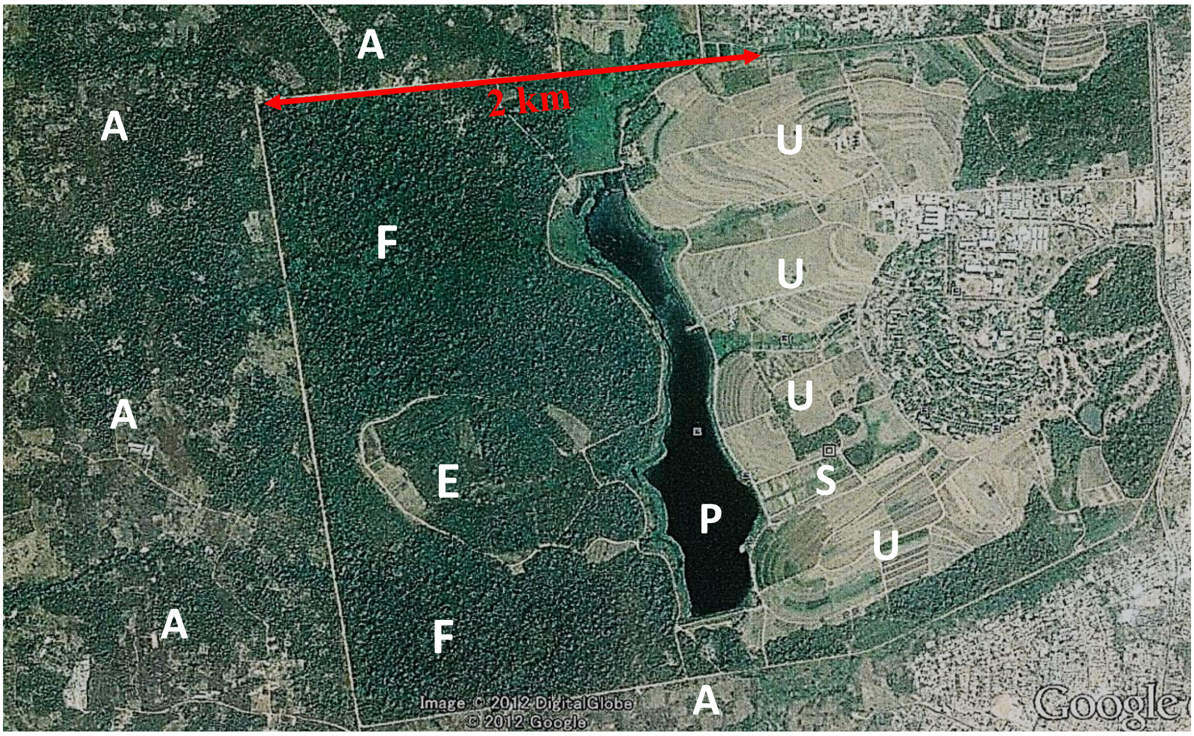

Fig.6. Sawah Hypothesis (1). Prerequisite platform to apply green revolution technologies exist in fenced 1000ha of IITA's research fields, but no such infrastructures farmers' fields. A: Farmers fields with the same soils, topography and hydrology. U: demarcated upland fields along contours. S: Sawah fields at valley bottom. P: Pond for irrigation. F: Regenerated forest, E: Erosion experiment site by Prof. R. Lal and his team in 1970-80s

To increase rice production, "varietal improvement" by breeding studies using biotechnology and "improvement/evolution of ecological environments of farmers' fields" by *sawah* studies using ecotechnologies are equally important. The two technologies are complementary to each other. Biology and ecology (environment) are the two basic components of agriculture. As shown below, we must accelerate standard *sawah* system development in Africa. Our first *sawah* hypothesis for realizing a GR in Africa is that farmers' standard *sawah* development should come first. We explain here that the core technology for a GR in SSA is *sawah* ecotechnology (Fig. 7) (Wakatsuki et al. 1998, 2001, 2005, 2009; Hirose and Wakatsuki 2002, Wakatsuki and Masunaga 2005, Oladele et al. 2010, Abe and Wakatsuki 2011, Igwe and Wakatsuki 2012). This '**Sawah technology (3) Principles**' paper and its companion '**Sawah technology (4) Practices and potential**' paper at the first international sawah workshop (Wakatsuki et al. 2011, Wakatsuki et al 2013) also explain four key skills necessary for the *sawah* ecotechnology to achieve a GR in SSA. These four are (1) site selection and sawah system design, (2) power tiller based efficient and low cost sawah development, (3) sawah based rice farming, and (4) farmers socio- economic empowerment measures, which are described in the separe paper of **sawah technology (4) Practices and potential.**

The rice GR includes three core technologies – (1) irrigation and drainage, (2) fertilizers and agrochemicals, and (3) the use of HYVs. Although these three technologies have been available for the past 40 years, they have not been effective in farmers' fields in SSA. In order to apply these scientific technologies, farmers' fields must develop *sawah* or other similar alternatives, typically in the lowlands that can conserve soil and control water, ***Sawah* hypothesis (I)** (Fig. 5, 6 and 7), which is equivalent to the British enclosure (Fig. 3). Essential components with regard to land development are (1) demarcation by bunding based on topography, hydrology, and soils, (2) leveling and puddling to control water and weeds and conserve soil, and (3) water inlets to get water (using various irrigation facilities) and water outlets to drain excess water. These are the characteristics of *sawah* fields.

