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Irrigation Potential in Nigeria

Some Perspectives Based on Factor Endowments,
Tropical Nature, and Patterns in Favorable Areas

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ABSTRACT

Increased adoption of irrigation is often considered critical for agricultural transformation in countries in Africa south of the Sahara such as Nigeria. Information is, however, still limited regarding how irrigation potential and comparative advantage may depend on endowments of various production factors, what are the feasible options for irrigation expansion in tropical regions like Nigeria, and what may be the challenges in favorable areas where current irrigation appears relatively productive but substantial room for improvement still exists. Addressing these questions is important because effectiveness of policies promoting irrigation expansion may depend partly on the answers to these questions. Addressing these questions in a rigorous way is challenging. In this paper, we briefly explore these three perspectives that can be useful in the future assessment of irrigation potential in Nigeria: (1) factor endowments, (2) challenges inherent in the tropics, and (3) experiences in a favorable area within Nigeria. In Nigeria, population (and to some extent agricultural population) is growing fast, the water to labor ratio is declining quickly, and expansion potential for agricultural areas is increasingly exhausted. Nigeria is becoming relatively water stressed. The share of irrigated areas in Nigeria may exceed that of more land-abundant countries like the United States or Australia in the long term but may not reach Asian levels. A successful expansion of irrigation, if it occurs, may be labor based in the short to medium term. Agricultural research and development (R&D) may critically affect general water productivity in farming, which determines whether water is used more intensively in the agricultural sector or diverted to the nonagricultural sector. Second, irrigation expansion in Nigeria is likely to face constraints due to the country's tropical environment. Expansion is affected by the climate, agricultural R&D efforts, growth of commercial demand, and the success of vertical coordination such as plantations. In the short to medium term, rice may have the greatest irrigation potential for achieving poverty reduction and food security improvement if complemented by, among other things, sufficient investments in rice R&D. Achieving these goals through irrigation of other crops will require more complicated processes. Third, a survey of the Bakolori irrigation scheme in northwestern Nigeria shows that it is possible in parts of Nigeria to realize high yields that are comparable to more advanced countries'. However, even there, substantial yield gaps still exist, possibly associated with insufficient domestic rice R&D in Nigeria. This is consistent with experiences in other countries.

Keywords: irrigation, factor endowments, tropics, rice, R&D, Nigeria

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1. BACKGROUND

Irrigation has played an important role in raising agricultural productivity around the world. Although its adoption and intensity are highly heterogeneous across countries, higher agricultural productivity and incomes are generally associated with greater shares of farmland irrigated. Africa south of the Sahara (SSA), whose agricultural productivity grew most slowly in the past several decades, has also seen slow irrigation expansion. Countries like Nigeria are no exception to this. Its share of irrigated area among all cultivated areas has been low (as low as 1 percent) up to present, which is less than one-tenth of irrigation potential in the country (You et al. 2011). Whether this low adoption of irrigation is responsible for the low agricultural productivity has been an important question among both policymakers and the research community.

The reasons for low irrigation use in Nigerian agriculture are generally not clear. On the supply side, there is no consensus about whether the investments in irrigation have been sufficient. While some studies suggest that investments have been sizeable, they have still been much lower than many other developing countries' investments given Nigeria's population and land size (Takeshima 2014b). Private investment in small-scale irrigation has been low as well, despite large-scale interventions including three phases of National Fadama Development Programmes (Nkonya et al. 2012). On the demand side, consumption of irrigation-intensive crops like rice is growing rapidly (Gyimah-Brempong, Johnson, and Takeshima 2014), and relatively stable economic growth and urbanization (albeit with substantial inequality and persistently high poverty) seem to raise demand for high-value irrigable crops like vegetables. Output market conditions for irrigation thus seem improving. But insufficient research and development (R&D), extension systems, or rising labor costs may be partly dragging down irrigation profitability (Takeshima 2014b).

In addition to these, there are other key issues related to irrigation potential in Nigeria that have not been addressed in the literature. They include (1) factor endowments in Nigeria—labor, land, and water—and their implications; (2) irrigation development experiences in the tropics around the world and their implications for Nigeria; and (3) relatively productive irrigation schemes within Nigeria and relevant international lessons.

In this paper, we briefly discuss these issues based on the descriptive analyses of available secondary data, small survey data, and reviews of the related literature. First, factor endowments play important roles in economic development. Private innovations sometimes can be induced depending on factor endowments (Ruttan and Hayami 1984), which affect comparative advantages of different economic activities. While SSA is sometimes considered land abundant compared to Asia, and some SSA countries are considered to have more water resources endowments, SSA also exhibits substantial heterogeneity. In Nigeria, population density is high and rising, which raises the demand for intensification in production. However, water is becoming scarce as well relative to arable land, and particularly to labor, which may affect the comparative advantages in irrigation-based intensification. We provide some hypotheses on the implications of the role of irrigation in agricultural transformation.

Second, historical experience in tropical countries exhibits certain patterns of irrigation growth, which appear relatively crop specific and considerably different from those in temperate zones. We briefly summarize such patterns and how they may apply to Nigeria. Based purely on the assessment of such patterns, rice may be the only crop in the short to medium term through which irrigation can contribute significantly to food security improvement and income growth, and similar potential for other crops may be considerably limited.

Third, while the use of irrigation for rice and its yields is generally low in Nigeria, high yields are observed in some public irrigation schemes. Based on a survey of randomly selected plots, we confirm the high rice yields in one such scheme and present the profitability. We then highlight experiences in countries with similarly high rice yields around the world (most are outside Asia) and draw key lessons, particularly about varietal improvement.

2. FACTOR ENDOWMENTS AND IRRIGATION IN NIGERIA

The conventional literature argues that the country gains from producing goods using relatively abundant factors more intensively. This argument has recently been extended to water through the virtual water concept (Qadir et al. 2003). Debaere (2014) argues that water-abundant countries tend to increase the water intensity of the goods that they export, though this has less impact than labor or capital. The relationships between factor endowments—particularly water, land, and labor ratios—provide partial but useful insights into where the Nigerian irrigation situation is placed in the international context. While irrigation use in Nigeria is considered low (the area equipped for irrigation is 0.5 percent of the total agricultural area), this share alone does not provide the full picture because similarly low shares of irrigated areas are observed in some of the advanced countries. For example, areas equipped for irrigation in Australia account for only 3 percent of the total agricultural area. Yet Australia has one of the most productive agricultural sectors in the world. Figures are similarly low for Argentina (2 percent), Brazil (2 percent), and the United States (7 percent).¹ These countries are characterized by land abundance. The low share of irrigated area must be discussed in the context of its factor endowments.

