Site-specific *sawah* development and management by farmers: Large-scale action-research in Ghana and Nigeria to actualize rice green revolution

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Abstract

Since the dramatic success of the green revolution in tropical Asia in the 1960s and 1970s, similar variety-oriented research for has been intensively and extensively conducted in sub-Saharan Africa (SSA). However, a green revolution has yet to be realized in SSA. Sustainable agricultural productivity is increased by balanced application of both varietal improvement through biotechnology and improvements in the rice ecological environment through eco-technology. Compared to biotechnological research for technology development and dissemination, eco-technology has been largely neglected in SSA since the late 1960s. *Sawah* eco-technology is one such key technology for African rice farmers. The term of '*sawah*' is of Indonesian origin, and refers to a leveled, bunded and puddled rice field with water inlets and outlets to improve water control and thus soil productivity. Since *sawah* eco-technolgy can improve fertilizer and irrigation efficiency, improved varieties could lead to the realization of a green revolution. Lowland *sawah* systems can sustain paddy yields higher than 4 t/ha through various macro-scale natural geological fertilization processes (from upland to lowland) and micro-scale mechanisms to enhance the supply of various nutrients. With the application of advanced agronomic practices, such as the System of Rice Intensification, sustainable paddy yields above 10 t/ha can be achieved in lowlands with quality *sawah*, and soil and water management. The lowland *sawah* system development potential is at least 20 million ha in SSA. However, African lowlands are quite diverse and differ from Asian lowlands. Therefore, careful site-specific *sawah* development and management technologies need to be investigated. After long-term basic and large-scale action-research during 1986–2010, we were able to establish basic technology for 'site-specific irrigated *sawah* systems developed and managed by farmers' through self-support efforts, i.e. '*sawah* approach', in various inland valley ecosystems in Ghana and Nigeria.

Introduction

In 1935, Dr Gonjiro Inazuka, a breeder at Iwate Prefectural experimental station, Japan, successfully bred Norin 10 wheat varietiy. In 1948, Norin 10 was collected by scientists who accompanied US occupying forces in Japan. In 1953, the variety was transferred to Dr Norman Borlaug at Chapingo, Mexico. By 1957, he had bred and released 14 high-yielding varieties using Norin 10. This research was the start of the dramatically successful green revolution and the start of the Consultative Group on International Agricultural Research centers in the 1960s and 1970s (Senda, 1996; Evenson and Gollin, 2003; Hesser, 2006; Hardin, 2008; Renkow and Byerlee 2010). Norin 10 was the first crop variety in which the characteristics of the semi-dwarf gene, *sd1*, were identified. All high-yielding varieties of wheat, maize and rice have the same *sd1* gene (Gale and Devos, 1998; Ashikari *et al.*, 2002; Sakamoto *et al.*, 2004; Matsuoka, 2004). Thus, Inazuka is the 'grandfather' of the green revolution.

Although the Africa Rice Center (AfricaRice) developed the NERICA technologies, and variety-oriented research and technology dissemination have been intensively and extensively conducted, a successful path to a rice green revolution in Africa remains unclear (Djurfeldt *et al.*, 2005; Otsuka, 2006; Otsuka and Kalirajan, 2006; Orr *et al.*, 2008; Wopereis *et al.*, 2008). In 2007, the Alliance for a Green Revolution in Africa (AGRA, 2009) started large-scale activities (Toenniessen *et al.*, 2008). The Government of Japan has committed strong support for increasing rice production in Africa through the establishment of the Coalition for African Rice Development (CARD, 2008), an outcome of the Fourth Tokyo International Conference on African Development (TICAD4, Yokohama, Japan, May 2008). Although some natural-resources-management oriented modifications have been stressed, all of these major world organizations hypothesize that the core technology to realize a green revolution in Africa will be varietal improvement achieved, similar to what happened in tropical Asia.