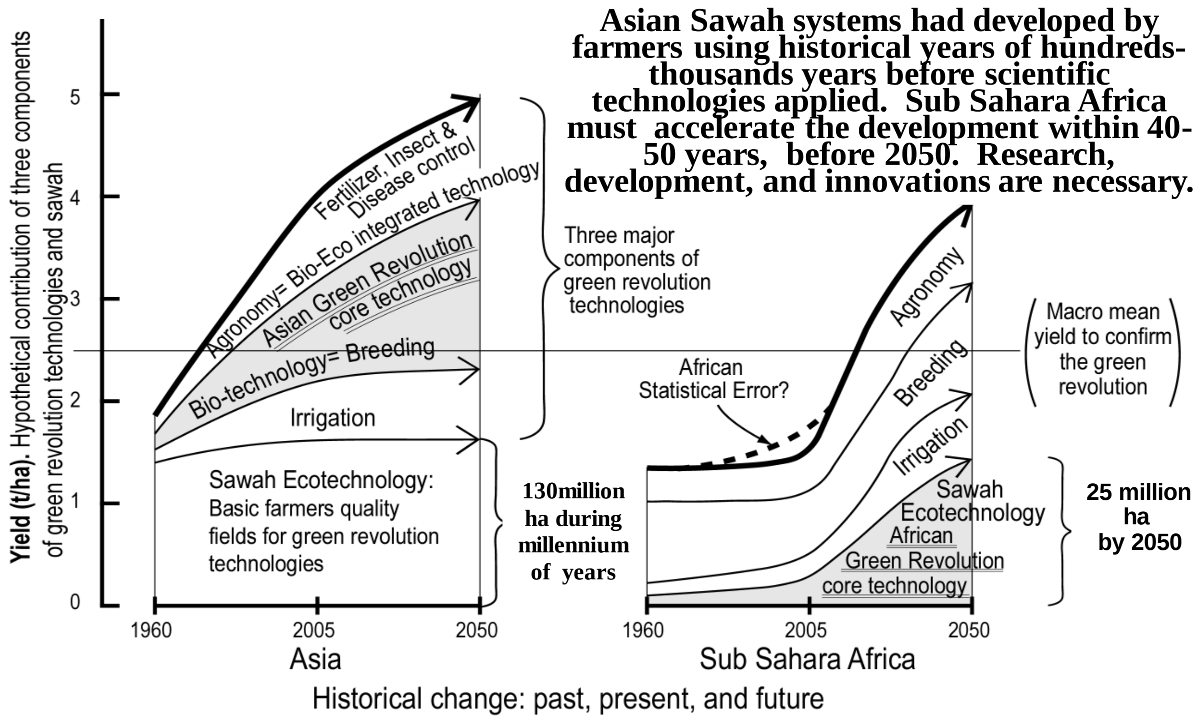

Fig. 7 : Sawah hypothesis (1) for Africa Green Revolution: hypothetical contribution of three green revolution technologies & sawah system development during 1960-2050. Bold lines during 1960-2005 are mean rice yield by FAOSTAT 2006. Bold lines during 2005-2050 are the estimation by the authors.