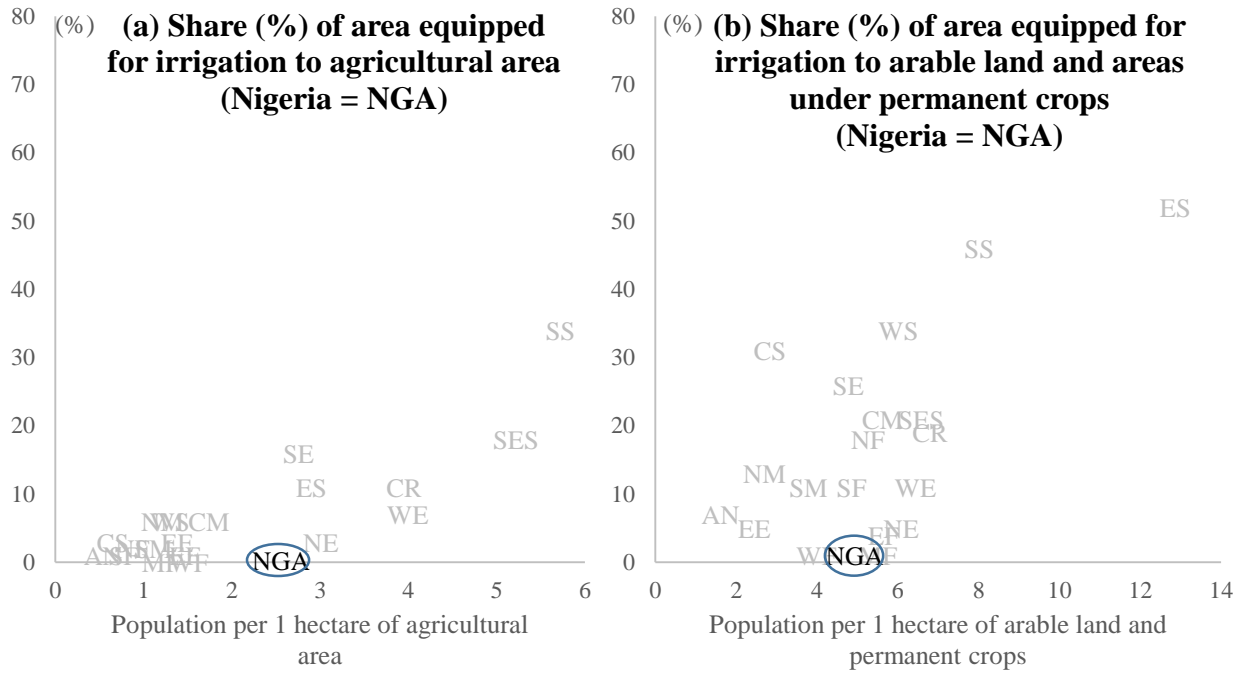
Land and Labor Endowments

Irrigation is often a land-saving technology, which is similar to fertilizers and different from labor-saving technology such as tractors. Given rapid population growth, the labor to land ratio in Nigeria has increased recently. Globally, there are rough positive correlations between the labor to land ratio and the share of agricultural area or arable land irrigated in each region (Figure 2.1). In South Asia, with one of the highest labor to land ratios, the shares of irrigated areas are also the highest. In land-abundant regions like Australia and New Zealand as well as North America, shares of irrigated area are quite low, as was mentioned above about Australia and the United States. Note there is substantial heterogeneity across countries within each region, and the direction of causality is unclear at this point in Figure 2.1. However, the data still provide some insight into whether the relationship between irrigation use and labor to land ratio in Nigeria is different from those in most regions around the world.

Population per agricultural area in Nigeria is twice that of eastern and western Africa and almost four to five times higher than that of southern and middle Africa (Figure 2.1). The ratio is reaching those of eastern Asia and southern and northern Europe. While Figure 2.1 illustrates only rough indications, the share of irrigated area among agricultural area in Nigeria seems slightly lower given its level of population per agricultural area (the left panel indicates that the share could be around 5 percent in Nigeria, which is about 3 to 4 million hectare (ha), rather than the current level of less than 1 percent). Similar indications seem to hold regarding the irrigated area within arable land or areas under permanent crops. While these are highly crude measures, they indicate that the level of irrigation is indeed low relative to its labor to land ratio in Nigeria compared to many regions outside Africa.

¹ The figures are the authors' calculations based on Food and Agriculture Organization of the United Nations (FAO 2014a; 2014b). These figures increase to 6, 8, and 15 percent if only arable land is considered, as more than half of the agricultural area is permanent meadows and pastures. These figures are, however, still considerably lower than those in many Asian countries.

Figure 2.1 Land endowment and irrigation use in Nigeria and other regions



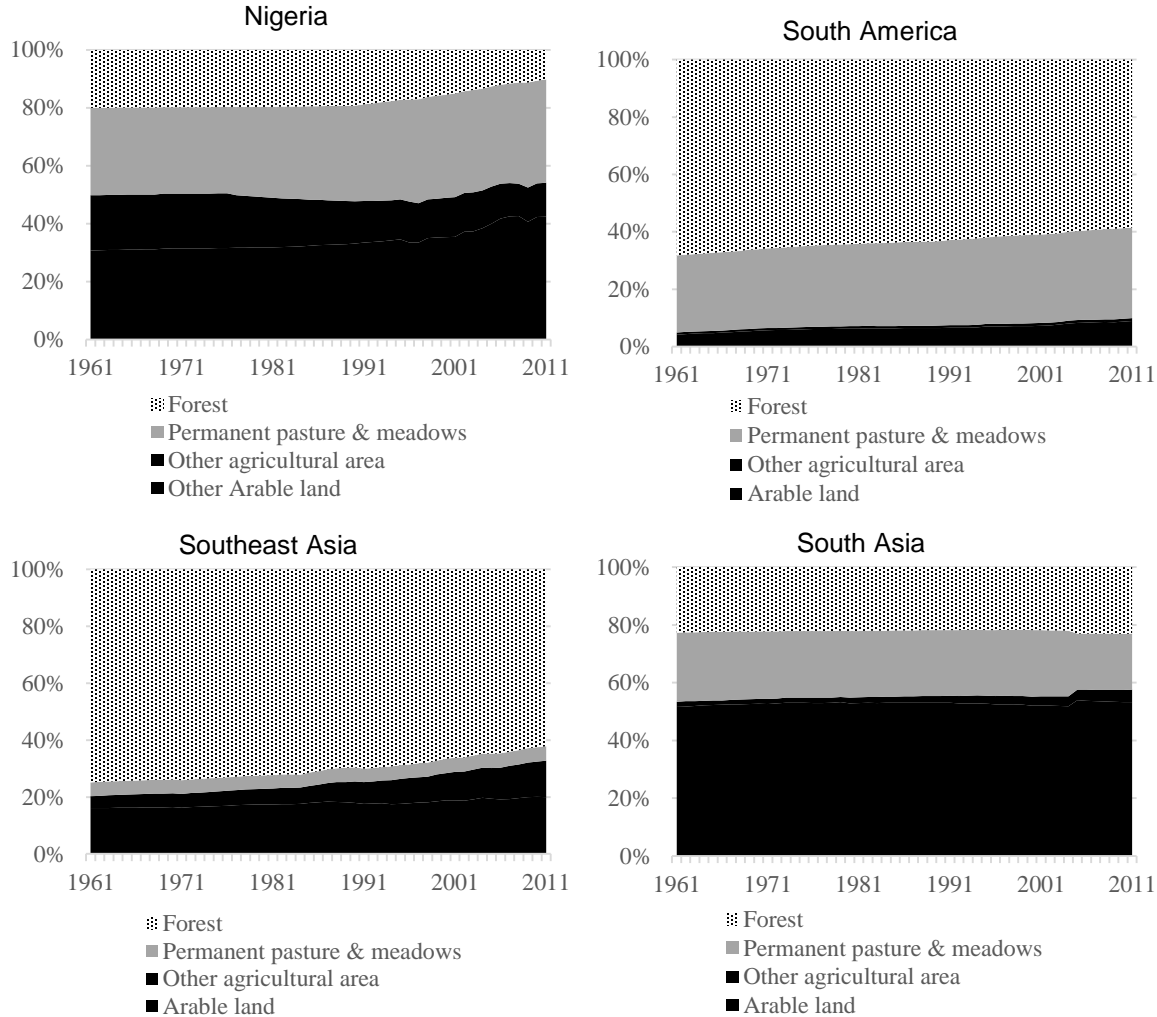
Source: Authors' calculation based on Food and Agriculture Organization of the United Nations (2014a, 2014b).