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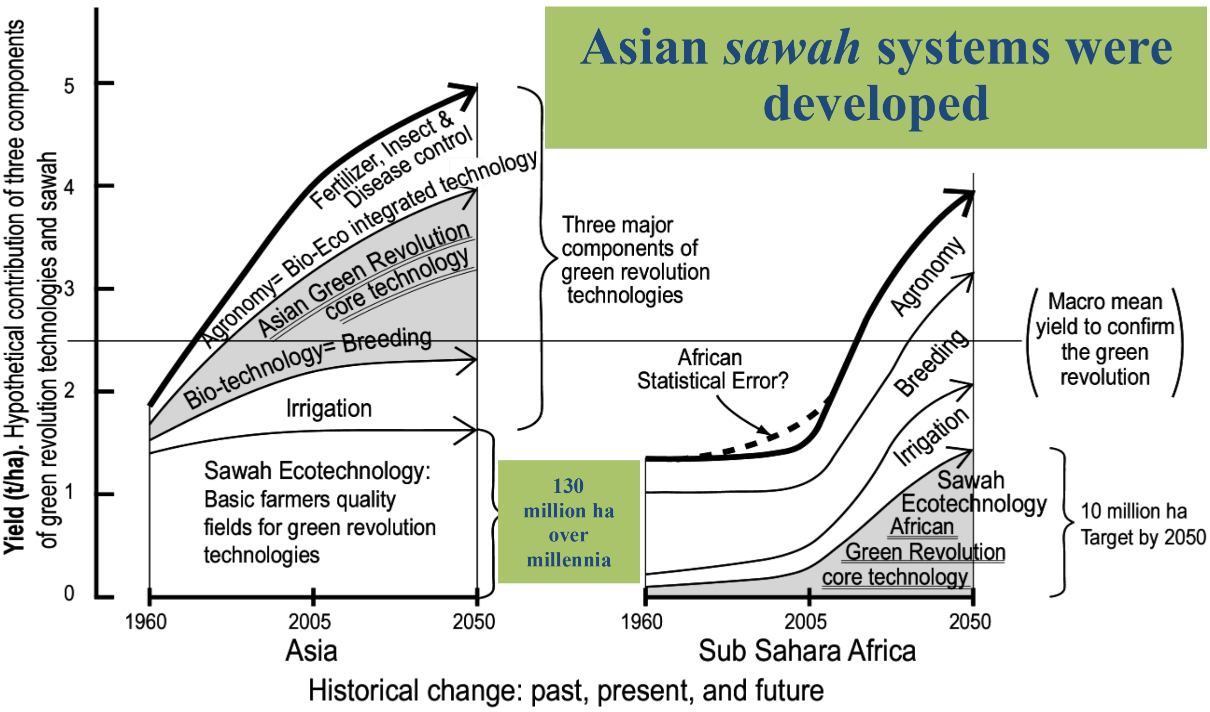

Figure 1. *Sawah* hypothesis I: *Sawah* ecotechnology is a prerequisite for applying the three green-revolution technologies to farmers' rice fields. Drawings show hypothetical contribution of the three green-revolution technologies and *sawah* system development during 1960–2050. Bold lines are mean rice yield for 1960–2005 (FAOSTAT, 2006) and the estimation by the authors for 2005–2050.

This paper explains that the core technology for an SSA green revolution is *sawah* eco-technology (Fig. 1) (Wakatsuki *et al.*, 1998, 2001, 2005, 2009; Hirose and Wakatsuki 2002; Wakatsuki and Masunaga, 2005; Oladele *et al.*, 2010; Abe and Wakatsuki, in press). This paper also explains five key technologies necessary for the *sawah* approach to realize a green revolution in SSA.

