Chapter 7
Intensification of Rice Farming: The Role of Mechanization and Irrigation

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Abstract PART III of this volume discusses complementary strategies toward the rice Green Revolution in sub-Saharan Africa (SSA), including mechanization, irrigation, and marketing efforts to enhance demand for domestic rice. In Asia, population pressure on land and high rice prices relative to input prices induced farming intensification, while mechanization and irrigation development boosted rice productivity. However, in SSA, increased rice demand has been partly met by rice imports without adequate investments in these important technologies. This chapter reviews the available evidence on the constraints and potentials of these complementary strategies in SSA. In particular, we argue that inadequate understanding of the complementarity of each strategy with rice cultivation training may be an important reason behind low technology adoption. The remaining chapters in PART III attempt to narrow this gap and provide relevant empirical evidence. Intensive land preparation using tractors facilitates the adoption of management-intensive practices, while the provision of rice cultivation training is associated with the improved economic viability of irrigation investment. Increased demand for domestic rice is also expected to raise the returns to rice cultivation training and technology investment. The adoption of modern milling technologies improves the quality of domestic milled rice and promotes rice value-chain transformation. Local traders offer quality-based pricing that incentivizes farmers to supply high-quality paddy, while urban traders and supermarkets sell domestically produced and milled rice with brand names at a premium. In sum, the use of tractors, irrigation investment, and modern milling, combined with improved rice marketing, play critical roles that complement rice cultivation training in achieving the rice Green Revolution in SSA.

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7.1 Introduction

During the Green Revolution era in Asia, population pressures on land and high rice prices relative to input prices kick-started farming intensification, while mechanization and irrigation investments boosted rice productivity (Barker et al. 1985; David and Otsuka 1994). Between 1950 and 1970, expanded irrigation area and tractor use each increased rice production by 26–30% and 15–16%, respectively, in Asian countries where more than 25% of the farm area was irrigated (Barker et al. 1985, Table 4.19).[1] Despite the significant gains realized during the rice Green Revolution in Asia, investment in these strategies remains low in sub-Saharan Africa (SSA), and rice imports from Asia are required to meet increased rice demand (Chap. 1 of this volume). This low investment is puzzling considering the transferability of improved rice cultivation technologies from Asia to SSA (see Chap. 2 of this volume). It can be hypothesized that some technical constraints interfere with investments in these strategies. Alternatively, the expected returns may be low because of SSA's unique natural and institutional conditions.

This chapter reviews the literature on the constraints and potentials of investment in regard to mechanization and irrigation development for rice production in SSA. We explore mechanization not only for land preparation and harvesting/threshing but also for modern rice milling. We consider properly mechanized rice milling essential because recent studies find that improved rice milling technologies enhance the demand for domestic rice through quality improvement (Tokida et al. 2014; Mano et al. 2022; Chap. 12 of this volume). We focus on demand-side, supply-side, and natural conditions among investment constraints for mechanization and irrigation development. The demand-side factors of mechanization initially include farming intensification due to land pressures (Diao et al. 2020; Boserup 1965; Pingali et al. 1987), and later, increased farm wages (Diao et al. 2016, 2020; Hayami and Ruttan 1970, 1985). The demand-side factors of irrigation development include rice prices (Kikuchi et al. 2021; Chap. 10 of this volume) and the complementary adoption of seed-fertilizer technologies (Otsuka and Larson 2012, p. 18).[2] The supply-side factors of mechanization include the profitability of hiring-out services, constrained by low cropping intensity and few opportunities for multi-functional use (Diao et al. 2020). The supply-side factors of irrigation development include the construction and management cost of irrigation schemes. The natural conditions affecting mechanization include the heavy soil in SSA, while those for irrigation include surface water and groundwater availability. We also explore whether mechanization facilitates farm size expansion and the adoption of improved rice cultivation practices and examine the extent to which irrigation increases rice yield.

[1] These countries are the Philippines, Indonesia, Malaysia, Sri Lanka, Pakistan, India, China, and South Korea.

[2] Irrigation demand here refers to farmers' demand for private irrigation systems and demand for public irrigation systems as perceived by irrigation authorities.