Note: EF = eastern Africa; MF = middle Africa; NF = northern Africa; SF = southern Africa; WF = western Africa; NM = northern America; CM = Central America; CR = Caribbean; SM = South America; CS = central Asia; ES = eastern Asia; SS = southern Asia; SES = southeastern Asia; WS = western Asia; EE = eastern Europe; NE = northern Europe; SE = southern Europe; WE = western Europe; AN = Australia and New Zealand.

Land is gradually becoming scarce in Nigeria as well, as areas convertible to farmland (*farmable land* hereafter) are running out. Figure 2.2 illustrates the breakdown of farmable land in Nigeria, South America, Southeast Asia, and South Asia. Using the Food and Agriculture Organization of the United Nations' (FAO's) classification, for simplicity, we assume that the farmable land is either forest, permanent pastures and meadows,² or area that is already cultivated (agricultural areas excluding permanent pastures and meadows). In Nigeria, 90 percent of farmable lands either are already used as agricultural areas (50 percent) or are permanent pastures and meadows (40 percent). This is in contrast to South America and Southeast Asia, where still 60 percent of these areas are covered with forest. In Nigeria, the expansion of agricultural area and pastures is exhausting the farmable land. This pattern is comparable to South Asia, where the share of agricultural area and permanent pastures is high.

² In some land-abundant regions, the most areas equipped for irrigation are found among permanent pastures, such as in Australia, New Zealand, Russia, and central Asia (FAO 2014b).

Figure 2.2 Land use share among agricultural area, permanent pastures and meadows, and forests (Nigeria, South America, Southeast Asia, and South Asia)^a



Source: Authors' calculations based on Food and Agriculture Organization of the United Nations (2014a).

Note: ^a Other areas such as deserts and residential areas, which are not convertible to farmland, are excluded from the total.

Population has been growing fast in SSA including Nigeria (Table 2.1). Between 1961 and 2013, the population has grown at 2.6 percent per year in Nigeria, higher than around 2 percent in Southeast and South Asia or South America. This difference has widened since 1990, where the rate in Nigeria remained at 2.6 percent while the rates of the other regions mentioned dropped to 1.4 to 1.7 percent. While urbanization is also occurring relatively fast in Nigeria, the agricultural population has also kept growing (1.4 percent per year between 1990 and 2013, faster than Asia and South America). Labor in Nigeria continues to be more abundant, and to some extent, so does agricultural labor.

Table 2.1 Population growth rates in selected regions and Nigeria (annual percentage)

Region	Population		Agricultural population
	1961–2013	1990–2013	1990–2013
Southeast Asia	2.0	1.5	0.8
South Asia	2.1	1.7	1.2
South America	1.9	1.4	–0.2
Africa South of the Sahara	2.7	3.2	2.6
Nigeria	2.6	2.6	1.4

Source: Authors' calculations based on Food and Agriculture Organization of the United Nations (2014a). Figures for Nigeria are based on Groningen Growth and Development Centre (2014).

Water Endowments (Renewable Internal Freshwater Resources)³

The share of irrigated area to agricultural area also depends on the water endowments. While Nigeria has relatively rich water resources, the water stress level has been rising as well due to the high and growing population. Nigeria's per capita water resources have been considerably lower than SSA as well as some West African countries like Cameroon or Côte d'Ivoire (Table 2.2). It has declined from 4,690 cubic meters (m³) to 1,346 m³ in 2011 (World Bank 2014). The fifth column shows the ratio of the levels in 2011 to the levels in 1962 (with the 1962 level standardized as 100). The level in Nigeria in 2011 is 29 percent of the level in 1962. Falkenmark (1989) defines water resources vulnerability in the following way using per capita water resources (m³ per capita): no stress (water resources per capita \geq 1,700 m³ per capita), stress (1000–1700), scarcity (500–1000), and absolute scarcity (< 500). Using this definition and the figure from World Bank (2014) of 1,346, Nigeria has become water stressed since 2000 (authors' calculations based on World Bank 2014) and will soon enter the water-scarce stage. At the current pace, it is also expected to soon surpass South Asia in terms of water scarcity.

Water resources per farmable land are generally the inverse of water resources per population. Water resources per farmable land are generally the highest in Asia and the lowest in Australia, the United States, and the Middle East and North Africa (MENA) region. Nigeria is in between these two extremes, with approximately 2,700 m³ per ha of farmable land.⁴ These indicate that Nigeria is more endowed with farmable land than water compared to Asia, and with water than farmable land compared to Australia, the United States, and the MENA region.

³ Measurements of water resources are complicated, as they can include both renewable and nonrenewable sources, as well as internal and external sources, among others. Here we use renewable internal freshwater resources, as it is widely used as one of the major indicators when dealing with water resources endowments. It is defined as "average annual flow of rivers and recharge of aquifers generated from endogenous precipitation" (FAO 2003, page xi), where endogenous precipitation means the precipitation occurring within the border of the country (Omer 2007).

⁴ Note that the water resources are much lower than the annual precipitation. For example, annual precipitation of 1,000 m³ which most of Nigeria enjoys, is equivalent to 10,000 m³/ha of total land mass of the country. This is because most precipitation is simply the movement of water between land and air, which does not affect the total amount of water.

