Chapter 2
Lessons from the Asian Green Revolution in Rice

Jonna P. Estudillo and Keijiro Otsuka

Abstract The Asian Green Revolution in rice entailed a long-term evolutionary process spanning more than four decades since the mid-1960s. The purpose of this chapter is to identify important lessons from the Asian Green Revolution in rice and examine whether the modern rice technology in Asia could be appropriately transferred to contemporary sub-Saharan Africa (SSA). While there are many lessons to learn, this study focuses on high-yielding well-adapted lowland rice varieties, appropriate fertilizer application, and favorable institutional and policy environment that played pivotal roles in launching and sustaining the Asian Green Revolution in rice. The Green Revolution in SSA could include more than one commodity as none of which dominates; we argue that such Green Revolution should include rice for a number of reasons.

Keywords Green Revolution • Asia • Sub-Saharan Africa • Modern variety • Lowland rice • Rice yield • Cereal yield

2.1 Introduction

There were fears in the 1950s and the early 1960s that the tropical Asian rice-based economy would be experiencing massive famine and starvation because the region had already reached its cultivation frontier – the limit of new land available for rice production – without any favorable prospect for increasing rice production from the existing paddy fields. In fact, rice production growth in South and Southeast Asia for the decade prior to1965 was mainly brought about by the expansion of cultivated area (Barker and Herdt 1985). The major source of rice production growth, however,

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shifted from area expansion to yield increase because of the Green Revolution (GR), which started in Asia in 1966, when the International Rice Research Institute (IRRI) released IR8, the first modern variety (MV) of rice. MVs refer to the short-statured, stiff-strawed, fertilizer-responsive, and non-photoperiod-sensitive rice varieties (Chandler 1982). Later MVs incorporated better traits such as short growth duration, multiple disease and insect resistance, superior grain quality, and tolerance for problem soils characterized by nutritional deficiencies and toxicities (Khush 1995; Evenson and Gollin 2003).

Farmers in tropical Asia quickly adopted the earlier released MVs, particularly those located in irrigated and favorably rainfed environment (David and Otsuka 1994; Byerlee 1996), where MVs tend to be more productive. Farmers were also quick in replacing older MVs with newer ones because newer MVs with better characteristics were privately more profitable (Estudillo et al. 1999). There was an increased demand for fertilizer partly because the yields of MVs were responsive to high application of fertilizer and partly because of favorable fertilizer prices brought forth by fertilizer subsidy programs (David 1976; Hossain and Singh 2000). Public investments in irrigation also accelerated because MVs increased the profitability of irrigated rice culture (Hayami and Kikuchi 1978; Kikuchi et al. 2002). In addition, credit programs were instituted along with the establishment of national research and extension systems in many countries (Barker and Herdt 1985; Herdt 2010). In short, the very essence of the GR in Asia is the development and diffusion of a series of MVs in irrigated and favorably rainfed areas and subsequent acceleration in public-sector investments in complementary infrastructures and institutions (Hayami and Otsuka 1994; Hazell 2009).

The Asian GR in rice entailed a long-term evolutionary process spanning more than four decades since the mid-1960s. The purpose of this chapter is to identify important lessons from the Asian GR in rice and examine whether the modern rice technology in Asia could be appropriately transferred to contemporary sub-Saharan Africa (SSA). While there are many lessons to learn, this study focuses on high-yielding well-adapted lowland rice varieties, appropriate fertilizer application, and favorable institutional and policy environment that played pivotal roles in launching and sustaining the Asian GR in rice.

The GR in SSA could include more than one commodity as none of which dominates; we argue that such GR should include rice for a number of reasons. First, Asia has already accumulated a huge stock of scientific knowledge and useful production methods in rice propagation.[1]

Second, there is an increasing demand and production of rice in SSA, but low self-sufficiency of only 60%. Third, lowland rice varieties suitable to lowland irrigated and favorably rainfed ecosystems that were earlier developed in Asia or elsewhere based on cross-breeding between Asian MVs and local varieties have exhibited high yield potential in lowland areas in SSA even with minimal fertilizer application. For example, the yield of IRRI-type varieties in a few well-irrigated areas of Senegal, Kenya,

[1] See Chandler (1982) and Khush (1987, 1995) for a review of the history of rice breeding program.

and Tanzania is as high as 5–6 t/ha, which exceeds the average irrigated rice yield in tropical Asia (Otsuka and Kijima 2010). Fourth, and finally, the New Rice for Africa (NERICA) shows high yield potential in the upland areas, where NERICA thrives well in the presence of high moisture stress (Chap. 6 and Chap. 7, in this volume). For example, in the uplands of Uganda, the average NERICA yield is 2.5 t/ha (Kijima et al. 2008), which is much higher than the average upland rice yield of 1 t/ha in SSA, and even higher than the yield of rice in upland areas in the Philippines, which is about 2 t/ha (Estudillo and Otsuka 2006). Thus, we hypothesize that the evolutionary process of rice GR could be launched in SSA, essentially because the potentially profitable new rice technologies are already available.

This chapter has five remaining sections. Section 2.2 presents the conceptual framework and our hypotheses. Section 2.3 compares the yield trends in major cereal crops in Asia and SSA. Section 2.4 briefly describes Asian GR in rice in terms of the evolution and spread of MVs, changes in irrigation, fertilizer use and trends in rice yield as well the subsequent changes in institutions and policies in Asia. Section 2.5 explores the sources of yield growth and describes the evolutionary processes underlying the GR in Central Luzon in the Philippines. Section 2.6 describes the current state of rice yield in SSA and the potential of transferring the Asian GR. Finally, Sect. 2.7 concludes this chapter.

2.2 Conceptual Framework and Hypotheses

The whole evolutionary process of GR in Asia could be best described in a simple schematic diagram shown in Fig. 2.1. Our main argument is that the GR in Asia is essentially technology-led and policy-supported, rather than policy-driven as is oftentimes assumed (Djurfeldt et al. 2005). The development of MVs induced subsequent public-sector investments in extension and national research programs, irrigation, and credit programs by increasing the rates of returns to such investments (Fig. 2.1). Responding to profitable opportunities created by the new technologies, both factor and product markets gradually developed in Asia. Such developments, in turn, led to enhanced profitability in research and extension investments that further induced the development of newer and better technologies.

We have two major hypotheses regarding the evolutionary processes of the Asian GR.

Hypothesis 1
The Asian GR was essentially technology-led, i.e., the development and adoption of early generation MVs and high fertilizer application in the presence of a well-developed irrigation infrastructure led to an increase in yield.

Hypothesis 2
The Asian GR was sustained by innovations in MVs and subsequent improvements in supportive policies and institutions, i.e., increased investments in irrigation, adaptive research, extension, and subsidy programs for purchased inputs.

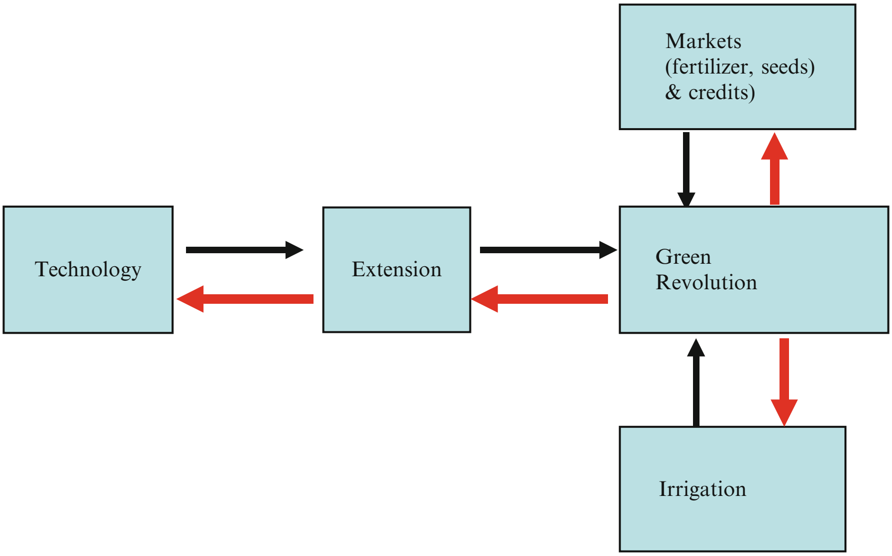

Fig. 2.1 The conceptual interrelationships between technology, extension, input markets, and irrigation investments

Based on the Asian experience, we would like to argue that the induced institutional innovations in the sense of Hayami and Ruttan (1985), such as the establishment of effective irrigation management systems, national agricultural research and extension systems, and marketing institutions, could take place in SSA, once new technological breakthrough is made. Since useful rice technologies are already available from Asia, it could be possible to initiate the technology-led evolutionary processes of GR in SSA.