Our literature review finds that SSA faces more significant constraints than Asia. Mechanization demand remains low in SSA partly due to farmers' inadequate knowledge of improved cultivation practices. This is a result of the shorter history of rice farming and limited use of animal traction, thereby reducing expected investment returns. Irrigation demand is also limited in SSA partly because of the low global rice prices realized after the Green Revolution in Asia. For the supply side, machinery service provision is constrained by heterogeneous soil types and cropping systems within each locality. These depress utilization rates of machines, a factor that is particularly constraining for large tractors that are popular due to the perception that soil in SSA is heavy. Irrigation development is tricky in SSA because of higher construction costs and improper operation and management. Rice yield improvement in irrigated environments is notable but still modest in contrast to its high potential in SSA.

Several additional issues related to investment in mechanization and irrigation have only recently become apparent and are awaiting more evidence. One such issue is the complementarity of these technologies with rice-farming intensification and improved cultivation practices. For example, proper land preparation using tractors can facilitate the adoption of management-intensive production practices (Mano et al. 2020; Chaps. 8 and 9 of this volume). Providing rice cultivation training is also associated with the improved economic viability of irrigation investment, as suggested in Chap. 10. Another issue is evaluating irrigation investment in a broader framework. We argue that standard cost–benefit analysis of irrigation development fails to consider the spillover (i.e., general equilibrium) effect on the related sectors, including agricultural input suppliers. The discussion also extends to the strategies to improve the demand for local rice, which enhances the investment returns to rice cultivation training, mechanization, and irrigation development. Millers adopt modern milling technologies to improve the quality of milled rice (Mano et al. 2022; Chap. 12 of this volume), while providing farmers with information about paddy quality-enhancing technologies and quality parameters appreciated by the market induces them to supply more aromatic varieties of paddy outside the village and receive a higher sales price (Chap. 13 of this volume). The remaining chapters in PART III examine these emerging issues.

Section 7.2 describes the status of mechanization and irrigation for rice farming in SSA. Section 7.3 discusses the constraints of mechanization for rice production in SSA, while the constraints and potentials of irrigation are considered in Sect. 7.4. Section 7.5 argues that some emerging issues require more empirical evidence. Section 7.6 summarizes this chapter.

7.2 Farm Mechanization, Irrigation, and Rice Milling in SSA

The extent of farm mechanization and irrigation remains low in SSA. Stocks of agricultural machines, like tractors and harvester-threshers, have stagnated in the region (Fig. 7.1) in contrast to the substantial growth in India and the rest of South Asia,

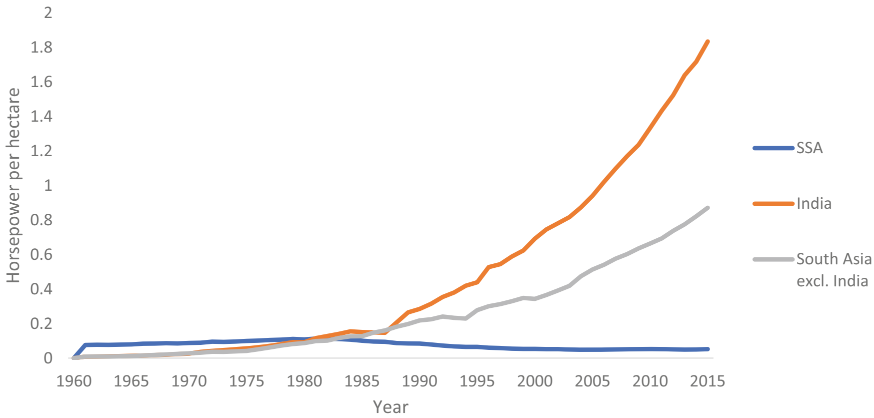

Fig. 7.1 The stock of major machines in use (horsepower per hectare of cultivated areas) in sub-Saharan Africa, India, and the rest of South Asia over time. *Source* USDA (2021). *Note* Horsepower is aggregated over four-wheel tractors, two-wheel tractors, harvester-threshers, and milking machines

where the agro-ecological conditions are similar to SSA. Although animal traction formerly played a significant role in rice-farming intensification in Asia,[3] the rising cost of draft animals combined with a farm wage increase induced tractorization (Binswanger 1978). In contrast, the use of draft animals has been less common in SSA due to the prevalence of sleeping sickness (trypanosomiasis) (Alsan 2015), coupled with deteriorating animal health services and recurring droughts (Takeshima et al. 2015, 2013). These factors have left farmers less familiar with intensive land preparation (Diao et al. 2020). The share of cultivated land under irrigation remained around 3% in SSA from 1973 to 2013. In contrast, it almost doubled from 24 to 46% in South Asia (Fig. 7.2),[4] slightly below the 56% achieved across the whole of Asia by 2005 (Seck et al. 2012).