Table 2.2 Water resources (renewable freshwater) per population and land

Country/Region	Water resources per capita**				Water resources per farmable land*	
	1962	1992	2011	Ratio of 2011 to 1962 (1962 = 100)	1992	2011
Australia	45.8	28.1	22.0	48	793	897
East Asia and Pacific	9.7	5.5	4.6	48		
China	4.2	2.4	2.1	50	4,350	4,053
South Asia	3.3	1.7	1.2	36	4,689	4,703
Latin America	57.9	29.2	22.4	39		
United States	15.1	11.0	9.0	59	611	531
Middle East and North Africa	2.0	0.9	0.6	29	651	582
Africa south of the Sahara	17.8	7.9	4.4	25		
World	13.2	7.9	6.1	46		
Cameroon	48.8	21.3	12.9	26		
Côte d'Ivoire	20.5	5.9	4.0	19		
Ghana	4.3	2.0	1.2	29		
Nigeria	4.7	2.2	1.3	29	2,737	2,680

Source: Authors' calculations based on World Bank (2014) and Food and Agriculture Organization of the United Nations (2014a).

Note: *Internal renewable water, cubic meters per hectare per year. **Internal renewable water, 1,000 cubic meters per capita per year

The agricultural sector is often the dominant user of water. Table 2.3 summarizes the rough indicator of the use intensity of water, labor, and land in the agricultural sector in selected regions and Nigeria. Excepting SSA and Nigeria, the use of three factors is fairly consistent with the factor endowments presented above. In Asia, labor is most intensively used, followed by water and then land. In the United States and Australia, on the other hand, land is most intensively used, followed by water and then labor. In other words, while the share of area irrigated among the total agricultural area is quite low in Australia and the United States, as was mentioned above, their irrigation use per labor is quite high. South America is in between these two extremes. In the MENA region, irrigation water use per labor is quite high despite the water scarcity indicated in Table 2.2, but this is possibly due to the fact that the share of agricultural population is also low and thus labor is also scarce for agriculture in MENA (only 6–7 percent of total population is economically active in agriculture).

Table 2.3 Use of water (for irrigation), labor, and land for agriculture in 2012

Country/ Region	Irrigation water use (cubic kilometer per year)	Irrigation water use per irrigated area (cubic meter per hectare)	Agricultural population (1,000)	Agricultur al area (1,000 hectares)	Irrigation water use per agricultural population (cubic meter per year)	Irrigation water use per agricultural area (cubic meter per year per hectare)	Agricultural population per 1,000- hectare agricultural area
Southeast Asia	326	14,344	142,536	130,562	2,288	2,498	1,092
South Asia	1,019	9,531	356,838	309,844	2,855	3,288	1,152
India	688	10,315	273,660	179,300	2,514	3,837	1,526
MENA	264	10,985	25,665	374,628	10,284	705	69
South America	138	8,648	25,307	613,441	5,459	225	41
United States	177	6,720	2,355	408,707	75,330	434	6
Australia	7	2,587	460	405,474	14,339	16	1
SSA ^a	58	10,031	224,772	959,165	258	60	234
Nigeria^b	7	NA	29,704	72,000	237	98	412

Sources: Food and Agriculture Organization of the United Nations ([FAO] 2014a) for irrigation water use. FAO (2014b) for irrigated area, agricultural population, and agricultural area. Figures for agricultural population in Nigeria are taken from Groningen Growth and Development Centre (2014). Figures for SSA are adjusted accordingly.

Note: MENA = Middle East and North Africa; SSA = Africa south of the Sahara; NA = not available. ^a Including Republic of South Africa. ^b Agricultural population is for 2010.

Irrigation potential in Nigeria is partly determined by factor endowments, particularly of water, land, and labor. From the above trends in land, population, and water resources, one can roughly assess how Nigerian factor endowments have changed. Purely from a factor endowments standpoint, Nigeria is becoming most abundant in labor, followed by land, and most scarce in water. Nigeria is becoming a densely populated area—more so than some Asian countries like Thailand and Nepal and much more so than Brazil. Given that current irrigation water withdrawal is small (about 2.5 percent of total renewable fresh water resources in 2004; FAO 2014a), there is some scope for increasing irrigation water use. But overall trends remain. If we extend the factor endowments argument by Qadir et al. (2003) and Debaere (2014) to the Nigerian case, Nigeria will not have a comparative advantage in intensifying widespread irrigation use to increase export of water-intensive agricultural goods such as rice, vegetables, sugarcane, and bananas.^{5,6} Rather, irrigation will be concentrated in relatively small areas where water productivity is very high.

From the growing population to water ratio in Table 2.2, as well as the fast-growing population and agricultural population in Table 2.1, a successful irrigation expansion in Nigeria, if it occurs, may be more labor based, as in Asia, in the short to medium term. Agricultural labor, however, may become scarce over time, which is also a growing trend in Nigeria. The implications of such a case are not immediately clear. If such decline is led by growth in the urban sector, the agricultural sector may start supplying crops that more intensively use land, water, or both—and less labor. But the urban sector (industry, manufacturing) may start consuming more water, lowering water endowments for farming, in which case only competitive, large, rainfed farming may prevail.

⁵ While Asia is also water stressed, countries like India and Thailand do export rice. Important to note, the shares of rice area irrigated are lower in India and Thailand compared to some other Asian countries. Thus, their comparative advantages may not be in water but possibly labor, particularly in the case of India. In fact, many Asian countries with intensive rice irrigation such as Japan, the Philippines, Indonesia, and China are importers of rice. Such patterns are consistent with the argument that water-scarce countries have no comparative advantages in exporting agricultural goods produced through intensive irrigation.

⁶ Since comparative advantage is a relative concept, if returns to water are lower in other sectors, there is still a comparative advantage in irrigation for agricultural export growth. However, in this case, average returns to water across sectors are low, and therefore economywide growth is also low.

Low share of and declining forest land in Nigeria (Figure 2.2) indicates that land convertible to agricultural uses (including pastures) is getting relatively exhausted, compared to South America and Southeast Asia. A relatively large presence of pastures in place of forests, on the other hand, indicates expansion of arable land can be possible without expensive land clearing (by substituting pastures to farmland) in the short to medium term, although it involves opportunity costs of livestock rearing. The implication is that in the short to medium term, development of farming that intensively uses land may be relatively less costly, though such expansion potential runs out in the long term. The endowment of agricultural land therefore is unlikely to increase substantially in Nigeria. Compared to land, water use intensity is currently lower in Nigeria, with irrigation using 2.5 percent of total renewable fresh water resources in 2004 (FAO 2014a). Therefore, irrigation share may rise in the long run. From water resources per land in Table 2.2, the share of irrigated area is unlikely to be as high as in Asia, and substantial agricultural growth may come from rainfed areas, but the share may exceed the shares of the United States or Australia in the future.

One scenario in which the irrigated area expands considerably given the current trends of factor endowments is the rise in general water productivity in agriculture, so that less water is needed per irrigated area, which has the effect of increasing de facto water endowments. Development through R&D of varieties with higher water response may have such effects. If returns to water in farming remain low, water will be increasingly diverted to use in other sectors with higher returns to water. Returns to water also can be raised through improved irrigation efficiency, particularly through switching from flood irrigation to pressurized systems like drip/sprinkler irrigation. However, these investments are often made by the private sector in response to higher profitability.