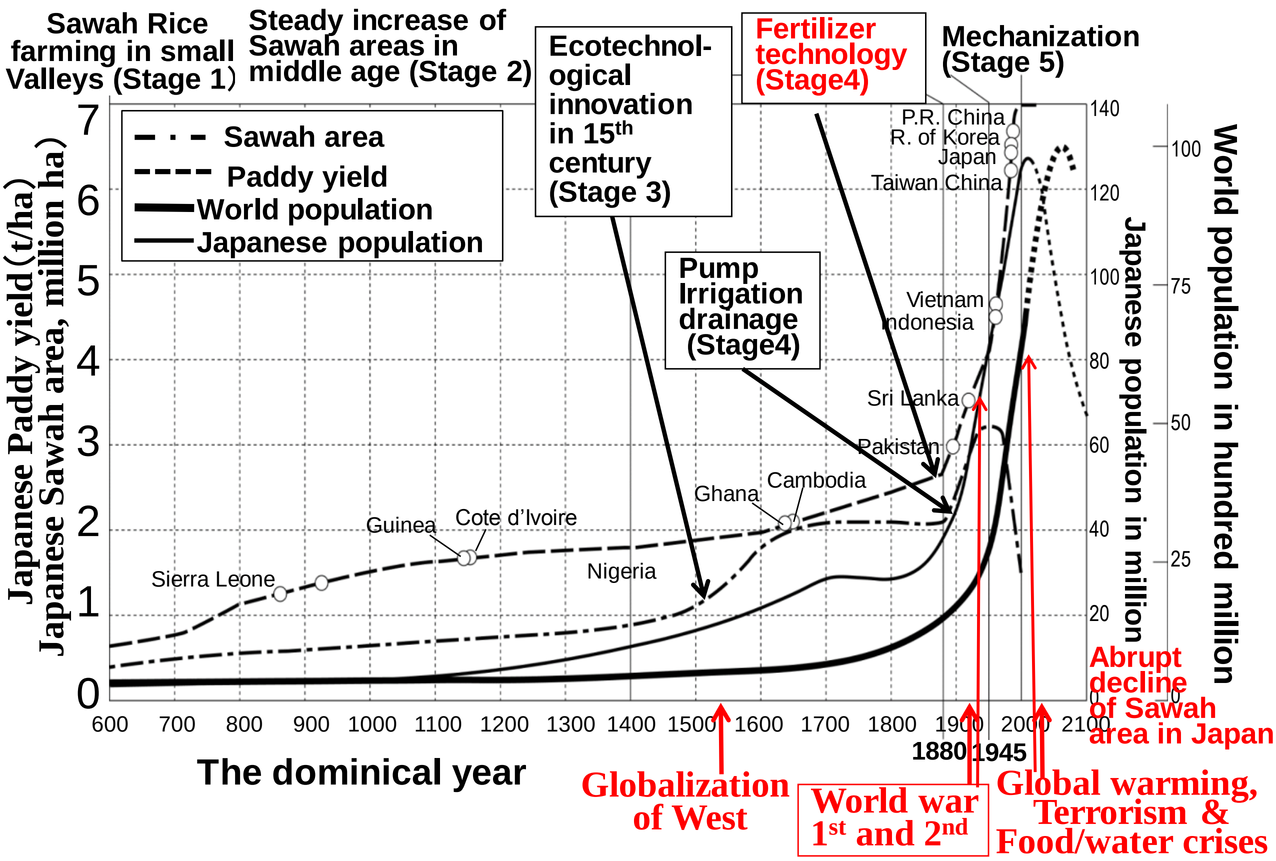

Figure 8. Historical path of Japanese and world population, Sawah area, and paddy yield in comparison with Asia and Africa at 2001/2005 of FAOSTAT data. (Takase & Kawano 1969, Honma 1998, JICA 2003, Kito 2007, Wakatsuki 2013b)

As shown in Figure 7 and 8, Asian *sawah* systems were developed over the past hundreds and thousands of years by farmers' self-support efforts, long before the advent of GR technologies. These are the basic infrastructures needed for the application of HYVs, fertilizer and government-assisted irrigation technologies. However, such infrastructures are very limited in SSA. For various social and historical reasons, the endogenous developments of these basic land and infrastructure have been disturbed in SSA mainly maybe by the globalization of the West, slave trade and colonization which started in 15th centuries (Hirose & Wakatsuki 2002). Because of rapid population increase we must now accelerate the development of standard *sawah* systems to realize a Green Revolution. As shown in Figure 8, before green revolution, there were long continued efforts to expand lowland sawah areas in the history of Japanese rice cultivation during the 6th to 20th centuries**.** The same is true for the other Asian countries although various difference due to the degrees of disturbances by the globalization of the West (Fig 8). The Figure 8 also shows the historical trends of paddy yield, sawah area and population of historical path in Japan in comparison with paddy yields in major Asian and African countries. The historical trends of world population are also shown in Fig.8.

Because of the sawah platform had been developed and sawah based farming been practiced, Japan's green revolution realized immediately after the introduction of fertilizer technology of the West at the end of 19th century. Then the rapid expansion of Sawah area was followed based on pump irrigation and drainage, with the rapid population increase, which was finally unfortunately exploded as the world war the II. Although world war the II was the biggest human disaster in our history, very fortunately colonized major Asian countries could get independence in 1950s and then African countries could follow in 1960s.

As seen in Fig 8 for the trend of Japan, however, only 10-20 years after world war the II, because of the expansion of the economy, through science and technology innovation based industrialization and urbanization, agriculture was declined and thus the sawah area had decreased rapidly. After the Japanese population maximum reached in 2008, decline and aging population is the major problem now. On the other hand, majority of Asian and SSA especially are expecting rapid population explosion and maximum within decades with possible world crises on global warming, terrorism, food and water shortage.

If we make close look at the stages of lowland sawah development in Japan in Fig. 8, we can distinguish five stages, i.e, (Stage 1) : BC10th to 7th century : Sawah development in various lowlands, which have hydrology of easy water control, such as small inland valley streams and springs (Stage 2) : 7th to 15th century: Steady increase of sawah development in bigger lowland and bigger river water sources (Satge 3) : 15th to 19th: Major ecotechnological breakthrough to control major flood plain of major rivers (Stage 4) : 19th to 1960s: Introduction of scientific fertilizer technology of the West. Pump irrigation and drainage made possible to develop big swamps, typically delta, (Stage 5): 1960s to date: Mechanization and major sawah reclamation for efficient mechanized operation.

In Sub Saharan Africa, we can now available all basic technologies used at all the five stages. Only major lacking is farmers' skills on sawah technology and sawah system infrastructure. Therefore if African farmers master the skills of sawah technology, lowland development and irrigation projects will be accelerated to achieve rice green revolution, hopefully by 2025.

Beyond Realizing African Green Revolution: Theoretical Consideration of Sawah Hypothesis (1) and Ultrahigh Sustainable Rice Yields Level Achievable in the Near Future by 2050.

Figure 9 shows the three major factors of productivity growth using production functions by Kalaitzandonakes et al 1994). The total productivity can be arranged into following major three factors, i.e., ①elimination of inefficiency, ②Scale adjustment, i.e., expansion to appropriate scale of farm land and management scale, and ③advancement of technology. Please note, it is an example of an extension by one of the authors (T. Wakatsuki) to add sawah hypothesis 1 as a cause of inefficiency elimination. The progress from A → B, or C → D are agricultural revolution by Paradim /Regime shift, which is the agricultural intensification (Boserup 1965). Even if inputs such as labor, output never increase, Geertz (1963) described shows the period of agricultural involution typically observed on sawah based rice farming in Indonesia during 1900-1960, just before the green revolution. This maybe describe as internal development or sustainable agriculture. If we observe the Fig 10, Japan's sawah based rice farming during 1700-1850 was the similar involution period. The position of Boserup(1965), Geertz(1963) and Marthus(1798) were cited based on the paper by Ellis et al (2013).

These theories, however, did never reflect the rapid increase in productivity by modern science, such as the green revolution of 1960 – 2014.