2.3 Cereal Yields in Asia and SSA

In order to launch the GR in SSA, it is necessary to identify strategic crops where new technology has been effective in increasing crop yield at the farm level. Figure 2.2 shows the yield of rice, maize, wheat, sorghum and millet in Asia and SSA. The difference in rice yield between Asia and SSA was about 80% around 1960 which could be partly attributed to a relatively well-developed irrigation infrastructure system in Asia and partly to the prevalence of low-yielding upland rice in SSA whose yield has been stagnant at 1 t/ha.[2] The small yield gap before the Asian GR indicates that it is the advent of MVs that essentially propelled yield growth in Asia.

[2] According to Balasubramanian et al. (2007), upland rice accounts for roughly 40% of rice area in SSA.

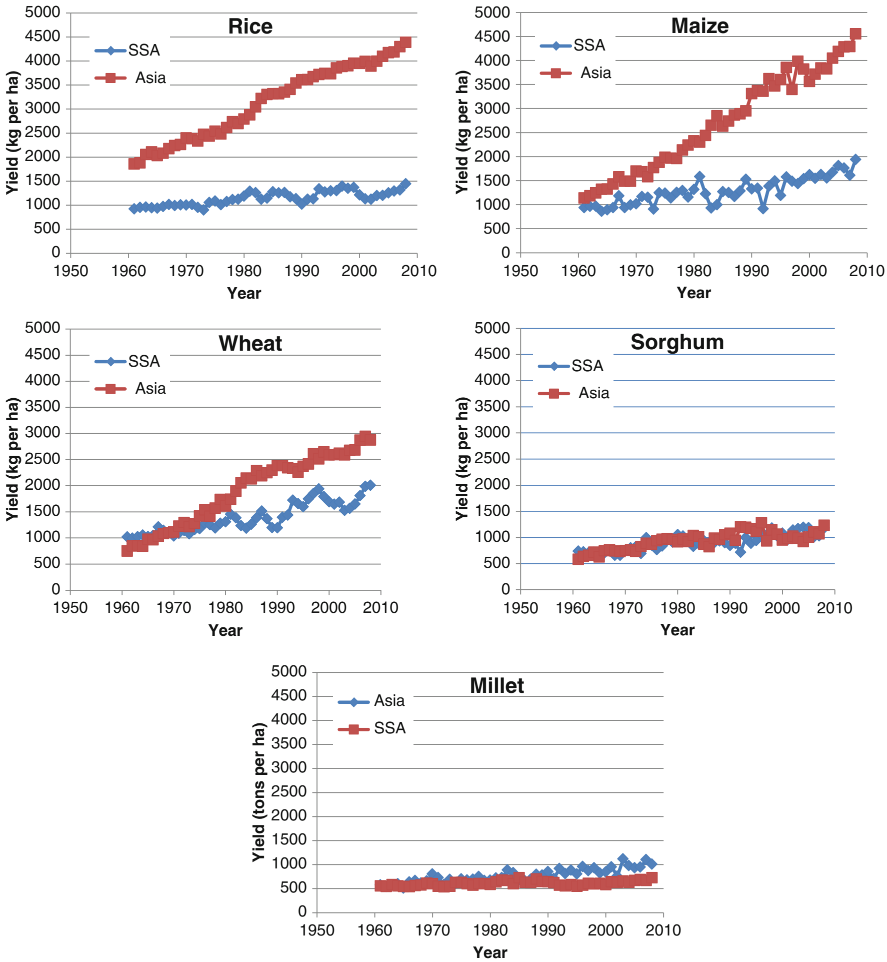

Fig. 2.2 Cereal crop yields in Asia and Sub-Saharan Africa, 1961–2008 (Source: FAO Stat online)

The difference in rice yield grew larger beginning in the mid-1970s, when the later generation of MVs that incorporated multiple pest- and disease-resistant traits became available. The difference in yield between the two continents was similarly visible in the case of maize at about the same period although maize yield was growing faster compared to that of rice in SSA. Indeed, Byerlee (1996) argues that maize is a single success story for the diffusion of MVs in SSA, where rice and wheat are less important food staples.

Yield of wheat in Asia continued to grow from about 1 t/ha in 1960 to 3 t in 2008. SSA similarly started at 1 t and achieved a modest progress with marked geographical concentration in Southern Africa and Ethiopia, reaching an average yield of about 2.0 t/ha, while Middle Africa lagged behind (with an average yield of 1.1 t).

One reason for the yield gap between Asia and SSA is the slow progress in the adoption of MVs of wheat in SSA. Heisey et al. (2003, Table 6) reported that MV adoption in Asia in terms of area planted rose from 19% in 1970 to 86% in 1997 while SSA started from a low level of 5% while rising to 66% in the 2000s.

Yields of sorghum and millet are fairly similar in the two continents and progress in yield increase in the two crops has been by far too slow compared to rice, maize and wheat, indicating that in these crops there could hardly be any vent for a technology transfer to SSA. According to Deb and Bantilan (2003), the adoption of MVs in sorghum and millet takes place largely in India, where farmers continuously change older MVs to newer ones. In SSA, Nigeria, Niger, and Sudan are the major producers of both crops where the adoption of MVs and yield growth were slow.

Overall, it is clear that Asia possesses a good stock of matured technology in rice and maize so that GR in these crops could be launched in SSA provided an appropriate adaptive research is undertaken to tailor the Asian technologies to the current conditions in SSA. Wheat is not important in SSA because it cannot be grown in tropical climate. In this chapter, we focus on rice, which is largely the GR crop in Asia. The comparative analyses of yield growth between India and SSA will be made in Chaps. 4 and 5.

2.4 The Asian GR in Rice

2.4.1 Evolution of MVs

The process of Asian GR in rice can be best understood as a long history of rice varietal improvements and steady productivity gains rather than a one-shot phenomenon (Hayami and Otsuka 1994). Before the release of IR8 in 1966, the increase in rice production came largely from expanding land area devoted to rice culture or by improving the resource base through expansion of irrigation. During this period, there was hardly any significant yield increase because MVs were not available and there was hardly any adoption of improved crop management practices. The earliest released MVs, the so-called "first-generation MVs" (e.g., IR5 and IR8 developed by IRRI and C4 developed by the College of Agriculture of the University of the Philippines) are semi-dwarfed varieties, photoperiod insensitive, and had medium growth duration (130 days) much less than the growth duration of the more common traditional varieties (TVs) (160–170 days). MV1 doubled the yield potential of tropical rice but its yield fluctuates greatly because it is susceptible to attacks of numerous diseases and pests (IRRI 1985; Pingali et al. 1990).