Limited household-level data suggest that in SSA, mechanization and irrigation development for rice farming are similar to the adoption levels for general agriculture and substantially limited compared to India. For selected countries with readily available nationally representative data, the shares of farm households using tractors were lower in the selected SSA countries than the level in India (90%) in the mid-2010s (Table 7.1). The irrigation use in rice farming was also much lower in the SSA countries than in India.

[3] Ox-plows were on a majority of farmland in India in the mid-1960s (Government of India 1977, cited in Delgado and McIntire 1982), and 98% of land was plowed by bullock in Bangladesh in the mid-1980s (IRRI 1986).

[4] The current irrigation adoption rate in SSA may be underestimated (Woodhouse et al. 2017). For example, FAO's AQUASTAT may exclude some form of farmer-devised private irrigation.

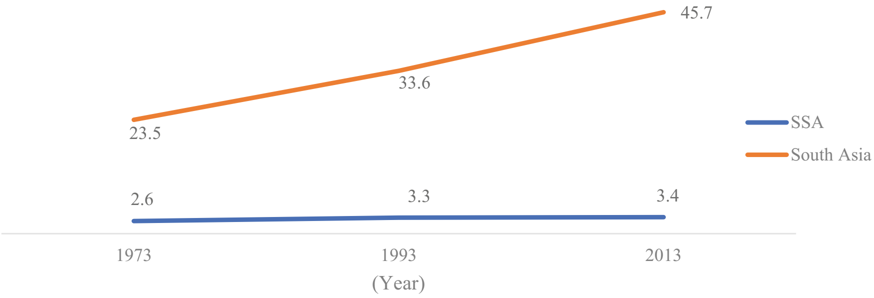

Fig. 7.2 The share of cultivated land under irrigation (%). *Source* FAO (2021)

Table 7.1 Share of farm households using tractors, animal traction, and irrigation for all crops and rice farming in selected SSA countries in the mid-2010s (%)

	Tractors		Animal traction		Irrigation		Data
	All farm	Rice farm	All farm	Rice farm	All farm	Rice farm	
Ghana[a]	13	23	N/A	N/A	2	4	2017 GLSS
Nigeria	10	15	25	39	4	14	2018 LSMS-ISA
Tanzania	9	12	37	41	3	2	2014 LSMS-ISA
Uganda[a]	<1	3	7	20	<1	<1	2018 LSMS-ISA
India[b]	90	90	N/A	N/A	45	57	See table note

Source Authors' calculations. Figures are nationally representative, adjusted using sample weights
[a]"Rice farm" figures for Ghana and Uganda comprise the use of tractors and irrigation among rice-farming households. However, these might not have been used for rice farming and may be used with non-rice crops
[b]Figures for India are area shares based on secondary national-level data. The shares of tractor-using farm areas and tractor-using rice farm areas are obtained from Diao et al. (2020). The shares of the irrigated area among all farm areas and rice farm areas are figures for 2017 from FAOSTAT and AQUASTAT. The figure for "all farm" is the proportion of area fully equipped for irrigation to total arable land. The figure for "rice farm" is the proportion of harvested irrigated rice area to total harvested rice area

As for the types of machinery used, two-wheel tractors (power tillers) have been popular in Asia due to the dominance of lowland ecology (Binswanger 1978),[5] even though four-wheel tractors have also been in use since the 1990s. In SSA, four-wheel tractors are more commonly used in upland areas or sometimes before flooding in irrigated rice farms, while puddling and other operations are implemented using two-wheel tractors in some areas of SSA (Diao et al. 2020). Data are scarce for other power-intensive farm activities, such as harvesting and milling. However, casual observation suggests that harvesting is primarily implemented manually, while large

[5] In the mid-1980s, when mechanization took off in South Asia (Barker et al. 1985, Table 3.1), 87% of rice was grown in lowland areas, while close to 40% of rice growing was in upland areas in SSA in 2010 (Seck et al. 2012).

combine harvesters are used in small pockets of intensive production areas rather than the smaller reapers or smaller combines typically used in Asia.