Among these three factors, with regard to the realization of the green revolution (GR) in Africa, the Asian GR was high yielding varieties (HYV) developed by international agricultural research centers, such as IRRI (International Rice Research Institute) and CYMMET (International Wheat and Maize Research Institute). Due to too dramatic success, it seems that it was too overburdened with the advancement of technology such as variety improvement by biotechnology, which is only one of technologies of the factor ③. The two curves showing by F1 and F2 in the figure are two production functions. The production function is describing general relationship between productivity (P), such as output (Y) or yield (Y), and various inputs when farmers produce rice by inputting labors and materials (L) to a certain farm lands (R). It is generalized that F1 shows what is due to the current farming system and F2 shows when it reaches high level production function due to technological progress (Kalaitzandonakes 1994, Watanabe 2010, Arahata 2014, and Sekine & Umemoto 2015).

The first factor ①elimination of inefficiency is to reach the frontier of the production function F through the elimination of base line causes of inefficiency (Arahata 2014). In British enclosure during 1500-1850 removed such technical inefficiency to reach the level such production function which made the foundation of the Agricultural Revolution (Kerridge 1967, Overton 1996). The enclosure made change the common shared lands through the eliminated the medieval open scattered small strips unfenced (no demarcated) field system to privately owned fenced/hedged straightly grouped larger lands, which formed the platform to change the long continued medieval agriculture and made begin various scientific improvement and innovation. Norfolk four crops rotation, wheat-turnips-barley-clover, has developed and been widely disseminated to improve soil productivity to convert the grazing land into a good crops farm lands, accelerate selective breeding, mechanization and chemical fertilizer application. Looking at the current status of SSA, under the current multilayered shared land right use system, irrigated sawah system development by either government or farmers' self-support efforts has been frequently challenged through the destruction of bunds, canals, dykes, weirs and surface levelling of sawah systems by nomads' cattle in dry season, and fisher men's traps. These are inhibiting the sustainable development and management of irrigated sawah systems.

The sawah hypothesis 1 mentioned in this paper is precisely the ① elimination of these inefficiencies. As shown in Photographs 1-5 as well as Fig 5-7, it is obvious that majority of current rice fields are difficult to control water in SSA even under irrigation. These are also somewhat similar to the British's medieval open

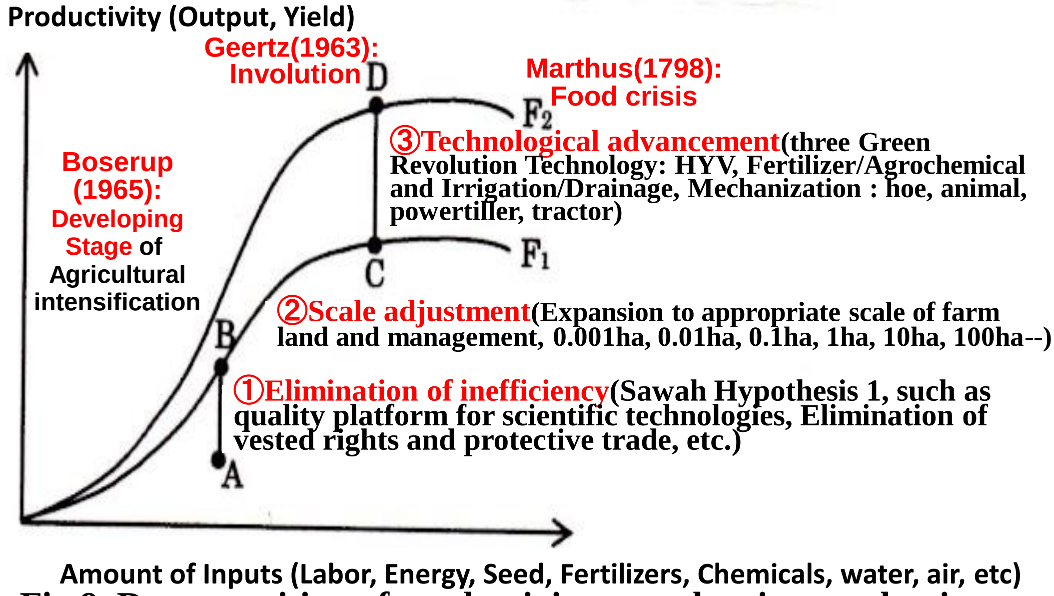

Fig 9. Decomposition of productivity growth using production functions. Total productivity=①Technological advancement +②Scale adjustment+③Elimination of inefficiency

Productivity Growth and Competitiveness, In Maurey E Bredahl、Philip C Abbott、and Michael C Reed、edited "Competitiveness in International Food Markets, p169-187", Westview Press., 1994. Inclusion of Sawah hypothesis 1, Boserup(1965), Geertz(1963) and Marthus(1798) were done by T. Wakatsuki. Cited from 関根久子・梅本雅、2015、小麦収量水準格差の形成要因—日本とドイツの比較分析、中央農研研究報告、24号:31-54、Bull. NARO.Agric.Res.Center、 scattered small strips unfenced (no demarcated) field systems. Majority of rice farmers' lands in SSA have not reach the frontier of the production function F1. Thus three green revolution technologies of high yielding varieties, fertilizer/agrochemicals, and irrigation/drainage are never effective. As the ① elimination of inefficiency, in the case of SSA, measures concerning the quality of agricultural land similar to enclosure and Sawah system, the necessity of infrastructure platform, i.e., quality standard irrigated sawah system, is the main issues. However, in the most other parts of the world where had already experienced the first agricultural revolution such as the green revolution, the main issue may be eliminating institutional inefficiencies such as stopping trade protection and encouraging free trade. In countries where priority have been given to industrial revolution rather than agriculture promotion like Japan in 1971-2016 and the current Asian countries since the period of high growth, aging and lack of personnel, the productivity may not reach to the frontier of the production function (point B of F1 curve).