Sawah hypothesis (I) for a green revolution in sub-Saharan Africa

A rice green revolution must include three core technologies: (1) irrigation, (2) fertilizers and agrochemicals, and (3) high-yielding varieties. Although all these technologies have been available since the late 1960s, they have not been effective in farmers' fields in SSA. In order to apply these scientific technologies, farmers' fields need *sawah* or other similar alternatives to conserve soil and control water, typically in the lowlands (*sawah* hypothesis I, Fig. 1). Essential components for such land development are: (1) demarcation by bunding based on topography, hydrology and soils; (2) leveling and puddling to control and conserve soil and water; and (3) water inlets to access water, typically various irrigation facilities, and water outlets to drain excess water. These are the characteristics of *sawah* fields.

For various social and historical reasons since the 1500s, it has not been possible for these basic land and infrastructure developments to make the scientific technologies necessary for a green revolution possible to be developed in SSA (Hirose and Wakatsuki, 2002).

Sawah hypothesis (II) for intensive long-term sustainability and to combat global warming

The upper portion of Figure 2 illustrates the concept of watershed eco-technology or 'watershed agroforestry' (Wakatsuki and Masunaga, 2005). The soils formed and nutrients released during rock-weathering and soil-formation processes in upland areas arrive and accumulate in lowland areas through geological fertilization processes, such as soil erosion and sedimentation, as well as surface and ground water movements or colluvium-formation processes. Ideal land use patterns and landscape management practices will optimize the geological fertilization processes through the optimum control of hydrology in a given watershed. Irrigation, surface and sub-surface water also increase the supply of nutrients, such as Si, Ca, Mg, K and sulfate. This contribution provides an ecological engineering basis for long-term intensive sustainability of lowland *sawah*-based rice farming (Greenland, 1997; Wakatsuki *et al.*, 1998; Hirose and Wakatsuki, 2002; Ofori *et al.*, 2005; Wakatsuki and Masuanga, 2005).

The lower half of Figure 2 shows the micro-scale mechanisms of the intensive sustainability of the *sawah* system. The *sawah* system can be managed as a multifunctional constructed wetland. Controlled flood water can efficiently control weeds. Under flood conditions, phosphorous availability is increased through the reduction of ferric iron. Both acid and alkaline soils are neutralized or mitigated by appropriate control of flooding. Hence, micronutrient availability is also increased. These mechanisms encourage not only the growth of rice plants, but also the growth of various aquatic algae and other aerobic and anaerobic microbes, which increase nitrogen fixation through increased photosynthesis, and control oxidation and reduction potential in *sawah* systems as multifunctional wetlands. Puddling is important to encourage a collaboration of diverse microbes through various interactions between mycelia nanowires in soft puddled *sawah* soils similar to marine sediments (Wakatsuki *et al.*, 1998, 2009; Hirose and Wakatsuki, 2002; Kyuma, 2004; Nielsen *et al.*, 2010).