3. IRRIGATION IN THE TROPICS: LESSONS FOR NIGERIA

The adoption levels of irrigation vary across crops and regions (Table 3.1). Globally, rice relies heavily on irrigation, with 62 percent of its area irrigated. Almost half of the areas for cotton and sugarcane rely on irrigation. Other major crops like wheat, maize, and potatoes rely relatively less on irrigation (10–30 percent). Sorghum and cassava rely only marginally on irrigation (less than 10 percent of the harvested areas). Within SSA, patterns are slightly different (Table 3.1). Shares of irrigated areas for rice and cotton are much lower in SSA than at the global level. The shares are also lower for maize in SSA, although they are only around 20 percent at the global level. Shares are similar for potatoes, sorghum, and sugarcane.

Table 3.1 Irrigated and rainfed harvested areas by major crops (global and Africa south of the Sahara)

Crop name	Global (2000)				Africa south of the Sahara (1997–1999)			
	Area harvested (million hectares)			Percentage irrigated	Area harvested (1,000 hectares)			Percentage irrigated
	Total	Rainfed	Irrigated		Total	Rainfed	Irrigated	
Cassava	15.5	15.4	0.0	0				
Cotton	33.2	16.9	16.3	49	4,325	3,960	362	8
Maize	151.5	121.6	29.9	20	24,417	24,083	333	1
Potato	19.7	16.0	3.7	19	595	539	56	9
Rice	165.7	62.6	103.1	62	7,077	5,564	1,514	21
Sorghum	40.2	36.7	3.4	9	22,348	21,834	514	2
Sugarcane	20.9	10.8	10.2	49	1,199	715	484	40
Wheat	214.6	147.9	66.6	31	2,501	1,944	558	22
Other perennial	73.1	60.3	12.9	18				
Banana					947	925	21	2
Vegetables					3,137	2,504	637	20

Source: Authors' modifications of Portmann, Siebert, and Döll (2010, Table 4) for the world and Riddell, Westlake, and Burke (2006, Table 2) for Africa south of the Sahara.

Variations in irrigation use across crops are also present within each country. Table 3.2 presents percentages of each crop area irrigated in major tropical and other countries, calculated by the authors using the crop-specific irrigated area and planted areas from FAO (2014a, 2014b) as well as other sources. There are crops that are mostly rainfed even in countries where some crops are highly irrigated, indicating that sufficient irrigation infrastructure is present and use of irrigation is widely accepted by farmers. For example, in some countries with considerable rice irrigation coverage, maize irrigation is not necessarily common. However, in countries like Egypt or Pakistan where there are wide networks of full-control irrigation facilities, we see consistently high irrigation coverage for most crops.

These variations in irrigation extents across crops are outcomes of various agroecological and socioeconomic factors present in each country, which cannot be fully examined here. There are, however, some systematic differences observed between tropical countries and other countries. In tropical countries (or those with large tropical areas) like Brazil, Colombia, Indonesia, Sri Lanka, and Venezuela, rice and sugarcane irrigation seem more prominent than irrigation of other crops like maize, potatoes, sorghum, and cotton. Wheat, which is also widely irrigated in temperate zones, is not usually grown in the tropics in the first place because the temperature is generally too high. In the next section, we describe how irrigation of these crops emerged in the past and its implications for future irrigation expansion and food security in tropical SSA.

This section summarizes irrigation expansion patterns for rice, banana, sugarcane, vegetables, potato, maize, cassava, sorghum, and cotton and their key implications for smallholder farmers and food security.

Table 3.2 Share (percentage) of irrigated area for each crop outside Africa south of the Sahara

Countries	Year when figures were available	Rice	Maize	Wheat	Sugar cane	Banana	Potato	Sorghum	Cotton
Tropical countries									
Brazil ^b	2008	38	4	1	27	5			15
Colombia	2011	48	7	0	100				
Indonesia	2005	91	35		25				
Sri Lanka	2006	77	3		91				
Other countries									
China ^b	2006	99	42	99	36		8		75
Egypt ^b	2002	100	100	100	100	100	99	100	100
India ^b	2006	52	18	91	98		32	8	33
Iran	2006	100	95	42	95	86			
Japan	2006	100	0	58	74		53		
Kazakhstan	2010	100	100	2			34		
Mexico ^b	2007	93	18	86	48	74	82	40	95
Myanmar	2006	24	7	84	43		14		
Pakistan ^b	2008	85	90	86	100	100	100	96	100
Philippines	2006	58	4		17	3			
Spain	2009	98	88	14			45		
Thailand ^a	2007	59	2		26				
Turkey ^b	2004	100	100	2			100		100
Turkmenistan	2006	20	0	99			30		
United States ^b	2008	90	15	7	53		91	19	52
Vietnam ^a	2005	93	4–25		40	59			

Source: Authors' calculations based on Food and Agriculture Organization of the United Nations (2014a, 2014b) and other sources cited in the text. Blank figures indicate the absence of information and may not necessarily mean the absence of irrigation uses.

Notes: ^a Maize for Thailand is based on 2010 (Gypmantasiri 2010). Lower figure for maize for Vietnam is based on Khiem et al. (2008). ^b Figures for cotton are from Chapagain et al. (2006).

Rice

There is wide consensus that irrigation is critical for rice production growth around the world (Otsuka and Kijima 2010), regardless of temperate or tropical zones. While irrigated rice yields have often exceeded 5 tons/ha and sometimes reach 10 tons/ha, yields of rainfed rice have rarely exceeded 3 tons/ha even in countries with advanced production technologies like China, Japan, Indonesia, and Sri Lanka (Seck et al. 2012). Rice irrigation in Asia particularly expanded during the wet season rather than the dry season, where irrigation was used to supplement rainfall (Chandler 1979, Table 3; International Rice Research Institute 1986). In tropical SSA, where rainfall is relatively high during the rainy season, returns from irrigation are still likely to be high for rice. Rice irrigation has been practiced mostly by smallholder farmers, particularly in Asia where typical rice farm sizes have remained small (Otsuka and Larson 2012), which is in contrast to many other crops irrigated in the tropics, as discussed below. Currently, the use of irrigation for rice in tropical SSA is highly limited (Seck et al. 2012). This is partly due to insufficient support for national rice R&D in many SSA countries to conduct adaptive research (Herdt 2012), which is particularly important for low-latitude tropical countries with lower solar radiations and shorter sunshine hours during the production season (Takeshima 2014a). The potential return for irrigation on rice can be high if appropriate varieties are made available, with significant benefits accruing to smallholder farmers.