Looking back on the history after the independence of SSA since 1960, erroneous policies of "let's not have feet on the ground" were taken, which means that the industrial revolution the 1st without considering the agricultural revolution. This adverse effect remains in society as a whole, as a disregard of agriculture seen in young people and society in general.

The second factor is ②Scale adjustment in Figure 9. If it expands to farmland of the proper scale, farm management of the appropriate scale becomes possible and cost reduction becomes possible. When reaching point B on the front line of the production function F1, productivity can be increased from point B to point C by rice cultivation with a farm of an appropriate scale. In the *Yayoi* period of Japan, 2400-2500 years ago and the current SSA (see the Photograph 1 and 5), the number of agricultural lands of 1 ha is divided to 1,000-400 sections of micro rudimentary sawah of 10-25 m^2, and water management and soil management are also impossible. Therefore, it is agriculture in an extremely close position at the origin of the coordinate axes of the production function F1. Therefore yield, remains low. Even if the scale of the sawah plots is increased, the quality of the sawah field is low (topographically irrigation and drainage is not easy, leakage from bunds of sawah plots, insufficient leveling of sawah soil surface, rice planted on ridge, water leakage from sandy sawah soils, etc.), cost reduction will not be realized. Also, if it is too large, it takes time to irrigate and drain, making it difficult to manage water control. In current Japan, after 2013, the scale expansion and the expansion of the area of one sawah field are in progress, but as in the U.S. and European agriculture, one unit of farm land of 10 to several 10 ha and total farm land 100-1000 ha of one farmer's management is not the proper scale, probably appropriate area of one sawah plot is 0.5 - several ha and total farm land of 10 - several 10 ha of one farmer's management scale. It will be clarified in about 10 years. In Japan, maintenance and improvement of farmland of this appropriate scale and management of sawah field farmers, i.e, the ② scale adjustment and expansion has been stagnated for last 50 years due to the controversial policy to discourage rice production, since 1970. As a result, productivity also stagnated, as seen in Figure 10.

The third factor ③Technological advancement is not the major problem in current SSA. If the other two factors can be satisfied similar to the level of Asin farmers' level, it will be no problem to reach national mean yield higher than 4t/ha. Then all over the world including SSA can come to the starting line of international competition for rice value chain market.

Standards quality of sawah system effectively utilizes water, nutrients and fertile topsoil gathered in the lowlands of the watershed area as will be described later as Sawah hypothesis 2. Weeds can be controlled by water management of appropriate flooding and drainage and appropriate puddling. Since geo-topographical and ecological nutrient supply amount to lowland sawah fields is higher than those of upland rice and wheat, the sustainable yield has been higher during 1700-1900 (Figure 10), almost double before 1900, i.e., before the popularization of modern agricultural technology, such as chemical fertilizers became common (Sawah Hypothesis 2, Figure 14 in next paragraph). The supporting data on the superiority of lowland sawah system in comparison with upland rice are also clear in Figure 11. The historical changes in the rice yield in Japan and the historical yield of wheat in the UK were compared and shown between 1700 and 2014 in Figure 10. The yield data in the UK shows 10 years moving mean data in Fig. 4. Figure 10 also shows the changes in the average yields of major rice countries in Asia and SSA during 1961-2014.

As shown in Figure 10, as already mentioned, after Japan, the rice yields of Asian countries, China, Viet Nam, Indonesia, Bangladesh, Philippines, and India, have been increasing rapidly since 1961 by the green revolution technology. After 2000, top group countries have been increasing their national mean paddy yields, such the countries of Madagascar and Mali which have higher ratio of standard irrigated sawah based rice farming than the other countries in SSA. Madagascar and Mali are now in 2014 similar national paddy yields to Thailand. The country's average yield is increasing, such as Ghana, Tanzania, Ivory Coast, etc., coupling with the progress of sawah system development and improvement. On the other hand, the yield increase of Nigeria and Sierra Leone is delayed because of majority of sawah system development in these countries as a whole are behind standard level of sawah system development. This can be understood from the Photographs 1, 2, and 5 as well as Figure 12 for Google earth comparison of UK, Japan and Sierra Leone as well as Fig. 13 and 14 for Google earth on 2009/2016 and old photographs taken in 1987 on our 1st on-farm research sites at Makeni area, Sierra Leone.