The "second-generation of MVs" (MV2) consisting of IR36 to IR62, which were developed from the mid-1970 to the mid-1980s, incorporated wide-spectrum of pests and disease resistance traits and early maturity period of 110–115 days (Khush 1987, 1995). Resistant MVs contributed significantly to the acceleration of yield growth by reducing yield variability thereby increasing the expected yield particularly during the dry season (Otsuka et al. 1994). The "third generation of MVs" (MV3) incorporated improved grain and nutritional quality with such traits as multiple pests and diseases resistance and shorter-growing period (Hossain et al. 2003). Typified of this innovation is IR64, which gained broad acceptance for many years since its release in 1985 because of its good cooking quality – it contains intermediate level of amylase that makes it moist and remains soft even when cool.

Rice breeders believe there are two new prospects for further improving MVs: (1) development of hybrids and (2) the use of new of biotechnologies that produce genetically modified (GM) rices.[3] Good quality hybrid rice seed could be purchased from private seed growers and is relatively costly whereas the yield advantage of hybrids over conventional MVs, which can be propagated by the farmers, tend to be modest (about 15% only) (Byerlee 1996). Thus, hybrid rice adoption is observed to be high only in favorable areas in China where the seed industry is well developed. Many scientists believe that biotechnology would be helpful in developing rices that are suitable to unfavorable production environments, notably flood-prone areas, for which the conventional breeding method has produced only a small number of rices (Khush 1995).

We can conveniently divide the GR into two phases: – (1) the replacement of TVs by MV1, which provided the potential for dramatically increasing yield ("revolutionary" phase) and (2) the replacement of MV1 by the newer and better MVs ("evolutionary" phase). Resistance against multiple pests and diseases contributed perhaps half of all the gains in total yield growth (Byerlee 1996) while the rise in cropping intensity (i.e., the number of rice crops that can be grown per year) because of shorter growth duration and photoperiod insensitivity was the major contributor to a substantial increase in rice production per year (Barker and Herdt 1985). Improved pest resistance also contributed to environmental sustainability through reduced usage of pesticides, which include some of the most environmentally harmful chemicals.

It is during the evolutionary phase when knowledge-intensive crop management practices were introduced and have started to substitute for input use and improved input efficiency (Byerlee 1994). These knowledge-intensive cultural practices can be effectively included in the package of inputs and production practices complementary to fertilizer in realizing the yield potential of MVs. In Asia, the most common crop management practices are selection of good quality seeds, leveling and bunding of fields, straight-row planting, direct-seeding, use of an appropriate mix of a variety of chemical fertilizers and manure, appropriate amount and timing of

[3] Byerlee and Fisher (2002) explore the policy and institutional option for biotechnology in developing countries given the presence of market failures in developing countries in accessing the new tools and technologies. The authors argue for a public-private partnership and market segmentation with active participation of the national agricultural systems to access proprietary tools and technologies.

pesticide and weedicide application, and water control management. While manure and chemical fertilizer are generally complementary in increasing yield of cereals (i.e., sorghum and maize) in India (Chap. 10 in this volume) and Ethiopia (Chap. 11 in this volume), the use of manure is generally not widely spread in rice-growing areas in Asia perhaps because of the low price of chemical fertilizer brought forth by subsidies. Overall, the evolution of MVs and adoption of improved crop management practices give support to Hypothesis 1.

2.4.2 Irrigation and the Spread of MVs

There was a general perception that the Asian GR in rice is a revolution in favorable areas only (Lipton and Longhurst 1989). Earlier released MVs were particularly developed to perform well under irrigated and favorably rainfed environment with intensive use of fertilizers, while rice yield remained stagnant in marginal environments, where water, climate and soil constraints cannot be overcome through varietal improvements (Evenson and Gollin 2003). There is a slow progress in developing improved germplasm for unfavorable environments (i.e., drought-prone rainfed lowland, upland, flood prone, and tidal wetlands) because these environments are extremely heterogeneous while it is necessary to develop rice varieties that are adaptable for each small area with specific growing condition (Khush 1995). The irrigated rice area consisting of 79 million ha remains the major granary producing about 75% of the world's rice output.

Adoption of MVs rose steadily over time in Asia since the mid-1960s reaching over 90% of rice area in the Philippines, Indonesia, and Vietnam in the early 2000s. MV adoption was generally faster in irrigated and favorably rainfed areas because the presence of irrigation is by far the most important factor affecting MV adoption (David and Otsuka 1994). Ruttan (1977) found in the early period of GR that neither farm size nor tenure affected the adoption of MVs. Indeed it is small farmers who actively adopted MVs and introduced intensive rice production management systems.

Figure 2.3 compares the rate of MV adoption and irrigation ratio (i.e., proportion of irrigated rice area) in the Philippines, Vietnam, Bangladesh and India. It is clear that the former far exceeded the latter, implying that MVs were widely adopted, not only in irrigated areas, but also in rainfed areas. In the Philippines, this could be attributed to the release of drought-resistant and early maturing MVs that allow the farmers in favorably rainfed areas to catch the late monsoon rains to plant a second crop of rice (Estudillo and Otsuka 2006). Spread of MVs suitable to unfavorable production environments in this country started in the mid-1990s.

Hossain (1993, 2009) reported that in Bangladesh beginning in the late-1980s, rice was increasingly grown in low-lying areas during the dry season using modern variety *boro* rice with pump irrigation. The rapid adoption of the high-yielding *boro* rice was facilitated by the government's market liberalization policies for minor irrigation equipment, most importantly, the shallow tube well. The rapid expansion