Similarly, SSA lags behind Asia in the modernization of the milling sector. In SSA, small-scale mills perform most rice milling, with few large-scale mills operating modern milling machines (Soullier et al. 2020). In contrast, in Asia, medium and large rice mills with upgraded milling equipment have grown substantially, improving the quality of milled rice, whereas small mills were forced to exit the market (Reardon et al. 2012). Rice millers in Asia have also often engaged in vertical coordination with farmers (Basu 1983), including interlinkage deals (i.e., contract farming),[6] along with supermarkets, large urban retailers, and wholesalers (Reardon et al. 2012). Most mills in SSA have not adopted modern rice milling machines or do not engage in such vertical coordination (Soullier et al. 2020).[7]

7.3 Roles of Mechanization in SSA

This section explores the reasons behind the low investment in mechanization in SSA through a literature review on the adoption of agricultural machines. Mechanization facilitates farmland expansion and farming intensification, which is particularly relevant now because the land-labor ratio in SSA has reached a level as low as that of tropical Asia in the 1960s, at the beginning of the Asian Green Revolution (Chap. 1 of this volume).[8]

The demand-side factors for mechanization include farming intensification due to population pressure on land and high rice prices (Diao et al. 2020; Boserup 1965; Barker et al. 1985, p. 111; Pingali et al. 1987). The farm wage increase due to urbanization and economic growth also facilitates the substitution of labor with machinery (Diao et al. 2016, 2020; Hayami and Ruttan 1970, 1985). However, mechanization has been limited in SSA. Increased rice demand has been partly met by rice imports in SSA because production has remained unresponsive to increased rice demand (Gyimah-Brempong et al. 2016) and the higher quality of imported rice (Mano et al. 2022; Chaps. 12 and 13 of this volume). The adoption of high-yielding seed-fertilizer technologies also raises returns to intensive tractor use for land preparation (e.g., Takeshima and Liu 2020). However, farmers' knowledge of intensive land preparation and cultivation practices often remains inadequate in SSA (e.g., deGraft-Johnson et al. 2014) because of the short history of modern rice cultivation and limited practice of animal traction (Alsan 2015; Diao et al. 2020).

[6] In such contracts, rice mills provide input credit and cultivation advice and receive paddy after harvest. In Latin America, rice mills also provide farmland and irrigation water (Bierlen et al. 1997).

[7] In West Africa, less than 1% of mills engage in vertical integration (Soullier et al. 2020).

[8] Mini tillers raised yield in mid-hills in Nepal (Paudel et al. 2019), which may be applied to hilly areas in SSA. In Tanzania and India's semi-arid region, using combine-harvesters significantly increased yield through reduced crop losses (Diao et al. 2020; Wilson and Lewis 2015). Mechanization also facilitates diversification (i.e., economies of scope) between rice and non-rice crops (Takeshima et al. 2020; Pingali 2007).

Four-wheel tractors are more popular than two-wheel tractors in SSA because they are considered more suitable for heavy soil (Diao et al. 2016).[9] By contrast, two-wheel tractors are ideal for lowland rice farming, where the soil is softened by stored water. Mechanization rates tend to be higher in SSA countries with more active land markets, enabling large tractors to achieve economies of scale (Takeshima et al. 2018; Jayne et al. 2019). However, smallholders remain dominant in the rice sector in SSA due partly to inactive land markets.[10] As in Asia, the development of the machinery service hiring market is critical to realizing the potentially high returns to machinery investment (Binswanger 1986; Diao et al. 2020).

The supply-side factors of mechanization include constraints on service providers to capitalize on a scale economy and recover investment costs. Heterogeneous soil types and cropping systems within each locality prevent machinery service coordination and provision in SSA (Diao et al. 2020). Compared to Asia, the machinery utilization rate is also lower in SSA due to there being fewer production seasons because of the dominance of rainfed agriculture and fewer opportunities for multi-functional use of machinery, such as its use as a power source to run irrigation pumps (Binswanger 1986; Diao et al. 2020). Poor road infrastructure in SSA also prevents service providers from reaching break-even utilization rates through extensive migratory services. Furthermore, inadequate, unstable paddy production also constrains investments in modern rice mills, which often require sufficient utilization rates to be profitable (Gyimah-Brempong et al. 2016; Takeshima et al. 2017).