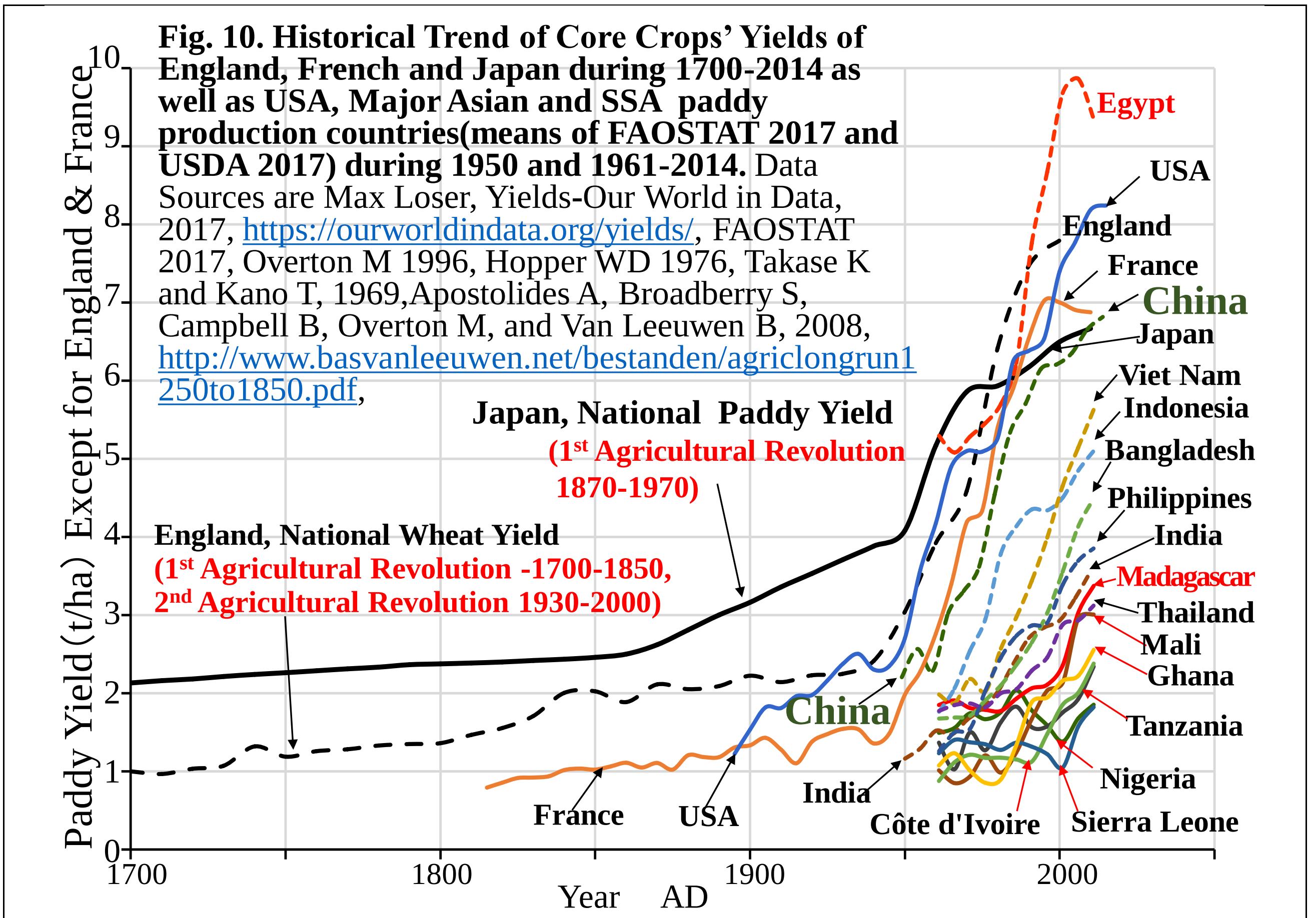

Fig. 10. Historical Trend of Core Crops' Yields of England, French and Japan during 1700-2014 as well as USA, Major Asian and SSA paddy production countries(means of FAOSTAT 2017 and USDA 2017) during 1950 and 1961-2014. Data Sources are Max Loser, Yields-Our World in Data, 2017, https://ourworldindata.org/yields/, FAOSTAT 2017, Overton M 1996, Hopper WD 1976, Takase K and Kano T, 1969,Apostolides A, Broadberry S, Campbell B, Overton M, and Van Leeuwen B, 2008, http://www.basvanleeuwen.net/bestanden/agriclongrun1250to1850.pdf,

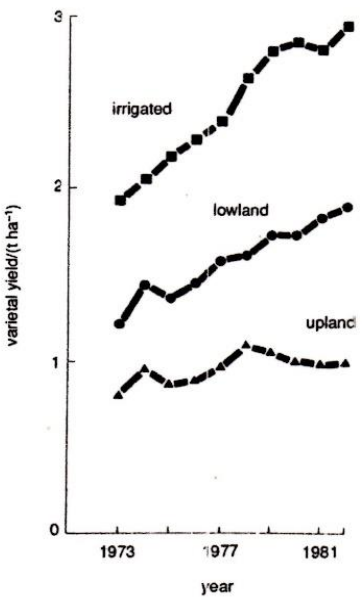

Fig.11 Yield trends for irrigated, lowland and rainfed upland rice crops in the Philippines (L.T. Evans, 1986).

It is very interesting to compare the historical paddy yields of Japan and wheat yields of UK during 1700-2014. Since lowland sawah system has eco-technological advancement, paddy yields had been higher, almost double, during 1700-1960 (Sawah Hypothesis 2). These periods are including the 1st agricultural revolution period of UK during 1700-1850 by enclosure and Norfolk Four Crops rotation. Japan's 1st agricultural revolution period was during 1870-1970 including a drop by World War the 2nd. Since Japan had semi dwarf varieties of both