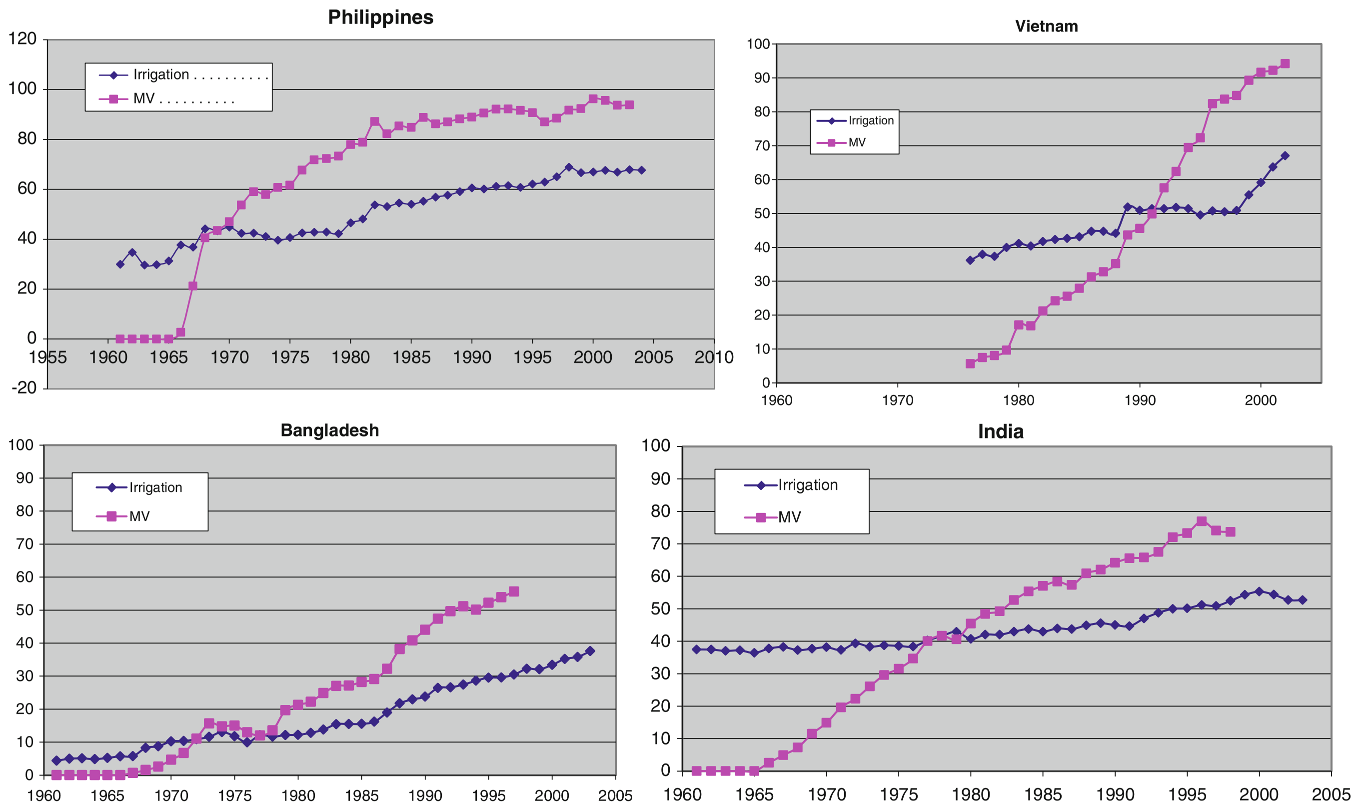

Fig. 2.3 Adoption of modern rice varieties and irrigation ratio in the Philippines, Vietnam, Bangladesh, and India (Data source: World Rice Statistics online)

of irrigated *boro* rice in the dry season contributed importantly to the accelerated growth in rice productivity in Bangladesh.

It must be emphasized that areas with irrigation were expanded much further on with an approximately10-year lag following the acceleration in MV adoption. Adoption of MVs was high in the Philippines in the 1970s due to large irrigation infrastructure projects that were implemented in the 1950s and 1960s, yet importantly, irrigation ratio rose further in the 1980s and 1990s when MV adoption rates had already reached more than 90%. In Vietnam, irrigation ratio rose sharply since the late 1990s with higher adoption rates of MVs and deeper involvement of Vietnam in international rice markets thereby making irrigation investments more profitable. In Bangladesh and India, the rate of MV adoption was low initially, but picked up later, starting in the late 1970s when the governments started to invest in flood control, drainage and irrigation projects, and give incentives to farmers to invest in groundwater irrigation through privately owned tube wells (Hossain et al. 2003). The experience of the four countries suggests that earlier MV adoption stimulated further investments in irrigation by increasing the rates of returns to such investments, thereby giving support to our Hypothesis 2.

2.4.3 Fertilizer Application

Application of fertilizer is one of the most critical factors in realizing the yield potential of MVs. Citing various agronomic studies, Hossain and Singh (2000, p. 159) reported that under a controlled experimental condition it is possible to obtain an average response of 50 kg of unmilled rice per 1 kg of applied nitrogen. Figure 2.4 which plots fertilizer use and rice yield over time shows that these two increased gradually and simultaneously over time, suggesting not only the critical importance of fertilizer in yield growth but also the involvement of long-term process of technological and institutional changes.

We believe that the rise in fertilizer application could be explained partly by the decline in real fertilizer price and the presence of fertilizer subsidy program, but more importantly, by the continuous development of fertilizer-responsive MVs. Later released MVs tend to be more responsive to fertilizer application partly because they incorporated some degree of resistance against environmental stresses and partly because of the expansion in irrigation and adoption of effective water control practices. Agronomic evidences reveal that droughts during the effective nutrient utilization period in the plant lifecycle adversely affect crop yield by limiting nutrient uptake (De Datta et al. 1990 cited in Hossain and Singh 2000, p. 160). Hossain and Singh (2000, p. 168) succinctly summarize the variations in fertilizer use across rice-growing Asian countries in various production environment: "The intensity of fertilizer-use is higher for modern varieties of cereals compared to traditional ones, on irrigated farming compared to rainfed, and on well-drained land with medium elevation than on lands that are subject to droughts and floods".

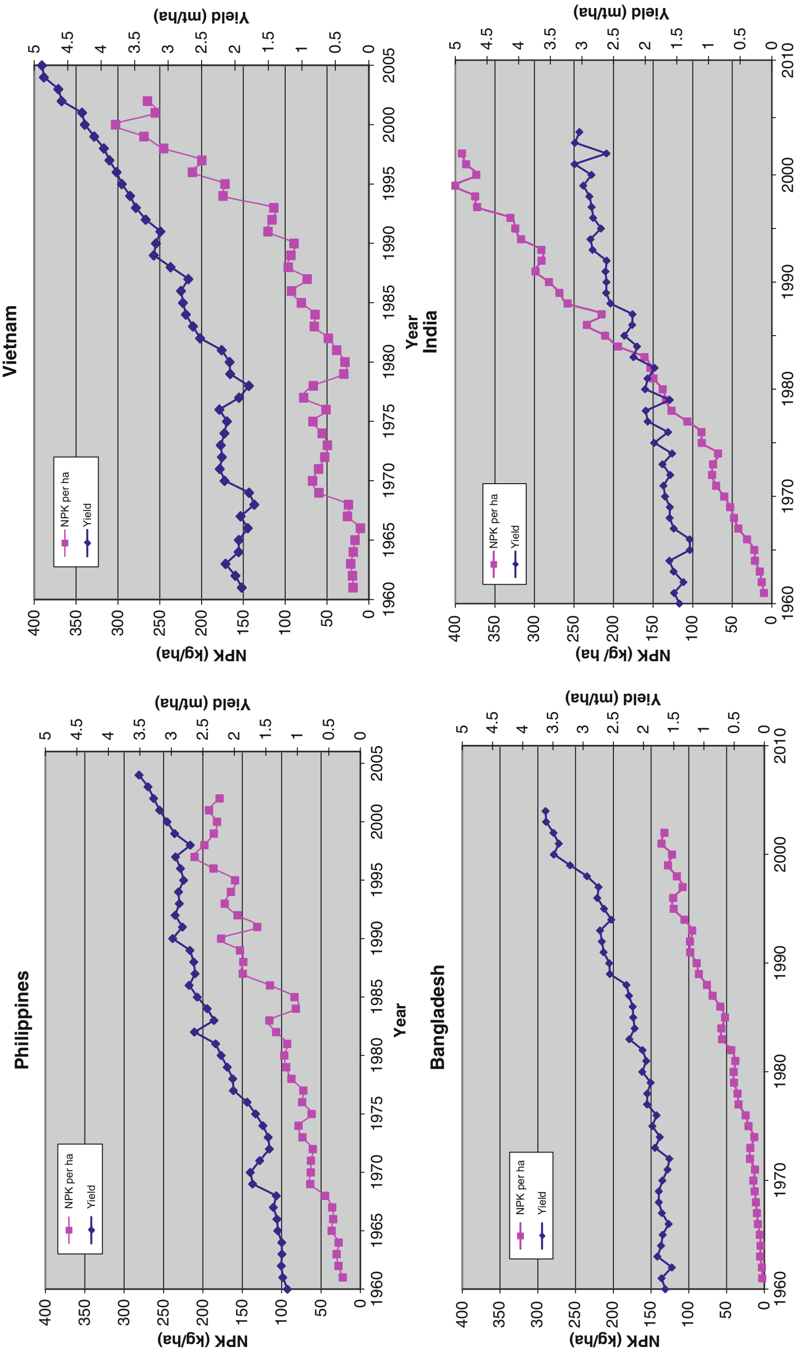

Fig. 2.4 Fertilizer use and rice yield in the Philippines, Vietnam, Bangladesh, and India (Source: World Rice Statistics online)

Table 2.1 Number of improved rice varieties released in selected Asian countries by time period

Time period	Philippines	Vietnam	Bangladesh	India
Pre-1970	14	93	13	208
1971–1980	38	11	29	211
1981–1990	20	44	28	347
1991–1999	56	67	30	170
Total	128	215	100	936
Rice land (million ha)	3.9	7.6	10.5	44.8
No. of varieties per million ha	33	28	10	21

Source: Hossain et al. (2003, Table 5.3, p. 79)

2.4.4 *Institutional and Policy Changes*

The initial success in increasing rice yield in the 1970s was followed by further improvements in institutional and policy environments: (1) enhanced public investments in research and development and extension services, (2) greater investments in irrigation and water management, and (3) stronger pricing incentives and credit systems to enable small farmers to purchase chemical fertilizer.[4]

When MVs started to spread, governments and international organizations gradually increased their investments in crop improvement research. One measure of such investment is the release of new varieties. Table 2.1 shows the number of improved rice varieties released by period in the Philippines, Vietnam, Bangladesh and India in terms of the total number of improved varieties released and number of varieties per million ha of rice lands. It is clear that the number of new varieties tends to increase over time due to the continuous efforts to improve the genes of rice varieties. It is also found that the Philippines, Vietnam, and India had a larger number of released MVs than Bangladesh presumably because these three countries invested more in rice research.