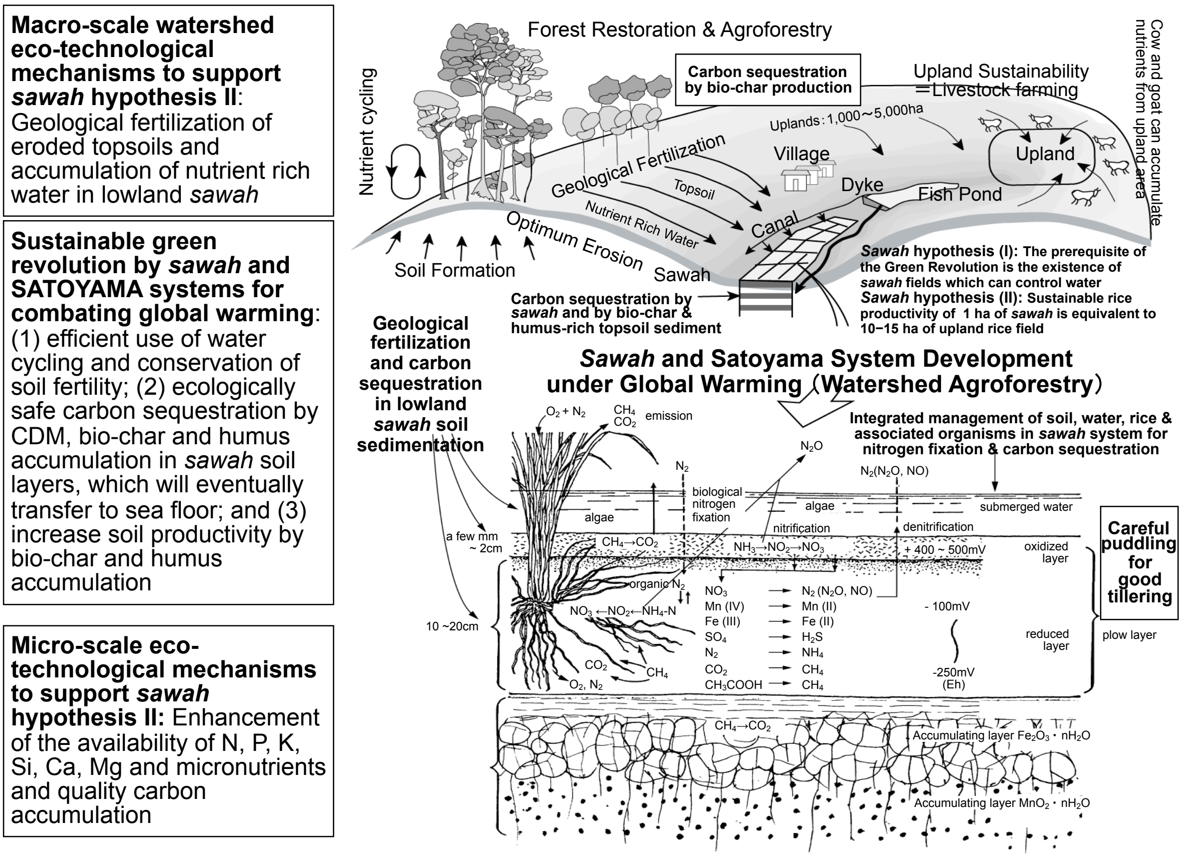

Figure 2. *Sawah* hypothesis II: Watershed agroforestry for sustainable intensive rice cultivation and to combat global warming.
Bio-char, charred biomass.

Lowland *sawah* systems can sustainably produce about 2 t/ha paddy without any chemical fertilizer application (Hirose and Wakatsuki, 2002; Wakatsuki *et al.*, 2009). In addition, lowland *sawah* systems can support rice cultivation continuously for decades, centuries or more without any fallow period. However, in upland slash-and-burn rice fields, the paddy yield without fertilizer never sustainably exceeds 1 t/ha. In addition to this lower yield, upland paddy fields require a fallow period to restore soil fertility — typically 2 years of cultivation and 8, sometimes more than 15, years of fallow. This means that 1 ha of sustainable upland rice cultivation requires at least 5 ha of additional land. Therefore, sustainable upland paddy yield is actually not 1 t/ha, but less than 0.2 t/ha. Thus, the sustainable productivity of *sawah*-based rice farming is more than 10 times that of upland slash-and-burn rice (*sawah* hypothesis II). Although we know this to be true based on a long history and experience of *sawah*-based rice farming in Asia, it has not been scientifically and quantitatively confirmed through experimentation. We must therefore determine the sustainable yields quantitatively under SSA conditions.

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 not only to increasing food production, but also to conserving forest, which in turn enhances the sustainability of intensive lowland *sawah* systems through nutrient cycling and geological fertilization processes (watershed agroforstry or African SATOYAMA system). Furthermore, *sawah* fields will contribute to the alleviation of global warming problems through the fixation of carbon in forest and *sawah* soils in ecologically sustainable ways (Fig. 2; Hirose and Wakatsuki, 2002; Wakatsuki *et al.*, 2009).