7.4 Roles of Irrigation in SSA

In the twentieth century, significant irrigation expansion was driven by the development of large-scale public irrigation schemes (Inocencio et al. 2007). In SSA, however, the long-term decline in global rice prices brought about by the Asian Green Revolution has made it difficult to justify new large-scale irrigation projects, even though the population growth and urbanization have increased the demand for rice. Indeed such projects had nearly disappeared by the late 1990s (Kikuchi et al. 2021; Chap. 10 of this volume).

Despite the popular belief that SSA has constraints on irrigation development due to the paucity of surface and groundwater endowments, SSA has considerable irrigation expansion and groundwater potentials (World Bank 2007, Box 2.5). Potential irrigation areas in SSA are as many as 22 million hectares compared with 7 million

[9] Diao et al. (2020) provide some indicative evidence that more SSA countries belong to land areas categorized as having greater soil workability constraints, for which larger, powerful tractors are arguably more suitable. However, it is still unclear whether the differences are substantial enough to limit the adoption of smaller tractors like power tillers in SSA today. Besides this, soil data for regions like SSA remain poor and require further improvement.

[10] Scale economy in rice production also emerged in Japan as large tractors were introduced in the 1980s (Hayami and Kawagoe 1989), whereas the inactive land rental market has prevented the further structural transformation of Japanese agriculture (Hayami and Godo 2001).

hectares already realized as of 2010 (You et al. 2011), including 6–14 million hectares in drylands (Xie et al. 2018). Groundwater potentials exploitable for irrigation expansion are also tremendous (Cobbing and Hiller 2019), including more than 10,000 km^3 found in Nigeria, Ethiopia, Angola, Botswana, South Africa, and Kenya (Cassman and Grassini 2013). However, there is heterogeneity in water availability because of different evapotranspiration rates (Burney et al. 2013) and few major rivers (Otsuka and Kalirajan 2006), as well as growing water scarcity due to population pressure[11] and climate change (World Bank 2007, p. 65 and Focus F).

The higher construction cost of public irrigation schemes than elsewhere has also prevented irrigation investment in SSA (Inocencio et al. 2007; World Bank 2007). Investment costs per hectare irrigated in West Africa have been three times higher than in Asia because poorly managed water supplies enabled only single cropping, reducing the effective irrigated area (Schoengold and Zilberman 2007, p. 2970). Furthermore, rice farming requires more significant infrastructure investments, such as dams and reservoirs, than non-rice crops, which require less water (Inocencio et al. 2007). Irrigation management is also critical for realizing the potential irrigation returns in SSA,[12] and some regional-level governance structures have been criticized for low efficiency (e.g., Barrow 1998). In Mali, for example, irrigation management reforms involving greater farmer participation quadrupled rice yield and increased rice income between 1982 and 2002 (World Bank 2007). Successful management transfer depends on legal frameworks defining the responsibilities of water user groups (World Bank 2007) and requires significant technical and managerial support for entities newly tasked with water management (Cambaza et al. 2020), which is inadequate in many SSA countries.

However, these practical difficulties do not mean that SSA should abandon the development of irrigation schemes. Inocencio et al. (2007) suggest that "successful schemes" in SSA are comparable with irrigation schemes elsewhere. While some studies indicate that small irrigation systems may be more sustainable (Burney et al. 2013), efficient expansion of irrigation schemes is possible in SSA with scale economy, improved management, and the right mix of system components (Inocencio et al. 2007; Faltermeier and Abdulai 2009; Akpoti et al. 2021). In expanding irrigation infrastructure for rice in SSA, it is crucial to identify appropriate areas based on agro-ecological and market conditions where rice irrigation can bring higher returns than other high-value crops (World Bank 2007; Herdt 2010).[13]

[11] A country is considered water-scarce if annual internal renewable water resources are less than 1000 m^3 per capita (Rosegrant and Perez 1997). As recently experienced in South Asia, intensifying water scarcity may lower the net returns to rice relative to other crops that require less irrigation water, like vegetables (Shah et al. 2009).

[12] In Asia, communal management of irrigation systems sustained the initial success of the Green Revolution (Otsuka and Kijima 2010), and public irrigation schemes also benefited from management decentralization (Alaerts 2020).

[13] There has been growing competition over water between rice and non-rice crops in SSA (e.g., Qadir et al. 2003). Because of intensifying water competition across sectors, arsenic-contaminated water used for irrigation in South Asia accumulates in produce, especially rice (Balasubramanya and Stifel 2020).