The Philippines had a long history of rice improvement program beginning in 1901 with the establishment of the Division of Plant Investigations within the auspices of the Bureau of Agriculture under the American colonial government (Halos 2005). Years after its political independence from America, the Philippines established the Cooperative Rice and Corn Seed Improvement Program launched in 1953, which was later replaced by the Philippine Rice Research Institute (Phil Rice) which was established in 1987.

In Vietnam, the number of released MVs rose more rapidly in 1981–1990 after the implementation of the liberalization (Doi Moi) policy in 1986 that promoted

[4] According to Herdt (2010, p. 3267), aid agencies and international organizations such as the United States Agency for International Aid, World Bank, and Asian Development Bank recognized irrigation as one of the most important agricultural development assistance targets. Investments of these institutions on irrigation were at its peak level in the 1970s following the introduction of IR8, the first MV, in 1966.

Vietnam to become a major rice exporter, thereby making rice research a socially profitable venture. Rice production growth in Vietnam is attributed to the continuous improvements of modern varieties. Hybrid and improved varieties imported from China have contributed to the GR in north Vietnam and those developed by IRRI in south Vietnam while the national agricultural research systems have successfully developed location-specific varieties (Ut and Kajisa 2006).

India had the largest number of released improved varieties mainly because it has the largest rice area in the world (46 million ha). This country had a long history of agricultural development programs since its independence in 1947. Prime Minister Jawaharlal Nehru allocated 31% of the country's budget to build massive irrigation projects, power plants, state agricultural universities, national agricultural research systems, and fertilizer plants (Hazell 2009). In Bangladesh, while the dry-season irrigated *boro* rice contributes about 60% of the country's rice production, there have been efforts from the national agricultural systems to develop rices that are locally adaptable to varied production environment susceptible to drought, floods, and salinity (Hossain 2009).

Investments in irrigation started even before the advent of MVs as a land-augmenting strategy to mitigate the high population pressure on land. Investments in irrigation together with farmers' long experience on rice culture were major factors behind the success of the development and diffusion of MVs in tropical Asia (Hayami and Otsuka 1994). Yet major investments in irrigation took place after the acceleration in MV adoption indicating that MVs had increased the rates of returns to such investments (Fig. 2.2). In the early phase of GR, the expansion in irrigation system was in the form of large gravity irrigation systems financed mainly by international organizations (Herdt 2010), which was later replaced by privately owned portable shallow tube wells particularly common in South Asia (Hossain 2009).

According to Hayami and Otsuka (1994), there was a substantial decline in fertilizer-rice price ratio in tropical Asia before the mid-1960s yet the increase in rice yield was very slow. The authors attributed this to the lack of major advancements in developing fertilizer-responsive rice varieties at a time when major public agricultural research centers for rice production were not yet established. This observation points to the importance of the development and diffusion of fertilizer-responsive rice varieties in increasing yield.

To make rice production profitable to the farmers, many Asian governments resorted to fertilizer subsidy and rice price support programs. According to Table 2.2, fertilizer-rice price ratios are different among the four countries because of the presence of fertilizer subsidy and rice market interventions in these countries. The price of fertilizer paid by the farmers had a declining trend since 1980 in the Philippines, Bangladesh and India.

The Philippines started a national fertilizer subsidy program in 1973, when MV adoption had already reached 60%, as part of a national program dubbed as Masagana 99 under the Marcos administration, which is a total package of production incentives to farmers including not only low cost production credit but also a fertilizer subsidy (Esguerra 1981). Fertilizer prices paid by the farmers were below the market price because the government controlled and regulated domestic fertilizer

Table 2.2 Producer price of rice and fertilizer price in selected Asian and African countries

Year	Philippines	Vietnam	Bangladesh	India	Kenya	Tanzania	Nigeria	Madagascar
Price of urea per ton of nitrogen paid by farmers (US$ per ton)								
1961	347		77	337				
1965	179		96	292				
1970	188		132	317	221			
1975	208		242	489	652			
1980	250		398	528	842			
1985	287		373	384	663	865		
1990	248	670	288	292	516			1236
1995	237	522	273	223	719			1108
2000	360	358	235	223	445	601	628	596
2002	358		219	216	497	544		
Farm harvest price of rough rice (US$ per ton)								
1961	114		70	80				
1965	77		86	137				
1970	61		108	97	71			
1975	130		165	91	142			
1980	146		182	134	203			
1985	149		157	119	189	na[b]		
1990	187	323	177	125	189			140
1995	239	176	176	151	107			169
2000	192	134[a]	119	133	300	na	279	190
2002	171		114	124	143	na		
Fertilizer-paddy price ratio								
1961	3.04		1.10	4.21				
1965	2.33		1.12	2.14				
1970	3.09		1.23	3.27	3.11			
1975	1.61		1.47	5.37	4.58			
1980	1.71		2.19	3.95	4.16			
1985	1.93		2.38	3.23	3.51	na		
1990	1.33	2.07	1.63	2.33	2.73			8.82
1995	1.00	2.96	1.56	1.48	6.70			6.55
2000	1.88	2.67	1.98	1.68	1.48	na	2.25	3.13
2002	2.09		1.92	1.74	3.47	na		

Source: FAOStat online for urea price and World Rice Statistics online for farm harvest price and exchange rates. Urea price and farm harvest price in the Philippines from 1980 to 1995 were taken from the Central Luzon Loop Surveys

[a] Refers to 1999

[b] na means not available

prices (Halos 2005). Fertilizer subsidy program continued on to the Aquino administration and in more recent years to the Arroyo administration through a cash voucher of PHP500 (about US$10) per bag of fertilizer purchased. The government in Bangladesh initiated a policy in 1979 to liberalize modern agricultural inputs, allowing privatization in the import and marketing of irrigation equipment and chemical fertilizer (Hossain 2009). In India, key inputs – fertilizer, power and water – were subsidized since the 1960s as part of public investments to launch and sustain the GR (Hazell 2009).

The Philippines has the highest farm harvest price of rough rice among the four countries and has the highest ratio of domestic to border price of rough rice. A comparison of the farm harvest price of rough rice with the border price of Thai rice 5% brokens shows a ratio of 1.41 in 1985, 1.33 in 1990, 1.52 in 1995, 1.94 in 2000, and 1.82 in 2002.[5] The farmers have been receiving a price premium for their rice because of government heavy intervention in the grain market through its marketing parastatal, the National Food Authority, which is involved in the domestic rice market through its buffer stock operations and in setting quantitative restrictions on rice imports on which it has a monopoly control.