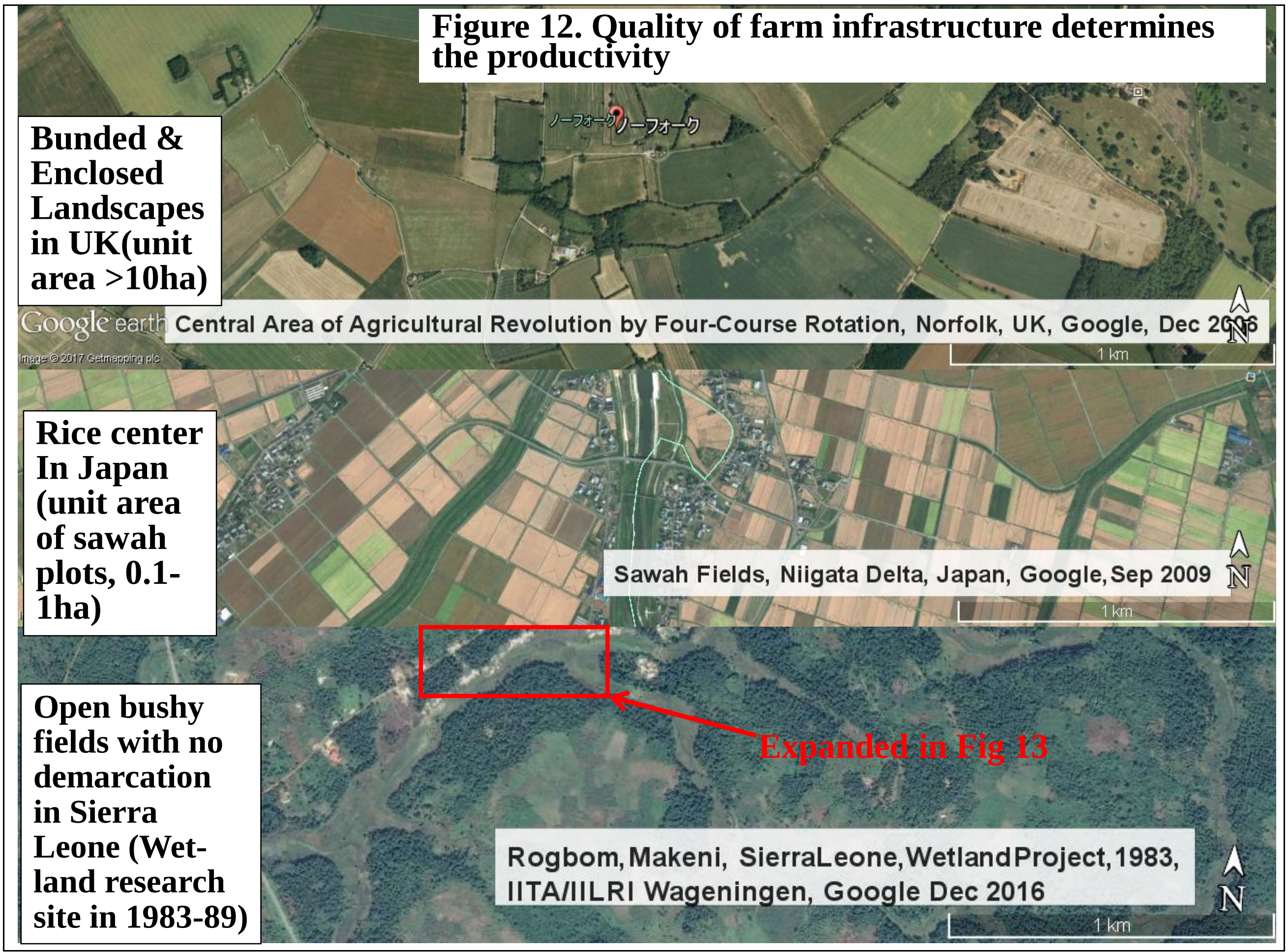

Figure 12. Quality of farm infrastructure determines the productivity

Fig. 13. Upper is Google earth on 2016. This is expanded the area of the red marked area of the Fig.12.Two photographs were taken on 1987, showing ground nuts and cassava cultivation after non-sawah rice cultivation.

Fig.14. Upper is Google earth on 2016 of inland valley of Matam village area, showing sawah system. This village was also under Wetland research of IITA. Lower two photographs were taken on 1987 showing discharge meter of IITA and non-sawah rice.

rice and wheat, chemical fertilizer and sawah system improvement were the major driver of this revolution. Although wheat yields of UK had been stagnated during 1840 to 1940, damatic yield increase has started and been continued during 1940 to the date, 2014. It was almost 4 times, 2t/ha to 8 t/ha. This trend is almost similar to the green revolution of Asia because of the major driver was again semi-dwarf wheat originated from Japan's Norin 10 and Akakomugi (Borojevic 2005). As seen in Figure 10, Lapan's paddy yield became much lower than the yields in Europe and the United States. In contrast to US and European countries, all factors to increase paddy productivities habe been stagnated, especially for scale adjustment and expansion for last 50 years due to the controversial policy to discourage rice production, since 1970. As a result, productivity also stagnated, as seen in Figure 10. This indicates that the advancement (improvement of yield) of agricultural technology can be realized by cooperative work with biotechnology for variety improvement/evolution and improvement of rice growing ecology, i.e., eco-technology for evolution of *sawah* fields (Figure 9). As a matter of course, the essence of agricultural technology is an integrated use technology of variety and growing ecology.

If we make comprehensive assessment of the above and following data, figures and photographs, ie., ① stagnation of the grain yield in Japan after 1975, ②the increase in the wheat yield in the UK, and ③the high degree of intensive sustainability of the sawah system (Sawah Hypothesis 2) described in the next paragraph, it will be possible to have the yield level of Japanese No.1 farmer, 12-13t/ha, and No.1 prefecture, 11-12 t/ha during 1951-1968(paddy yeild base, Monya 1989), if we will continue relevant scienctifc improvement of both bio-technology and eco-technology. Asian countries will be able to achieve the similar results as well. To this end, it is necessary to normalize current agricultural research which is prejudiced in breeding research to balanced agricultural research of Bio-tech Eco-tech, including more balanced sawah system research, for example, FOEAS (Fujimori 2012). In addition, all the national best farmers during the national rice competitive years, 1951-1968, had been improved their *sawah* system infrastructure on its own efforts. They tried to improve and devise their *sawah* system and *sawah* based rice farming suitable for their local environment and keep improving. Our *sawah* technology also places great emphasis on farmers' self-help efforts and ingenuity. Agricultural research that makes use of farmers' ingenuity is important.

If this yield level can be realized, no food crisis will occur even with 10 billion people on Earth. As can be seen from the fact that in Africa, even the present Egypt also achieves a paddy yield of 9 t / ha, if the irrigated sawah system suitable for Africa can be developed, since the sunshine in Africa is blessed more than Asia, somewhat lower soil fertility can be covered enough.