Table 7.2 Agro-climatic potential yield for irrigated and rainfed rice in SSA and elsewhere (lowland rice and upland rice)

Regions	Lowland rice (in areas where irrigation is at least marginally suitable)		Upland rice (in areas where irrigation is at least marginally suitable)
	Irrigated	Rainfed	Rainfed
Sub-Saharan Africa	7.6	5.1	3.2
Rest of the world	7.8	5.5	3.2

Source Authors' calculation based on FAO and IIASA (2021)
Notes These simulation exercises assume production with "high-input levels" (FAO and IIASA 2021), adopting high-yielding varieties, fully mechanized with low labor intensity, and the application of proper nutrients and pest, disease, and weed control chemicals. The results should therefore be interpreted as potentials arising in the long term. Although the simulation assumes the RCP 8.5 climate scenario, results are similar under other RCP scenarios. While FAO and IIASA (2021) limit the analysis to irrigated conditions in certain agro-ecological areas, results for rainfed conditions are also presented exclusively for the same agro-ecological areas for comparison purposes

Irrigation is expected to enhance rice productivity (Nakano et al. 2012), reduce production risk in SSA (Gebretsadik and Romstad 2020),[14] and reduce rice prices, thereby promoting food security and poverty alleviation (e.g., Hanjra et al. 2009; Dillon 2011; Gyimah-Brempong et al. 2016). A secure water supply raises the productivity of modern varieties and chemical fertilizers (Otsuka and Larson 2012, p. 18), and extension efforts are likely to be more effective in irrigated areas (Fuwa et al. 2007; Kijima et al. 2012; Chap. 2 of this volume). While globally, rice yield under irrigated conditions attained 5.3 tons per hectare in 2000 (Dobermann 2000), irrigation in SSA has agro-climatic potential of lowland rice yields that is comparable to that in Asia. Simulation models, such as FAO and IIASA (2021), suggest that irrigation can improve the agro-climatically potential lowland rice yields in SSA compared to rainfed conditions in a similar way as the rest of the world (Table 7.2). Despite such high potentials, farmers attain 2–5 tons per hectare in most irrigated areas in SSA due to irregular irrigation, inadequate input use, and poor cultivation practices (Miézan and Sié 1997; Riddell et al. 2006; Balasubramanian et al. 2007).[15]

[14] Reduction in production risk due to irrigation has also been reported in China (Wang et al. 2018) and Indonesia (Gatti et al. 2021).

[15] Although yields in Mali and Senegal are comparable to those in South and Southeast Asia (Cassman and Grassini 2013), they are lower elsewhere in SSA (e.g., Borgia et al. 2012; Gyimah-Brempong et al. 2016). Even within an irrigation scheme, there are variations in irrigation facility utilization rate and rice yield fluctuations over the medium-to-long term caused by soil-nutrient depletion (Dembele et al. 2012; Borgia et al. 2012).

7.5 Emerging Issues

In addition to a somewhat established understanding of constraints on mechanization and irrigation development in SSA, several issues have been increasingly recognized as important, including the complementarity between investments in farm mechanization and irrigation and improved rice cultivation practices. The complementarity between the increased demand for domestic rice through the adoption of modern milling machines and the investments in cultivation training, farm mechanization, and irrigation development has also been increasingly recognized. These issues are important for consideration because ignoring this complex complementarity would underestimate the true potential of investments in farm mechanization, irrigation, and modern rice milling facilities. As shown in the details below, we highlight emerging evidence that intensive land preparation using tractors facilitates the adoption of improved rice cultivation practices, and rice cultivation training is more effective in irrigated areas. Furthermore, improved milling technologies when combined with rice value-chain modernization enhance the quality and price of domestic rice. They also contribute to increased returns to rice cultivation training for timely harvesting and appropriate drying, as well as promoting investment in farm mechanization and irrigation development. We thus argue that insufficient understanding of these issues may reduce expected investment returns and prevent farm mechanization, irrigation development, and modernization of rice value chains. These issues are discussed in the remaining chapters in Part III.

7.5.1 Complementarity with Improved Cultivation Practices

As emphasized in Part II, rice-farming intensification is crucial for increasing rice productivity in SSA. Emerging literature further finds suggestive evidence on the complementary roles of investments in mechanization and irrigation and rice-farming intensification, consistent with the conceptual framework illustrated in Fig. 1.8 in Chap. 1.