The government of Bangladesh embarked into a freer food market regime between 1991 and 1993 by abolishing major food ration channels, reducing domestic rice procurement, and liberalizing foreign trade in food grains. The ratio of farm harvest price of rough rice to the border price of milled rice converted to rough rice equivalent was close to unity in Bangladesh in 1995. According to Ahmed et al. (2000) such regime was put into place because of the surge in the adoption of MVs in the second half of the 1980s coupled with sustained investment in rural infrastructure, which contributed to a steady decline in domestic real rice prices.

Overall, it is clear that the Asian GR is a continuous evolutionary process involving the development and spread of superior MVs accompanied by high application of chemical fertilizer, expansion of irrigated area, and adoption of better cultural practices complemented by public investments in agricultural research and development and price stabilization mechanisms that made modern rice technologies profitable to farmers. In our view, governments are not leaders but supporters of the long-term process of the Asian GR.

2.4.5 Sustainability of the GR

There are a few important issues on the long-term sustainability of the Asian GR: (1) slow down in rice production growth, (2) loss of biodiversity, (3) degradation of soil and water quality, and (4) withdrawal of land and labor from rice production to other uses. Barker and Dawe (2002) enumerated the causal factors on stagnation of rice production growth. The production-related factors are: (1) MV adoption ceiling, (2) full exploitation of yield gains based on the conventional breeding technique (the so-called "yield plateau" (Pingali et al. 1997)), and (3) the decline in soil fertility and greater pest infestations due to many years of continuous mono

[5] We converted the border price of milled rice to rough rice equivalent by adjusting the border price of milled rice for marketing and processing costs of 25% and milling recovery rate of 65% (Estudillo et al. 1999).

cropping of rice. The market-related factors are (1) lower rice prices and (2) rising wages thereby making rice farming a less profitable venture.

Many naysayers argue that GR could lead to a loss of biodiversity because only a few MVs dominate in the farmers' fields thereby narrowing the genetic base of readily available rice varieties. Norman Borlaug (2002) has this to say "The high yields of the Green Revolution also had a dramatic conservation effect: saving millions of acres of wild lands all over the Third World from being cleared for more low-yield crops…We can save the farmers' old varieties through gene banks and small-scale gene farm, without locking up half of the planet's arable land as a low-yield gene museum".

Whereas excessive use of chemical fertilizers and pesticides could lead to a serious degradation of soil and water quality, there have been serious efforts since the 1970s to develop rices that are resistant to various forms of infestations and make integrated pest management locally adaptable. In two villages in Central Luzon in the Philippines the proportion of adoption of integrated pest management rose from nil in 1985 to 25% in 2004.

There are fears that the withdrawal of land and labor from rice production to the growing nonfarm sector may lead to rice supply shortages. Yet there have been improvements in international rice trade facilitated by the GATT Uruguay rounds of talks and the return of Myanmar, Cambodia, and Vietnam in the rice market. Countries located in Asia's major river deltas could have the greatest comparative advantage in rice production because they have plenty of water resources and cheap labor.

2.5 Decomposition of Growth in Rice Yield in Asia

2.5.1 Yield Growth Decomposition

It is by now well-known that yield growth, rather than area expansion, is the most important contributor to rice production growth in Asia. In this section, we explore the sources of yield growth in the Philippines, Vietnam, Bangladesh, and India in separate periods of time (i.e., 1970–1980, 1980–1990, 2000–2005) corresponding to different phases of GR in these countries. The first phase can be described as the early phase when MV adoption rates are still low and released MVs are susceptible to attacks of pests and diseases. The second phase is the period when MV adoption rates have achieved higher levels and released MVs are resistant against pests and diseases. The third phase is the period when MV adoption rates have gone up higher and released MVs have incorporated stronger resistance against pests and diseases and better grain quality. While recognizing the importance of increased fertilizer application in increasing yield, our decomposition technique simply assesses the relative importance of changes in MV adoption and yield growth of MVs and TVs.

We decompose the sources of yield growth using the simple decomposition technique. Since the average yield is a weighted average of yield of MVs and TVs, we have

$$Y = s_{MV} Y_{MV} + s_{TV} Y_{TV}, \tag{2.1}$$

where:

Y = average yield
s_{MV} = ratio of MV area
s_{TV} = ratio of TV area
Y_{MV} = MV yield
Y_{TV} = TV yield.

Since $s_{TV} = 1 - s_{MV}$, we can write Eq. 2.1 as,

$$Y = s_{MV} Y_{MV} + (1 - s_{MV}) Y_{TV} \tag{2.2}$$

Taking the difference of each variable and dividing by Y, we can derive

$$\frac{\Delta Y}{Y} = s_{MV} \frac{\Delta Y_{MV}}{Y} + (1 - s_{MV}) \frac{\Delta Y_{TV}}{Y} + \Delta S_{MV} \left(\frac{Y_{MV} - Y_{TV}}{Y} \right). \tag{2.3}$$

The first term on the right hand side, $s_{MV} \frac{\Delta Y_{MV}}{Y}$, is the contribution of change in MV yield, the second term $(1 - s_{MV}) \frac{\Delta Y_{TV}}{Y}$ is the contribution of the change in TV yield, and the last term $\Delta S_{MV} \left(\frac{Y_{MV} - Y_{TV}}{Y} \right)$ is the contribution of the change in MV ratio. To the extent that continuous improvement of MVs yield is achieved assisted by increased fertilizer application, the first term tends to be large. On the other hand, the last term tends to be large, when the yield gap between MVs and TVs is large, which is particularly the case when MVs are grown under irrigated condition and TVs are grown under rainfed condition. We expect that the contribution of the change in TV yield is small.

2.5.2 *Sources of Yield Growth*

MVs have been continuously improved by IRRI, which is located in the Philippines. Thus, we expect to observe that the change in MV yield is a major contributor to the overall yield growth in the Philippines even in the early years of GR. In contrast, improvement of locally adaptable MVs was carried out mainly by the national research programs in Vietnam and India, which have been strengthened over time. Thus, we expect to observe the increasing contribution of the change in MV yield in these countries. In Bangladesh, TVs grown under rainfed condition were often replaced by MVs, which were adopted during the dry season by using irrigation pumps and tube-wells. Thus, the contribution of the change in MV ratio is likely to be large.

Table 2.3 shows the decomposition of changes in rice yield in the Philippines, Vietnam, and Bangladesh and India.[6] In the Philippines in 1970–1980, the main contributors are the change in MV yield and change in MV ratio. The first MV2, which is IR36, was released in the Philippines in 1976, when it gained wide acceptance immediately because of the widespread tungro infestation in 1971–1972 (Chandler 1982; Barker et al. 1985). MV yield rose in 1970–1980 partly because of the initiation of the Masagana 99. As a result, fertilizer use in the Philippines rose sharply in 1975–1980, thereby increasing MV yield, which responds favorably to high application of fertilizer. There was a slow and gradual increase in irrigation ratio when the National Irrigation Administration (NIA), which was established in 1964, embarked into a program in expanding irrigated rice area through investments in gravity irrigation system (Halos 2005). The NIA program and the introduction of pests- and disease-resistant MVs contributed to rice self-sufficiency in the country in the period 1978–1983. From 1980 to 1990, the contribution of change in MV yield to overall yield growth had been sustained. Meanwhile the contribution of the change in MV ratio declined continuously over time because MV adoption reached the ceiling of well over 90%. It is also interesting to note that the change in TV yield somehow contributed positively to yield increase beginning in 1980–1990, albeit small, and this is attributed to the release of improved TVs particularly those coming from the Phil Rice.