Sawah Hypothesis 2 for Intensive Sustainability and to Combat Global Warming

The sustainable yield in upland rice and non-sawah fields in Africa is 1 ton per hectare (2 tons even if fertilized), but if standard sawah fields are developed in lowlands, As shown in Fig 8 and 11, there is about twice as much difference as 2 tons without fertilization (4 tons if fertilized). The yield difference between UK wheat and Japanese paddy rice shown in Fig. 10 before the establishment of modern agriculture until about 1700-1900 is also about twice as large. It is necessary to restore the soil fertility by fallow in upload rice, and it is necessary to secure extra 5 ha of farm land usually to sustain 1 ha upland rice cultivation as shown in Table 2. However, due to the use of macroscale mechanisms in watershed level and micro-scale ecotechnological mechanisms described in Figure 15, fallow is unnecessary and it is possible to cultivate continuously in units of 1000 years. Therefore, sawah system have sustainable productivity more than 10 times that of upland fields. 1ha sawah field allows more than 10 ha of upland fields and forest conservation (Table 2). The functions of sawah fields in the global environment and biodiversity conservation should be emphasized more and more in the future. From a global perspective, sustainable sawah system development in Africa could save the earth society around the year 2050. It could be one of the strategies to realize the "2030 Agenda for Sustainable Development" recently adopted by the United Nations.

The upper part of Figure 15 illustrates the concept of watershed ecotechnology, or "Watershed Agroforestry"

(Wakatsuki and Masunaga 2005). This system is equivalent to Japanese term of SATOYAMA system. The soils formed and the nutrients released during rock weathering and soil formation processes in upland areas gravitate to and accumulate in lowland areas through geological fertilization processes. These processes include soil erosion and sedimentation, surface and ground water movement, and the formation of colluviums. Ideal land-use patterns and landscape management practices will optimize the geological fertilization processes by ensuring optimum hydrology in a given watershed. Irrigation, surface, and subsurface waters also contribute to an increase in the supply of such nutrients as Si, Ca, Mg, K, and sulfate. This contribution provides an ecological engineering basis for the sustainability of intensive lowland *sawah*-based rice farming (Greenland 1997, Wakatsuki et al. 1998, Hirose and Wakatsuki 2002, Ofori et al. 2005, Wakatsuki and Masunaga 2005).

Sawah hypothesis 2: The sustainable productivity of 1 ha of lowland Sawahs are over 10 ha of upland fields, i.e., yield difference(>2) x Soil fertility recovery(>5)

Reason (1) Watereshed geological fertilization to lowland sawah: fertile topsoil production in forests, sedimentation in lowlands and accumulation of nutrient rich water, which are promoted by lowland sawah systems. It is also important to control appropriate soil erosion and formation of mountain topsoil.

Reason (2) Sawah system is an ecological factory, it can artificially strengthen and control nutrients such as N, P, K, Si, etc. It is also the platform to control various redox microorganisms to develop carbon sequestration.

Reason (3) Sawah system has dam and groundwater recharge function to improve water cycling. Thus promote intensive sustainability through forest and biodiversity conservation

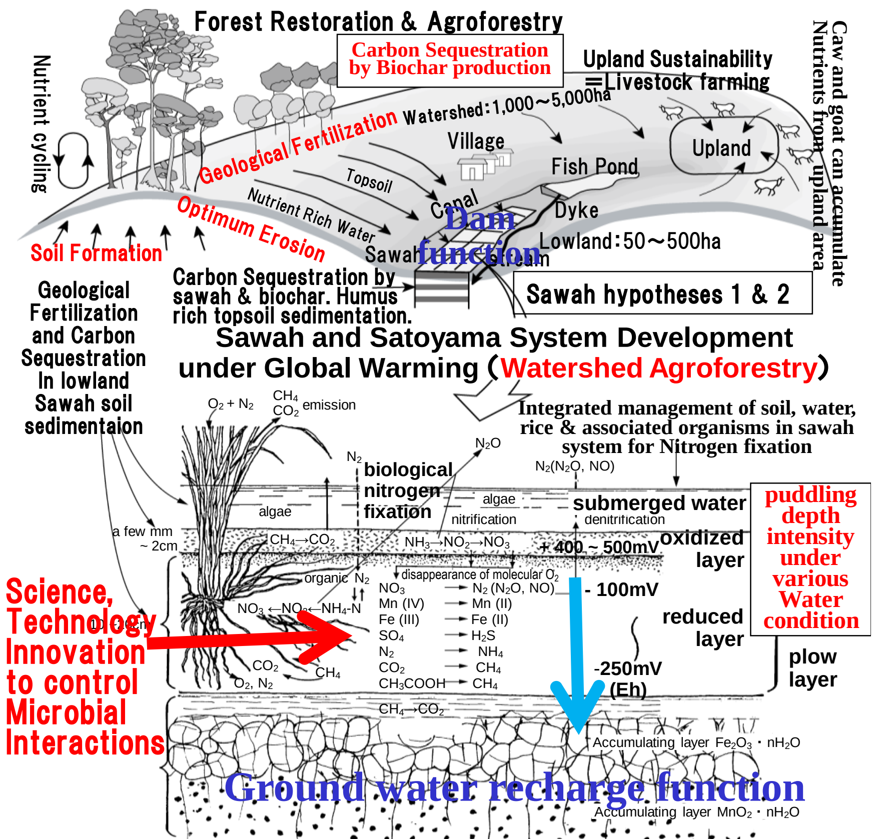

Fig 15. Sawah hypothesis (2): The platform for Sustainable Intensification through Watershed Eco-Technology for Watershed Agroforestry and African SATOYAMA