Sawah approach: Farmers' personal irrigated* sawah *systems through site-specific* sawah *develoed and managed by farmers to realize a green revolution and Africa's rice potential

Among the 250 million ha of lowlands in SSA (Windmeijer and Andriesse, 1993), only about 10% (20 million ha) are estimated as appropriate sites for sustainable irrigated *sawah* system development, of which 10 million ha are in small inland valleys, 7–9 million ha in floodplains, and 1–3 million ha in coastal deltas (Wakatsuki *et al.*, 1998). Appropriateness is affected by hydrological, topographical and pedological considerations (Hirose and Wakatsuki, 2002). Of all the lowland types, inland valley land is the priority for application of the *sawah* approach, because controlling water in them is relatively easy. Both large-scale and small-scale irrigation projects, typically created under Official Development Assistance (ODA), have been very costly because of dependence on heavy engineering works and outside expertise (Table 1) (FAO, 1998; Wakatsuki *et al.*, 2001; JICA, 2008; FOFIFA and AfDB, 2008). Due to the high construction cost, the economic returns remain negligible or negative for a long period of time (20–30 years). Project ownership remains with the government (engineers) rather than with the farmers, because farmers cannot develop the systems by themselves. Therefore, neither the development nor the management are sustainable.

Table 1. Comparison of farmers' site-specific irrigated *sawah* system development with large- and small-scale ODA-based developments, and traditional rice cultivation system in inland valleys of Ghana and Nigeria

	Large-scale development	**Small-scale development**	***Sawah* approach**	**Traditional system**
Development cost ($/ha)	20 000–30 000	10 000–30 000	1000–3000	30–60
Gross revenue ($/ha)†	2000–3000	2000–3000	2000–3000	500–1000
Yield (t/ha)	4–6	4–6	4–6	1–2
Running cost, including machinery ($/ha)†	600–800	600–800	400–600	200–300
Farmer participation	Low	Medium–High	High	High
Project ownership	Government	Government	Farmer	Farmer
Adaptation of technology	Long, difficult	Slow, relatively easy	Medium to short, needs intensive demonstration and on-the-job training program	Low technology transfer
Sustainable development	Low (contractors' heavy machinery used in development)	Low to medium	High (farmer-based and small power-tiller used in development and management)	Medium
Environmental effect	High	Medium	Low	Medium

† Assuming 1 tonne paddy is worth US$ 5000; one power-tiller costs $5000 (2009 values).

The *sawah* approach offers low-cost irrigation and water control for rice intensification with sustainable paddy yield of more than 4 t/ha. If we apply improved agronomic practices, such as the System of Rice Intensification (SRI) with the *sawah* systems, paddy yield can reach more than 10 t/ha (Tsujimoto *et al.*, 2009). However, African lowlands are quite diverse and different from Asian lowlands. Therefore, careful site-specific *sawah* development and management technologies must be researched, developed and disseminated. The development and management of *sawah* systems requires local farmers to be self-motivated and to have access to small-scale equipment, such as hydropower tillers. After many trial-and-error processes, the *sawah* system was successfully tested from 1997 to 2009 in Ghana and Nigeria, especially in locations where appropriate sites were selected, local leading farmers trained and proper backstopping provided by scientists (Hirose and Wakatsuki, 2002; Wakatsuki *et al.*, 2001, Wakatsuki and Masunaga, 2005; Oladele *et al.*, 2010; Oladele and Wakatsuki, 2010; Abe and Wakatsuki, in press).

Table 2. Five important skills required by farmers to develop and manage personal irrigated *sawah* systems through their own efforts

(1) Site selection and *sawah* system design

(a) Water sources for site selection
(>10 L/s, >5 months/year)
- Stream/River, Spring, Seepage, Flood, Rainfed

(b) Topography and soil for site selection
- Potential area
- Slope & surface roughness
- Soil