GR in Vietnam shares similar features with the Asian proto-type GR that involves the development and rapid spread of MVs followed by increase in irrigated area and increased chemical fertilizer application. Early spurt of GR started in the late 1960s, with the introduction of IR8, but was interrupted by the Vietnam War that ended in 1975. Rice production grew faster than the harvested area in the 1980s and 1990s. The GR in Vietnam has been sustained by the continuous improvement of modern varieties by the regional research institutes (Ut and Kajisa 2006). In the south, The Cuu Long Delta Rice Research Institute, Can Tho University, Southern Agricultural Sciences, and IRRI are involved in the development and dissemination of improved MVs that thrive well in saline-affected rainfed rice fields with semi-deep water, which are prevalent in Mekong River Data. In the north, the Vietnam Agricultural Science Institutes, Plant Protection Institute and agricultural research institutes in China are the major players in the development and dissemination of newer and improved MVs. Such adaptive research contributed to the sustainable growth of rice yields in this country, which is reflected in the increased contribution of changes in MV yield over time in this country (see Table 2.3).

[6] Data on the adoption of MVs in India are available from 1961 to 1998 only while separate data on the yield of MVs and TVs are not available. Thus, we simply extrapolated the yield of MVs and TVs by regressing yield using MV ratio, time, and interaction between MV ratio and time as explanatory variables.

Table 2.3 Decomposition of the changes in paddy yield in selected Asian countries[a]

Source of change in yield	Philippines	Vietnam	Bangladesh	India
	1970–1980		1975–1980	1970–1980
Total change in yield	0.2730		0.0756	0.1391
	(100)		(100)	(100)
Due to change in MV yield	0.1629		–0.0208	0.0755
	(60)		(–27)	(54)
Due to change in TV yield	0.0019		0.0324	0.0141
	(1)		(42)	(10)
Due to change in MV ratio	0.1082		0.0640	0.0495
	(39)		(85)	(36)
	1980–1990	1980–1990	1980–1990	1980–1990
Total change in yield	0.2262	0.3993	0.226	0.2159
	(100)	(100)	(100)	(100)
Due to change in MV yield	0.1586	0.1267	–0.0082	0.1467
	(70)	(32)	(–3)	(67)
Due to change in TV yield	0.0209	0.2098	0.065	0.0007
	(9)	(52)	(29)	(1)
Due to change in MV ratio	0.0467	0.0628	0.1692	0.0685
	(21)	(16)	(74)	(32)
	1990–2000	1990–2000	1990–2000	1990–1998
Total change in yield	0.0996	0.2995	0.2505	0.1861
	(100)	(100)	(100)	(100)
Due to change in MV yield	0.0647	0.1572	0.0708	0.1334
	(65)	(52)	(28)	(72)
Due to change in TV yield	0.0084	–0.0291	0.0352	0.0039
	(8)	(–9)	(14)	(2)
Due to change in MV ratio	0.0265	0.1714	0.1445	0.0488
	(27)	(57)	(58)	(26)
	2000–2005	2000–2002	2000–2005	
Total change in yield	0.1637	0.0522	0.1232	
	(100)	(100)	(100)	
Due to change in MV yield	0.1647	0.0381	0.0533	
	(100)	(73)	(43)	
Due to change in TV yield	0.0060	0.0000	0.0339	
	(4)	(0)	(28)	
Due to change in MV ratio	–0.0073	0.0141	0.036	
	(–4)	(27)	(29)	

Source: Authors' calculations
[a]Numbers in parentheses are percentages

In Bangladesh, yield growth in 1975–1980 could be largely attributed to the change in MV ratio. Adoption of MVs was rather slow in Bangladesh till the late-1980s when irrigation investments accelerated (Fig. 2.3). There was hardly any increase in TV yield (1 t in 1975 and 1980) and MV yield even declined from 2.35 t in 1975 to 2.21 t in 1980. There was huge variability in the yield of earlier MVs that are susceptible to a wide spectrum of pests and diseases. The contribution of the change in MV ratio was by far the largest in 1980–1990, when MV adoption was gaining momentum and, as maybe expected, its contribution declined over time when both the MV and TV yields rose. Like the Philippines, Bangladesh has a stock of improved TVs that contributed to yield increase. By 2000–2005, however, the increase in MV yield was clearly the dominant source of yield growth.

Punjab and Haryana in northwestern India were the earliest to adopt MVs and became the breadbaskets for the entire country. Because of the rapid spread of MVs in these two states the change in MV ratio contributed to 36% of the change in yield between 1970 and 1980 (Table 2.3). Yet more importantly, the contribution of the change in MV yield to the total change in yield continued to rise from 54% between 1970 and 1980 to 67% between 1980 and 1990 and further to 72% between 1990 and 1998. Similar to the case of the Philippines, more improved MVs were released and adopted by Indian farmers coupled with increased usage of inputs such fertilizers and tube wells as the Indian government has been heavily involved in the production, dissemination, and adoption of these inputs since the mid-1960s. In brief, there is no doubt that the main contributor to yield increase in the four Asian countries had been the continuous MV improvements.

2.5.3 The GR in Central Luzon, the Philippines

Here we discuss the gradual evolutionary processes of GR in Central Luzon in the Philippines, which was one of the earliest to experience the GR in Southeast Asia. As early as 1966 the irrigation ratio among our sample farmers was as high as 60% and it increased further to 71% with the opening of Pantabangan Dam in 1975 and since the early 1990s there was a spread of small-scale deep well water pumps. Rice cropping intensity in Central Luzon increased from 1.1 in 1966/1967 to 1.6 in 1979/1980, and then decreased to 1.5 in 1998/1999 coinciding with the trends in irrigation ratio.

When the first survey was conducted in Central Luzon in 1966, the entire area was planted with TVs (Table 2.4). There was a fast rate of adoption of MV1 immediately after its first release that by 1970, 66% of sample farmers were adopting MV1. The speed of MV diffusion in Central Luzon in the early period of release of MVs was almost the same as in the irrigated ecosystem in the Philippines as a whole (Estudillo and Otsuka 2006). The adoption of MV2 was quicker than MV1 because MV2 are more resistant to attacks of major insects and diseases. A few years after the release of IR36 in 1976, 92% of sample farmers in Central Luzon were already adopting MV2 in 1979, when TVs were completely replaced by MVs. The adoption of MV3 was also fast and their adoption reached 90% by 1990. It is noticeable that the adoption rates of MVs in Central Luzon far exceeded the irrigation ratio suggesting that MVs were grown well in rainfed production environments.

Table 2.4 Adoption of generations of modern varieties of rice (% area) in the central Luzon provinces, the Philippines, 1966–2004

Year	% area planted				NPK (kg/ha/season)	Average rice yield (mt/ha/season)
	TV	MV1	MV2	MV3		
1966	100	0	0	0	9	2.3
1967	94	6	0	0	17	1.9
1970	34	66	0	0	29	2.5
1971	8	92	0	0	59	2.4
1974	27	73	0	0	39	2.2
1979	0	8	92	0	62	3.6
1980	0	9	91	0	78	4.3
1982	0	3	97	0	63	4.1
1986	0	1	38	61	67	3.6
1987	0	2	6	92	88	4.3
1990	0	2	8	90	70	4.6
1991	0	3	15	82	103	4.5
1994	0	0	6	94	93	3.9
1995	0	0	0	100	125	4.6
1998	0	0	0	100	150	4.8
1999	0	0	0	100	143	3.4
2003	0	0	0	100	136	4.2
2004	0	0	0	100	165	4.7

Data source: Central Luzon Loop Surveys, International Rice Research Institute

The most important factor affecting farmers' adoption of MVs is the availability of irrigation, which became much more important in the adoption of MV2 and MV3. A possible reason could be that MV2 and MV3 are more resistant to attacks of various pests and diseases, which tend to be frequent in irrigated environments because of continuous mono-cropping of rice, the decline in genetic diversity of the more common MVs, and the ability of pests to evolve genetically over successive crops of rice (Khush 1995). Socio-economic factors such as age and schooling of head, farm size and tenancy were, in general, not significant determinants of the adoption of MVs (David and Otsuka 1994).