Bananas and Other Tree Crops

The tropics have temperatures more favorable for banana growth and development than do cooler zones (Robinson 1996), although constant and heavy rainfall in the tropics causes severe constraints to banana production through leaching, low pH, erosion of fertilizer, and reduced photosynthesis. Having a shallow rooting system and permanent green canopy, bananas are thought to require an abundant and constant supply of water for optimal production, thus with potentially high returns from irrigation (Robinson 1996). Major irrigated banana areas are found in (1) areas of the tropics with pronounced dry seasons, (2) semiarid subtropics, and (3) Mediterranean environments (Robinson 1995, 1996). In humid plains of the Atlantic zone of Costa Rica and the region of Changuinola in Panama, rainfall is distributed year-round; annual rainfall can exceed 2,500 millimeters (/year, and no irrigation is needed except the drainage system (Persley and Langhe 1987, 41). Irrigation is often needed if rainfall is concentrated in eight to nine months with deficits in the remaining months, such as in plantations of the Aguan Valley in Honduras, Santa Marta in Colombia, and Machala in Ecuador (Persley and Langhe 1987, 41). Major banana exporters in SSA (such as Côte d'Ivoire and Cameroon) have distinct dry seasons as well, and irrigation is likely to be needed for commercial banana production.

Bananas for export often are produced in a vertically coordinated system because of the economies of scale in shipping and the need for timely refrigeration after harvesting (Binswanger and Rosenzweig 1986). Irrigation for banana tends to be practiced only in these large-scale plantations. Worldwide, about two-thirds of bananas grown for export are irrigated (Stover and Simmonds 1987; Carr 2009). This is because initial investment costs of an establishment plot are high and require economies of scale in production. Cameroon and Côte d'Ivoire account for 98 percent of banana exports from Africa. There, most bananas are grown on medium to large plantations that are located near major road networks, allowing for efficient transport of the produce (United States International Trade Commission 2008; Minot and Ngigi 2004). Many of them are operated by multinationals like Del Monte, Compagnie Fruitère, or Dole. Côte d'Ivoire has a total of about 5,500 ha of banana plantation (United States International Trade Commission 2008). Bananas are exported through sea freight, using refrigerated freighters (Minot and Ngigi 2004).

On the other hand, banana for domestic consumption is rarely irrigated. In the eastern Africa highlands where banana is grown mostly for domestic consumption, it is completely rainfed (van Asten, Fermont, and Taulya 2011). This is also the case in Cameroon and the Philippines where only bananas exported to Japan are irrigated (Arias et al. 2003). Small-scale banana irrigation seems relatively limited, though some parts of the world, like tropical China, have experienced its growth (Zhang, Kono, and Kobayashi 2014). There, however, relatively sophisticated and efficient irrigation systems had been established before commercial banana production emerged; it is likely their establishment was induced by successful rice varieties that were reaching close to 6 tons/ha of yield with irrigation. Growth of small-scale banana irrigation may be unlikely unless efficient irrigation facilities are already in place.

Agricultural R&D is likely to have played an important role in the expansion of banana irrigation. Botanically, crossbreeding and other known techniques of producing new varieties with selected characteristics of existing varieties are very difficult for banana (Evenson, Houck, and Ruttan 1970). The search for varieties resistant to pests and diseases (such as Panama diseases) has been a major drive in the history of banana breeding (Arias et al. 2003, 47; Evenson, Houck, and Ruttan 1970). Major plant-breeding programs for banana started in the 1920s at the Imperial College of Tropical Agriculture in Trinidad and in Jamaica (Persley and Langhe 1987). In the 1970s, new breeding programs were initiated throughout the world to combat Black Sigatoka and have been carried out by institutions like Empresa Brasileira de Pesquisa Agropecuária in Brazil (Arias et al. 2003, chapter 4).

Investments in irrigation within banana production systems have been led by the private sector, mostly the multinationals. In Cameroon, Dole and Del Monte made large investments in irrigation facilities, fruit-handling facilities, and sanitation equipment (Arias et al. 2003). For R&D other than breeding, companies like United Fruit and Standard Fruit invested significantly in long-range research programs on banana production, particularly to tackle Sigatoka, one of the major diseases for banana

(Evenson, Houck, and Ruttan 1970). They developed a treatment method based on periodic applications of fungicide (Bordeaux mixture) suspended in water (Evenson, Houck, and Ruttan 1970). By 1939, most large banana plantations were equipped with elaborate, permanent networks of pipes and spray facilities (Evenson, Houck, and Ruttan 1970). Development of new varieties induced the private-sector invention and application of processing and handling techniques specifically designed to accommodate the physical and economic attributes of the new varieties of banana (Evenson, Houck, and Ruttan 1970).

Promoting irrigation for smallholder banana farmers may be challenging. For small-scale subsistence banana production, appropriate support can be provided to stimulate private R&D (Kremer and Zwane 2005), which may be more effective than supporting irrigation. Employment of workers on the plantations can be another pathway for benefiting the poor through banana irrigation. In Côte d'Ivoire, about 35,000 people are estimated to be employed by the banana and pineapple plantations (Minot and Ngigi 2004). However, wages of these workers may not be substantially higher than outside the plantations because plantations may have monopsonic powers.

Other tree crops are generally not irrigated in the tropics. Oil palm is mostly rainfed and only grown in wet tropics without the need of irrigation (Hoogeveen, Faures, and van de Giessen 2009; Müller et al. 2008), including in Indonesia (Comte et al. 2012). Plantains in West Africa generally require a hot and humid environment where the average air temperature is about 30 degrees centigrade and monthly rainfall is at least 100 mm (Swennen 1990). Irrigation of plantain seems worthwhile only when larger fields are cultivated in areas with long dry seasons and not worthwhile for family farms (Swennen 1990).

Sugarcane

Sugarcane requires an ample supply of water (1,200–1,500 mm) (Tarimo and Takamura 1998) for effective development of stems. Not only the total water supply but the duration of rainfall is important because the production season can stretch more than ten months. These water requirements may be higher than those for rice, which can usually mature in three to four months. Sugarcane production therefore takes place either in areas with abundant rainfall like northern Brazil or in areas with full-control irrigation systems like India (Müller et al. 2008). The humid tropics like Brazil and Democratic Republic of the Congo have sufficient potential for rainfed sugarcane (Müller et al. 2008). However, outside these areas, substantial irrigation investments may be needed for sugarcane production. Sugarcane plantations tend to rely on vertical coordination, as do banana plantations (Binswanger and Rosenzweig 1986). Therefore, irrigation constraints similar to those discussed above may apply to sugarcane, where large-scale investments in irrigation facilities as well as other plantation facilities are needed up front, while the benefits for the poor through employment may be limited.