(c) Socio-economics of site selection
- Participating farmers
- Land tenure

(d) *Sawah* system design
- *Sawah* layout & total potential area
- Mean *sawah* size
- Water intake, distribution & control
  - Canals: from source (spring, stream or seepage), between *sawahs*, and diversion
  - Simple dike & diversion canal
  - Weir & canal
  - Fish pond or dam lake
  - Pump
  - Interceptal canal
  - Contour-bund system
  - Flood control by drainage/dam
  - Drought control by pond/ water-harvest
- Soil movement and leveling
- Bund system layout & quality

At first local farmers do not know *sawah* technologies, they know site-specific hydrological conditions that are the most important for site selection

On-the-job collaboration between farmers and scientists, engineers, and extension office is essential

(2) Development skills and costs

(a) Skills for development
- Skill for power-tiller operation:
  - Plowing and puddling
  - Soil moving
  - Surface leveling & smoothing
- Skill for power-tiller management

(b) Costs
- Power-tiller for development
- Power-tiller spare parts
- Fuel for development
- Bush-clearing, de-stumping
- Bund & surface treatment
- Canal construction
- Additional hired labor
- Tools & materials
- Scientist & engineer costs
- Extension officer costs
- Farmers' training

(3) Farmers' group quality
- Leader & group collaboration
- No. farmers
- Ethnic composition
- Skills & incentives
- Gender composition

(5) Training
- Trainer
- Trainee
- International scientists
- National scientists
- Extension officers
- Leading farmers & farmers

Action-research and on-the-job training on site-specific *sawah* development & management

(1) Cost of power-tiller for *sawah* development: at least 10 ha per power-tiller

(2) Cost of scientists, engineers, extension officers & leading farmers

(4) *Sawah* system agronomic management
- Rice monocropping
- Rice and other 2nd-season cropping
- Rice double-cropping
- Overall water control
- Water sources
- Water distribution
- Leveling & smoothing
- Bunding
- Puddling
- Weed control
- Water consumption
- Water requirement
- Water quality
- Soil fertility
- Fertilization ($N–P_2O_5–K_2O$)
- Variety
- Yield

(1) Immediate target paddy yield >4 t/ha

(2) 3 t/ha is not enough to sustain *sawah* development

(3) >5 t/ha will accelerate *sawah* development

(4) Basic research on sustainable paddy yield >8 t/ha is important

(3) Target cost: $1000–3000/ha

To train:
(1) *Sawah* farmers who can develop *sawah* and manage *sawah*-based farming by themselves;
(2) Leading *sawah* farmers and farmers' group to train new *sawah* farmers and farmers' groups

The *sawah* approach involves five important skills and technologies: (1) site selection and site-specific *sawah* system design; (2) skills for cost-effective *sawah* system development using a small hydropower-tiller; (3) co-ordination of farmers' group formation and land-tenure arrangements to sustain *sawah* development; (4) *sawah*-based rice agronomy, including best variety selection and management to realize at least the sustainable paddy yield of more than 4 t/ha; and (5) establishment of institutional training and dissemination systems for *sawah* eco-technology transfer (Buri *et al.*, 2009). The most important factor in site selection, appropriate *sawah* system design, development and management is collaboration between researchers and farmers. Scientists and extension officers should have the skills for *sawah* development. Although local farmers do not know *sawah* technologies (before the project starts), they are very familiar with the site-specific hydrological conditions that scientists and extension officers need to know for *sawah* development. Thus, collaborative action-research between farmers and scientists is essential. The priority for site selection is inland valleys. Floodplains will be a lower priority at the beginning of the application of the *sawah* approach. The water conditions of inland valley streams are critical. Water has to flow for more than 5 months continuously, with a discharge of more than 10 L/s, otherwise farmers have to develop additional ponds and tanks to secure the water for sustainable *sawah*-based rice cultivation. If floods reach deeper than 50 cm and continue longer than one week (i.e. discharge >10 L/s), major flood control measures have to be put in place, which is difficult for farmers' groups at the first stage of *sawah* development. Therefore, inland valleys that will require such extra inputs should be avoided in the demonstration and training stage.