In Asia, intensive land preparation enabled by animal traction facilitated farming intensification and the adoption of improved rice cultivation practices, with tractors only substituted for animal traction later (Pingali et al. 1987; Binswanger 1978). By contrast, animal traction has been less common in SSA (Alsan 2015), and intensive land preparation using tractors plays a key role in facilitating rice-farming intensification and the adoption of improved rice cultivation practices, as suggested by emerging studies from Benin, Cote d'Ivoire, and Tanzania (Tanaka et al. 2013; Mano et al. 2020; Chaps. 8 and 9 of this volume). In particular, two-wheel tractors used for intensive land preparation enable even water depth that prevents the overgrowth of weeds and promotes straight-row transplanting, among other improved rice cultivation practices (Baudron et al. 2015). These effects are stronger than four-wheel tractors, the dominant types of tractors in SSA, which may be less suitable because of the difficulty in maneuvering them in heavy muddy fields.

Irrigation is also complementary to rice-farming intensification and improved cultivation practices. Kajisa and Payongayong (2011) find complementary roles of irrigation with fertilizer application and yield enhancement in Mozambique. Based on the literature review, Chap. 2 of this volume finds that rice cultivation training effectively improves rice yield in irrigated and favorable rainfed areas (see Chaps. 3–6 of this volume for evidence from SSA). Furthermore, although the estimated returns to irrigation projects are typically modest in SSA, Chap. 10 of this volume argues that the economic viability of irrigation investment can be enhanced through the provision of proper rice cultivation training.

Increased demand for domestic rice through post-harvest value-chain modernization is also expected to raise the investment returns to mechanization and irrigation development, as well as to rice cultivation training. Recent studies discuss strategies to increase the demand for domestic rice by improving its quality during the milling process (Soullier et al. 2020). The introduction of improved milling machines,[16] including a destoner component, enhances the quality and price of milled rice in Tanzania (Kapalata and Sakurai 2020), Uganda (Tokida et al. 2014), and Kenya (Mano et al. 2022; Chap. 12 of this volume).[17] In the Kenyan case, a significant rice value-chain transformation is observed, and millers increasingly source paddy from local traders and sell milled rice to urban supermarkets and urban traders and consumers. Traders can facilitate farmers to improve paddy quality by informing them about paddy quality-enhancing technologies and introducing quality-based pricing in Ghana (see Chap. 13 of this volume).[18] Nonetheless, few millers engage in contract farming or provide cultivation advice in SSA due to limited paddy availability (Soullier et al. 2020), suggesting a complementarity between strategies to increase rice production and improve rice quality.

7.5.2 Technological Knowledge and Operating Skills

Maximizing the complementarity mentioned above between technologies and improved rice production practices also requires mastering these technologies themselves. Insufficient machinery knowledge and operating skills, including the advantages of different tractor types, machine operations, maintenance, and repairs, may remain key constraints in mechanization. In Nigeria, for example, machine-hiring service providers promoted by the government lacked proper knowledge of machine

[16] Emerging modern rice mills reduced milling costs in Ghana's Kpong Irrigation Scheme to a level comparable to Asia (Takeshima et al. 2017).

[17] Large modern rice millers have also voluntarily fortified rice with micronutrients to raise market premiums in countries like Colombia (Tsang et al. 2016).

[18] Bernard et al. (2017) also find that quality-based pricing improves the quality and price of onions in Senegal.

types compared to experienced informal service providers and failed to keep their businesses viable (Diao et al. 2020). In a successful case, after introducing modern milling machines from China, entrepreneurial rice millers in Kenya learned machine operations and maintenance from Chinese suppliers, thereby improving the quality of milled rice to compete with imported Asian rice (Mano et al. 2022; Chap. 12 of this volume). Late adopters also learned such technological information from the early adopters operating in the neighborhood and chose smaller, more improved milling machines than before, a practice that is not yet widespread across SSA.

Knowledge and operating skills of irrigation are also insufficient among farmers in SSA. A review of irrigation challenges in SSA highlights inadequate knowledge and skills in using irrigation water at the farmers' level (Nakawuka et al. 2018). Scientific knowledge of irrigated agriculture may not be adequately transferred from research institutions and universities to farmers. Inadequate knowledge of proper irrigation use, scheduling methods, and benefits from irrigation technologies often results in water wastage and high fuel and labor costs.