Public R&D has played an important role in the development of sugarcane varieties and potentially their responses to irrigation. This is similar to banana, but the evolution of adaptive breeding research is more widely documented for sugarcane compared to banana, which has received more private R&D by multinationals. Sugarcane breeding went through several development stages up to the 1960s (Evenson, Houck, and Ruttan 1970). In 1887, for the first time, sugarcane seedlings were produced through a process of sexual reproduction in an experiment station newly founded in British West Indies and Java. This was significant since the cane plant usually does not flower and produce seedlings readily (Evenson, Houck, and Ruttan 1970). With successful crossing, a single superior seedling can be reproduced asexually and create a completely new variety. This required an elaborate process through temperature and light control, and few experiment stations were successful in the early days. Since then, testing and selection of superior seedlings from thousands of candidates is a major activity in modern cane breeding.

Over time, adaptive research in each sugarcane production region has intensified. India, one of the world's largest sugarcane producers, has developed strong domestic R&D systems, including the Coimbatore Sugarcane Breeding Institute, which set the stage for location-specific R&D on sugarcane varietal development (Ruttan 2007). Since 1930, locally developed varieties have become increasingly important in each production zone in the world (Table 3.3). By the late 1940s, more than half of the area

in Hawaii, Louisiana, and Mauritius had been planted with locally developed varieties. By the 1960s, the same patterns emerged in Queensland, Puerto Rico, and South Africa. In some countries, private sectors (sugar mills) invested in sugarcane research, such as the Colombian Sugarcane Research Center in Colombia, which was created by sugar mills and assumed responsibility for all sugarcane research previously conducted by the Colombian Agricultural Institute (Beintema, Romano, and Pardey 2006). Similar to the case of rice, irrigation potential for sugarcane in tropical SSA is going to be limited unless investment in national R&D is strengthened.

Table 3.3 Percentage of sugarcane acreage planted with varieties developed by the experiment stations of selected areas, 1930–1965

Area	1930	1940	1945	1950	1955	1960	1965
Hawaii	50	65	82	100	100	100	100
Queensland	20	20	33	54	83	85	85
Taiwan		32	46	56	10	4	42
Louisiana	0	23	52	77	65	65	
Puerto Rico	0	9	12	10	3	35	50
Mauritius		8	53	98	93	78	
South Africa	0	0	0	3	49	78	

Source: Evenson, Houck, and Ruttan (1970, Table 1.2).

Vegetables

In the tropics, vegetable irrigation is somewhat limited. This is despite the vegetable-exporting business emerging in various parts of Africa including Kenya and Senegal (Dolan and Humphrey 2000; Minot and Ngigi 2004; Weinberger and Lumpkin 2007). Many tropical countries including Indonesia, Venezuela, Sri Lanka, and Colombia have not successfully expanded irrigated vegetable production, even though their uses of irrigation are extensive for rice, sugarcane, and other crops. This is because some vegetables prefer cooler environments. In Indonesia, tomato⁷ is grown mostly on highlands (Purwati, van Marrewijk, and Jaya 1992). In Colombia, tomatoes are mostly produced in departments on higher elevations and with warm-to-cool temperatures (Jaramillo 2009). In Thailand, major vegetable production areas are in the northern region, with cooler temperatures (FAO 1999, Table 12). Similar to many other crops, comparative advantages of production and irrigation expansion are limited for some vegetables in the tropics due to climatic conditions.

For most vegetables, irrigation is mostly used in the export business. Similar to banana irrigation, irrigation of some vegetables around the world has grown as part of the value-chain development led by the multinationals. In Colombia, production of chili pepper is concentrated in the Valle del Cauca region, where the yield is high due to good irrigation infrastructure, the favorable climate of evenly spread rainfall, and the absence of an extremely hot period (Meléndez and Uribe 2012). Export of chili pepper is dominated by a firm called Hugo Restrepo y Cía, originally from Venezuela (Meléndez and Uribe 2012). The drip irrigation system used in chili pepper production was brought in by the firm, an example of a company focusing on the export business that privately invests in irrigation infrastructure.

Private R&D has played a potentially critical role in vegetable irrigation growth. Successful development of hybrid tomato varieties with good root systems that are more efficient in searching for soil moisture coincided with adoption of drip irrigation (Pritchard and Burch 2003). Irrigation of vegetables may make sense only if it is part of such exporting businesses. However, for many vegetables like tomato, due to lower competitiveness, multinationals are unlikely to come in to start the business in the tropics. Much breeding by Heinz Seeds (the largest tomato seed suppliers in the world) has been in the temperate zones rather than the tropical zones, such as California, and Victoria in Australia (Pritchard and Burch 2003).

⁷ Throughout the text, tomatoes are classified as vegetables, following FAO (2005).

Growth in commercial vegetable irrigation can provide some employment for surrounding marginal areas (Barron and Rello 2000). However, since commercial vegetable irrigation is competitive only with cheap labor, employment effects and income effects of vegetable irrigation on these workers are still relatively marginal, as was the case for northern Mexico (Barron and Rello 2000).

Outside the export business, irrigation of vegetables is limited, particularly if rainfall is relatively sufficient. In the humid tropics in Africa, pepper (*Capsicum spp.*) is mostly grown as a rainfed crop, and water exceeding 650 to 1,250 mm can cause shedding of leaves, flowers, and fruits; poor fruit set; and rotting of the fruits (Purseglove 1968; Olasantan, Salau, and Onuh 2006). Okra is another tropical vegetable that is widely grown in tropical SSA, with Nigeria being the second largest producer in the world after India. Okra is more tolerant to heat than are tomato or dry onion in tropical Asia, and seeds do not germinate at less than 20 degrees centigrade (Riley and Moomaw 1979; Rai and Rai 2006). Okra does not do well on waterlogged soil (Düzyaman 2010). Okra production is mostly rainfed in West and central Africa (Kumar et al. 2010) and in South Asia (Choudhary, Yadav, and Chandra 2012). Okra irrigation is found relatively commonly only in Thailand, which is one of the major okra export origins to Japan.

While private R&D played an important role for vegetables like tomato in temperate zones, public R&D played a critical role for some tropical vegetables like okra. Okra has been considered an economically minor crop, and until recently little attention was paid to its improvement in the international research program (Düzyaman 2010; Kumar et al. 2010). Similar to yields of other crops, okra yields vary across locations, suggesting the need for breeding for specific environments (Ariyo 1990; Kumar et al. 2010). Such R&D is particularly insufficient in the tropics. Despite such minority, many okra varieties have been developed in countries like the United States and India through breeding efforts (Kumar et al. 2010), but SSA has remained an importer of these varieties. Because markets for fresh vegetables are less integrated than markets for crops like rice, insufficient local R&D may lead to higher equilibrium production costs. In fact, production costs of irrigated okra in southern Nigeria are around 38 cents/kg, much higher than 18 rupees, and about 15 cents/kg in Sri Lanka (Abeykoon et al. 2010). Because of this, producers of fresh vegetables in the tropics can still compete at the local level against producers in temperate zones, including producers using the urban vegetable irrigation that is emerging in West African cities, albeit in small scale (FAO 2012). However, the high equilibrium production costs and thus market prices in the local market indicate that the food security benefits of irrigated vegetable production are limited in tropical SSA without significant productivity growth through R&D.

