: yield will increase to 4.5 t ha^{-1}, vegetable production will also increase by same rate. Then total sales will be \$7,300 per group. The net income will be \$5,125 after paying mean annual loan, \$1,175 and depositing the necessary annual running cost, \$1,000. Mean annual income per each farmer will be \$500 (currently about \$250).
8. Continue to produce more sawah up to about 10 ha. Then annual income will be \$1,000.
9. During the project period, plots of multipurpose tree species and other useful trees are enlarged. Fishponds are constructed and tilapia, catfish, etc. are cultured there.

In 2003, a new but continuing 5 year research project had started under the title of "Watershed Ecological Engineering for Sustainble Increase of Food Production and Restoration of Degraded Environment in West Africa" (Wakatsuki 2005). Major outcome will be to consolidate the long term comprehensive plan for sustainable development of 20 million ha of lowland sawah systems in SSA. Based on the sustainable increase of food production through the sawah development, our final target is the regeneration of 200 million ha of forest in SSA.

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