Although some essential knowledge can be acquired and diffused by profit-seeking individuals, the question of whether governmental interventions, such as providing training, is necessary for accelerating knowledge acquisition can be an important area for future research.

7.5.3 Other Issues that Affect Irrigated Rice Production in SSA

Several other issues also remain relevant in assessing irrigation's potential contribution to rice-sector growth in SSA. These issues require closer investigation, including the spillover (i.e., general equilibrium) effects of irrigation development to related activities, the environmental externality of irrigation schemes, and financing for irrigation development.[19]

The general equilibrium effects of large irrigation infrastructure development on the related rice-sector activities are strongly felt by input suppliers expanding business with rice farmers cultivating in the irrigation scheme (see Chaps. 10 and 12 of this volume). These effects are usually neglected in the standard cost–benefit analysis of large-scale irrigation investments, which restricts attention to direct benefits to the farmers on the irrigation scheme and local and urban traders and rice millers. However, these spillover effects may bring about significant social benefits triggered by farming intensification and productivity improvement directly associated with the irrigation infrastructure.

The effect of environmental externalities is another issue to be investigated as rice irrigation expands in SSA. Large irrigation infrastructure, such as dams, improves

[19] Higher waterborne disease rates in SSA have also been linked to irrigation, including greater malaria incidence through mosquitoes (Malabo Montpellier Panel 2019; Mutero et al. 2004; Schoengold and Zilberman 2007; Asenso-Okyere et al. 2011).

water supply stability in downstream basins while incurring external costs in more upstream basins that experience displacement (e.g., Strobi and Strobi 2011; Duflo and Pande 2007). Dam construction often leaves native populations worse off (Schoengold and Zilberman 2007). SSA needs to deal with these social costs seriously when developing irrigation infrastructure with dams.[20]

Financing irrigation expansion in SSA requires a significant increase in public investments. In Zambia, however, only 3% of the government budget went to irrigation development and other rural infrastructure (World Bank 2007, p. 116, Box 4.8). In Nigeria, public investments in irrigation development used to be comparable to several Asian countries but have substantially declined since the 1990s (Gyimah-Brempong et al. 2016). Countries like Tanzania experimented with providing supplementary funds on a competitive basis to local governments to finance medium-scale irrigation schemes and focused national public spending on inducing private irrigation investment (World Bank 2007, p. 243).

7.6 Summary

Mechanization and irrigation development played significant roles in the Asian Green Revolution, but investments in and updates of these technologies have remained low in SSA. Our literature review finds that such underutilization of these technologies occurs partly because SSA faces greater constraints and heterogeneous potentials. Machinery service provision is constrained by heterogeneous soil types and cropping systems within each locality, while large tractors, typically adopted in SSA, require a higher utilization rate to break even. Irrigation development is constrained by higher construction costs in SSA, while its potential is heterogeneous because of heterogeneity in water availability and irrigation management quality.

However, recent studies also suggest that there is some scope to enhance the returns to these technologies in SSA by exploiting their complementarity with rice-farming intensification and improved cultivation practices. An inadequate understanding of this complementarity and underappreciation of achievable potentials are likely to comprise some of the reasons behind the low investment in and adoptions of these technologies for rice production in SSA. PART III of this volume fills this gap by providing evidence for these complementary strategies, including efforts to promote the supply of high-quality domestic rice through the improvement of rice milling activities toward the Green Revolution in SSA. Chapters 8 and 9 find that land preparation using two-wheel tractors improves productivity and profitability by facilitating fertilizer application and the adoption of improved cultivation practices in Cote d'Ivoire and Tanzania. Chapters 10 and 11 find that the high economic viability of irrigation construction is associated with farming intensification and improved rice cultivation practices in Kenya and Senegal. Chapter 12 examines a case in

[20] In the early 2000s, the number of large dams reached 6,575, 4,291, and 2,675 in USA, India, and Japan, respectively, compared to, for example, less than 100 in Nigeria (WCD 2000).

which millers enhanced the quality of milled rice and demand for domestic rice by adopting improved milling technologies in Kenya. This technological improvement in the milling sector also induces rice value-chain transformation and likely increases the demand for high-quality paddy. Chapter 13 analyzes the case in which traders incentivize farmers to provide high-quality paddy by offering quality-based pricing in Ghana.

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