Table 3. Cost and income (US$) of site-specific personal irrigated *sawah* development and *sawah*-based rice cultivation (Ghana and Nigeria, 2009)

Activity	Cost/income elements, performance or durability of pump and power-tiller	Spring-based (mean slope 1.5%)	Floodplain-like (mean slope 0.5%)	Stream dike-based (mean slope 1%)	Pond-based (mean slope 1%)	Pump-based (mean slope 1%)	Non-*sawah* (mean slope 2%)
A. *Sawah* development activities (first year only, per ha)							
Clearing & destumping	10–20 work-days†	70	70	70	70	70	35
Bunding	20–30 work-days†	100	70	85	85	85	NA
Plowing	20–30 work-days†	100	70	85	85	85	NA
Puddling, soil movement, leveling	30–50 work-days†	200	135	170	170	170	NA
Pumping machine cost	**3 ha/year‡**	NA	50	NA	30	200	NA
Power-tiller cost§	**2–3 ha/year, 6–15 ha/life**	700	500	600	600	600	NA
Main canal	$1000 for 100 m per ha	NA	NA	100	100	NA	NA
Branch canal	$35 for 100 m per ha	70	35	70	70	70	NA
Interceptor canal	$35 for 100 m per ha	35	NA	35	35	35	NA
Dike/weir	$400 for 20×5×3 m per 3 ha / 3	NA	NA	150	NA	NA	NA
Pump fuel	3–20 days ($20/day)	NA	100	NA	60	400	NA
Flood control	$700 for 150×2×2 m per 3 ha / 3	NA	270	70	NA	NA	NA
Pond construction	$1400 for 20×20×2 m per 3 ha / 3	NA	NA	NA	500	NA	NA
Total cost of development		1275	1300	1435	1805	1715	35
B. *Sawah*-based rice farming cost (first year only, per ha)							
Nursery bed	1–2 work-days†	5	5	5	5	5	15¶
Seed cost	30–90 kg ($10 per 5 kg)	40	40	40	40	40	120
Sawah water management	20–50 work-days†	60	60	60	60	150	NA
Transplanting	15 work-days ($3/work-day)	45	45	45	45	45	NA
Rope & markers	5 bundles ($2/bundle)	10	10	10	10	10	NA
Weeding labor	6–7 work-days ($3/work-day)	20	20	20	20	20	50
Herbicide	5 L ($8/L)	40	40	40	40	40	NA
Fertilizer	5 bags ($20 per 50 kg)	100	100	100	100	100	NA
Fertilizing	2–3 work-days ($3/work-day)	10	10	10	10	10	NA
Bird-scaring	15–45 work-days ($1.5/work-day)	20	20	20	20	20	40
Harvesting	15 work-days ($4/work-day)	60	60	60	60	60	30
Threshing	10 work-days†	35	35	35	35	35	15
***Sawah*-based rice farming cost**		445	445	445	445	535	270
Total cost in the first year		1720	1745	1880	2250	2250	305
Yield	4–4.5 t/ha	4.5	4.0	4.5	4.5	4.0	1.5
Gross income	$500/t paddy	2250	2000	2250	2250	2000	750
Net income		530	255	370	0	–250	445

† 1 work-day costs $3.5.
‡ Pumping machine: 15% depreciation, 10% spare parts.
§ Power-tiller cost: $5000 for 3–5-year life, 15% depreciation, 10–20% spare parts; initial *sawah* development claims heavy load on power-tiller, which comprises 50% of cost of development.
¶ Direct sowing and/or dibbling.
Although *sawah* approach gives sustainable low-cost personal irrigated *sawah* system development, which costs about 10% of ODA-based irrigated *sawah* development, there may need to be special subsidization to encourage *sawah* development by farmers in the first year.

Table 3. Cost and income (US$) of site-specific personal irrigated *sawah* development and *sawah*-based rice cultivation (Ghana and Nigeria, 2009) (cont.).