There was an increasing trend in the application of chemical fertilizer starting in the mid-1970s and rice yield rose remarkably in this period. TV has an average yield of about 2 t/ha per season, MV1 has about 2.5 t, MV2 has about 4 t, and MV3 has more than 4.5 t. According to Otsuka et al. (1994), MV2 had a statistically significant yield advantage over MV1 and the adoption of MV2 contributed to yield growth under irrigated condition and during the dry season.

Overall, the experience in Central Luzon demonstrates that the diffusion of new MVs has been remarkably fast and there has been no reversal back to TVs and older MVs indicating that the use of newer and betters MVs has been more profitable. Indeed, the achievements in varietal improvements and farmers' acceptance of newer MVs played a catalytic role in sustaining the GR in Central Luzon.

2.6 Rice in SSA

There are many episodes of success stories in rice production in SSA, even though these successes are inadequate to fully launch a GR in rice. They indicate, however, that there is a high potential of rice production and sustainability even without heavy government support. We would also like to argue that markets are now working much better than in the past and that the increasing population pressure on limited land resources makes intensive Asia-type farming systems more profitable. It must be also pointed out that there has been little effort in the past to develop lowland rice sectors in SSA in contrast to cassava, maize, cotton, and horticultural crops (Haggblade 2004). In fact, even the very basic production practices, such as leveling, bunding, and flooding are not adopted by many farmers in SSA, which indicates inadequate extension efforts as well as the lack of efforts to transfer production methods from Asia to SSA. Indeed, there are very few extension workers in SSA who are knowledgeable about rice production. In our observation, rice yield could double by simply introducing bunding, leveling, and flooding without using additional external inputs.

There has been an on-going debate on the strategies to launch a GR in SSA. Djurfeldt et al. (2005) argue that a broader process that is "state-driven, market-mediated, and small-farmer based" is necessary while Dorward et al. (2009) argues to identify constraints imposed by market and state and explore their complementary roles in technology transfer. On the contrary, Borlaug (2002) believes that the African GR could be simple and straightforward consisting only of two fundamental ingredients (1) modern technology and (2) remunerative and stable prices to farmers. By modern technology, Borlaug (2002) refers to high-yielding seeds well-adapted to local conditions, irrigation, chemical fertilizers, and integrated pest management. In order to follow Borlaug's paradigm, Otsuka and Yamano (2005) recommend increasing investments in agricultural research and enhancing the capacity of national systems for adaptive research. Indeed, according to Pardey et al. (2007), real research spending in Africa as a whole has stagnated since the 1970s with the spending per scientist declining continuously in the past 30 years and most dramatically during the 1980s.

Otsuka and Kijima (2010) compare the states of agricultural development in Asia and SSA. First, in the early 1960s, the yield difference in rice between Asia and SSA was in the order of about 20–30%, which could be largely attributed to a well-developed irrigation system in Asia. Second, yield difference in rice appeared since the mid-1960s with the advent of IR8, which began the GR in Asia. Irrigation investments and government-sponsored credit programs, and the establishment of the national research and extension services were accelerated following high adoption rates of MVs. And thirdly, irrigated rice yields in SSA are highly comparable to irrigated yields in Asia despite the absence of major technological breakthroughs (Chap. 3 in this volume). This likely reflects the increasing intensification of farming systems, including the adoption of IRRI-type MVs in selected areas, because of the continued population pressure that makes land-saving and yield-enhancing technologies profitable.

Markets for inputs and outputs have started to develop in SSA. For example, prices of bean seeds in Kenya and milk prices in Kenya and Uganda are determined largely by transportation costs, which indicates that market prices are competitive (Staal and Baltenweck 2008). Kijima et al. (2008) reported that in Uganda, where NERICA were adopted, access to rice millers was greatly improved owing to the rapid increase in the number of rice millers. Tsuboi (2008) reported that the total number of private rice mills in Uganda rose from 183 in 2000 to 591 in 2007. Seeds have been increasingly available from seed suppliers and purchase from neighboring farmers (Chap. 6 in this volume), indicating the development of both formal and informal seed markets. African maize farmers have become more aware of the importance of seed selection in increasing yield that they are willing to purchase good quality maize seeds even at a premium price (Chaps. 9 and 12 in this volume). These are good examples to show that markets could respond favorably to the diffusion of new profitable technology in SSA.

There are numerous success stories on the use of Asian rice technology that indicates the possibility of inducing the evolutionary processes of a GR in SSA. First, MVs that were developed in Asia and grown in areas with simple irrigation canal in Côte d'Ivoire have an average yield of 3.6 t/ha while those varieties that were grown in areas without canal have an average yield of 2.5 t/ha with minimum or even zero application of chemical fertilizer (Sakurai 2006). Second, Kajisa and Payongayong (2011) demonstrate that paddy yields can be potentially high (3.8 t/ha) in irrigated areas of Mozambique, where irrigation facilities are poorly maintained. Third, the NERICA could potentially increase the yield potential of upland fields from 1 t to 2–3 t/ha as in the case in Uganda (Chap. 6 in this volume). NERICA is an upland variety that thrives well in fields that tend to experience water stress and believe to be the most appropriate variety suitable for nearly 40% of the total rice area in SSA. Yet a resurvey of the same farmers in 2006 (the first survey was undertaken in 2004), Kijima and Otsuka (Chap. 6 in this volume) reported that dropout rate was generally high even as high as 75% in areas where the Vice President distributed free NERICA seeds. This is quite different from the experience in Asia where farmers never reverted back to TVs but were instead continuously adopting newly released MVs. The dropout rate in the case of NERICA is high because of lower yield performance particularly of NERICA seeds that are self-propagated by the farmers. Fourth, and finally, a study in Doho irrigation scheme in Eastern Uganda reveals that paddy yields are as high as 3 t/ha even without application of chemical fertilizer and despite continuous double cropping of rice for the last few decades (Nakano and Otsuka 2011).

It appears that the GR in rice in SSA is not an impossible dream at all given the comparable yield performance of SSA vis-à-vis that of Asia. Indeed, what is needed for a take-off in SSA is first to develop rice varieties that are better adaptable to local African condition and then to strengthen extensions system, enhance the development of seed and fertilizer markets, increase investments in irrigation and water management, and give price incentives to farmers as is illustrated in Fig. 2.1.

2.7 Conclusions

This study has attempted to demonstrate that the fundamental lesson from the Asian GR is the continuous development of MVs and the subsequent acceleration in public sector investments in supporting measures. The Asian GR is essentially technology-led and policy-supported, rather than policy-driven as is oftentimes assumed. The continuous development of MVs induced subsequent acceleration in public sector investments in irrigation, credit and fertilizer subsidy programs, and national research and extension services as the rates of returns to these investments rose. Farmers were induced to adopt the GR technologies because the favorable policy environment made the new technologies privately profitable. Factor and product markets were also induced to develop further to internalize the gains from profitable opportunities associated with the new technologies. We believe that if GR is to start in SSA, it is likely to include rice because rice has a matured transferable technology that is readily available from Asia.

In order to realize a GR in SSA, we believe that a focused, concrete, and carefully designed strategy is needed, rather than the commonly accepted comprehensive approach, which allocates scarce budget thinly to a large number of purposes. As Ruttan (1984) properly emphasizes, the economists ought to design effective strategies to develop agriculture with a particular focus on institutional reforms and with a clear recognition of the inducement effects of technological and institutional changes. In the case of rice in SSA, it is critically important to recognize that productive technologies are either already available or transferable from Asia. What is badly needed now are adaptive research to transfer Asian rice technology and extension systems to disseminate available new technologies to farmers. Subsequently, such efforts should be supported by investing in low-cost irrigation and marketing infrastructure, while recognizing that expected rates of return to investments in extension, irrigation, and marketing will be enhanced by the *inducement effects* of new promising technologies.

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