Activity	Cost/income elements, performance or durability of pump and power-tiller	Spring-based (mean slope 1.5%)	Floodplain-like (mean slope 5%)	Stream dike-based (mean slope 1%)	Pond-based (mean slope 1%)	Pump-based (mean slope 1%)	Non-sawah (mean slope 2%)
C. *Sawah*-based rice farming cost (subsequent year, per ha)							
Pump	2–10 days ($20/day)	NA	50	NA	30	150	NA
Plowing	5–7 work-days†	20	15	20	20	20	NA
Puddling, leveling	7–12 work-days†	40	30	40	40	40	NA
Power-tiller	**10 ha/year, life 5–7 years**	100	90	100	100	100	NA
Maintenance of canal, dike & pond	15% of new construction	15	70	70	90	15	NA
Nursery bed	1–2 work-days†	5	5	5	5	5	15‡
Seed cost	30–90 kg ($10 per 5 kg)	40	40	40	40	40	120
Water management	20–50 work-days ($3/work-day)	60	60	60	60	150	NA
Transplanting	15 work-days ($3/work-day)	45	45	45	45	45	NA
Rope, etc.	5 bundles ($2/bundle)	10	10	10	10	10	NA
Weeding labor	7 work-days ($3/work-day)	20	20	20	20	20	50
Herbicide	5 L ($8/L)	40	40	40	40	40	NA
Fertilizer	5 bags ($20 per 50 kg)	100	100	100	100	100	NA
Fertilizing	3 work-days ($3/work-day)	10	10	10	10	10	NA
Bird-scaring	15–45 work-days ($1.5/work-day)	20	20	20	20	20	40
Harvesting	15 work-days ($4/work-day)	60	60	60	60	60	30
Threshing	10 work-days†	35	35	35	35	35	15
***Sawah*-based rice farming cost**		620	700	675	725	860	270
Yield	4–4.5 t/ha	4.5	4.0	4.5	4.5	4.0	1.5
Gross income	$500/t paddy	2250	2000	2250	2250	2000	750
Net income		1630	1300	1575	1525	1140	480

† 1 work-day costs $3.5.
‡ Direct seeding and/or dibbling.
Once *sawah* developed, power-tiller cost for rice farming will not be a major problem. Since farmers were well trained during the first year in difficult *sawah* development, *sawah*-based rice farming will be more sustainable than old-style ODA-based irrigation projects.

Other criteria for site selection at the demonstration stage include accessibility, size of lowland, number of active rice farmers and topography.

Cost-effective *sawah* development is critical (Table 3). Although the cost of applying the *sawah* approach is less than 10% of the cost of ODA-based irrigation schemes (Table 1), the initial *sawah* development relies heavily on use of a power-tiller, which makes up 50% of the development cost. Therefore, apart from training in power-tiller operation (Ademiluyi, 2010), high-quality, durable and low-cost power-tillers are necessary. Asian farmers can buy similar power-tillers for just $2000–3000, while commercial prices of power-tillers in Ghana and Nigeria are $5000–9000, so it may be necessary to apply a special subsidy to encourage farmers to develop *sawah* in the first year. Fortunately and paradoxically, African inland valleys have quite adaptable topography and wide areas of virgin land to develop *sawah* systems rapidly. Therefore, once African farmers have mastered the necessary skills and *sawah* systems have been developed, power-tiller costs for rice farming will not be a major problem. Since farmers can be trained well during the first year in the difficult practice of *sawah* development, *sawah*-based rice farming will be more sustainable than the old style ODA-based irrigation projects.

Since rice farmers have to master a wide range of skills, including ecological engineering, intensive on-the-job training continuing for 5–6 months is very important. Once mastered, the skills can be transferred farmer-to-farmer and *sawah*-to-*sawah* to scale up the success from Ashanti (Ghana) and Bida, Abakaliliki, Akure, Zaria, Adani and Ilorin (Nigeria) to the wider (potential) rice-growing areas in SSA to realize Africa's rice green revolution. This *sawah* approach has arrived at such a scaling-up stage.

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