Potato

Potato is another crop that is grown widely around the world and often irrigated. Guenther (2001, 39) classifies major potato production zones in three types. First is the temperate zone. Temperate zones cover most of the developed countries in northern Europe, North America, and portions of Argentina and Chile, where temperature is low enough for potato growth and storage and day length is suitable for most available potato varieties. In some cases, potato is grown immediately after the harvesting of maize or rice, which are often irrigated, on the same plots (Guenther 2001). Second is the highland area where cool temperatures make potato production profitable, though climate can be volatile and production can be inconsistent. This system is found mostly in the Andes Mountains of South America and the Himalayas. In the Andes, potato irrigation has one of the longest histories. Incas built sophisticated terraces and irrigation systems for their potato crops and made their homes on rocks where potatoes could not grow (Guenther 2001).

The third is the lowland tropical and subtropical zones, where average monthly temperatures are 10 degrees centigrade or higher (Guenther 2001). Until recently, this zone had been considered too hostile for potato production, but in the latter half of the 20th century, new techniques were developed specifically for tropical lowlands. Notable examples are the Indo-Gangetic Plain, southern China, Cuba, Egypt, the coast of Peru, and Vietnam (Guenther 2001). This system, however, still requires that nighttime temperatures remain less than 20 degrees centigrade for much of the growing season for proper potato development. Seed potatoes are planted at the beginning of the cool winter season, which is the dry

part of the year when irrigation is used. In Egypt, production of winter potato grew after successful adaptation of European varieties (Guenther 2001). Production growth was led mostly by domestic consumption growth, but Egypt has also become a significant supplier to the European fresh produce and processing market during the winter.

In hotter tropical areas, potato yield potential becomes lower, and the response is limited irrigation. At least until the mid-1990s, irrigation had not been used for potato production in West Java, Indonesia, which accounts for about a third of the country's potato production (Adiyoga et al. 1999). Potato production in the highlands, which is one of the major production areas, is also mostly rainfed (Fuglie et al. 2006). Hot and humid environments in most of tropical SSA may be unfavorable for potato production. In the Sudan Savannah to Sahel zones, nighttime temperature often drops below 20 degrees centigrade for several dry-season months (Hijmans et al. 2005), where potato irrigation may be possible in a similar manner as in other lowland tropical and subtropical zones elsewhere. However, realizing such potential depends on investment in publicly funded irrigation, agricultural R&D, and private investment in cold storage facilities, which have driven expansion of potato irrigation in Asia (Guenther 2001, 50).

Maize

Maize generally requires less water for plant growth compared to rice. Many modern genetic improvement methods like hybrid and genetic engineering have been more easily applied to maize compared to rice or wheat. Because of this, many countries have experienced rapid maize productivity growth without substantial irrigation expansion.

In the United States, irrigation is used in only 15 percent of the maize area (Table 2.2). Irrigated maize production is typically limited to areas with major aquifers such as the High Plains Aquifer located in the central area (USDA 2002), indicating that unless irrigation costs are low, irrigating maize may have only modest profit returns. Rainfed maize yield in the United States has reached 8 tons/ha (United States Department of Agriculture 2014), which is lower than 11 tons/ha for irrigated maize but still considerably high. By the late 1990s, rainfed maize yield in northeastern China had reached 5 tons/ha (Meng et al. 2006, Table 2.3). In Asia outside China, rainfed maize yields often exceed 3 tons (Swastika et al. 2004), which is lower than the yields of the United States or China but still sufficiently higher than rainfed rice yields. In SSA, hybrid maize-based Green Revolutions in Zimbabwe occurred mostly in rainfed areas (Eicher 1995). Overall, maize yields depend more on the variety types, that is, traditional, improved, open-pollinated or hybrid varieties, than the use of irrigation (Gerpacio and Pingali 2006; Gerpacio 2008, Table 2.5). It is true that significant yield growth of irrigated maize has been observed in some temperate zones like Mexico's Sinaloa region (Eakin, Bausch, and Sweeney 2014). This area, however, has had a long history of intensive irrigation of other crops like wheat and soybean, and the expansion of irrigated maize areas seems to have occurred mostly by replacing these crops.

In tropical Asia, such as Indonesia and Thailand, irrigated maize areas are relatively small. Irrigated maize production typically happens within irrigated rice ecologies, where tube wells and communal irrigation systems are present, primarily to supply water for rice production (Gerpacio 2008). In these ecologies, maize is planted in the dry season immediately after the harvesting of wet-season rice (Swastika et al. 2004). Such ecologies are found in the irrigated lowlands of East Java in Indonesia and in northern Thailand (such as Phichit or Chiang Rai). Maize irrigation in East Java is associated with hybrid maize supplied by seed companies (Swastika et al. 2004). In Thailand, maize irrigation is mainly for hybrid seed production through contract farming arrangements with private multinational seed companies such as Pacific Seeds, Pioneer Hi-Bred, Monsanto, and Syngenta, and the seeds are later exported to other Asian countries (Gypmantasiri 2010). In Vietnam, irrigated maize production occurs in lowland ecosystems, which are likely to have been developed for more irrigation-dependent crops like rice, where tube wells and communal irrigation systems cover much of the total arable land (Ha et al. 2004). Groundwater irrigation is widespread in the central highlands of Vietnam but is mostly used for higher-value crops like coffee and black pepper (Ha et al. 2004), indicating that maize irrigation may face competition from irrigation of more profitable cash crops. Similarly, while the discovery of successful

open-pollinated maize varieties led to agricultural intensification in northern Nigeria between the 1970s and the early 1990s (Goldman and Smith 1995), irrigation expansion had been mostly for vegetables, while maize intensification had been more through increased fertilizer use rather than irrigation.

Overall, maize irrigation seems to be adopted only if profitable irrigation systems already exist for other crops like rice in Asia or other crops in Mexico. However, when such irrigation systems exist, there tend to be cash crops that are more profitable than maize. Therefore, maize irrigation, when possible, may often be only the second-best option, adopted only because production systems for other potentially more profitable irrigation crops are not yet established. In addition, around the world including in the tropics, sufficient maize yield growth has been achieved through yield increases of rainfed maize with relatively less reliance on irrigation. In the Guinea Savannah zone of SSA, potential roles of irrigation for maize may be limited unless soils are considerably poor and rainfall patterns are variable enough to cause substantial variations in rainfed maize yield (Cassman and Grassini 2013).

Other Crops with Relatively Limited Irrigation Potential in the Tropics—Cassava, Sorghum, and Cotton

Cassava, sorghum, and to a lesser extent, cotton are all widely grown but rarely irrigated in tropical SSA. Cassava irrigation has been uncommon at the global level, including in large exporting countries like Thailand. When it exists, irrigated cassava production is highly integrated into industrial production where cassava is a raw material. One such exception is the Salem district in Tamil Nadu, India, which has the largest number of cassava-based industrial units in the world (Srinivas 2009; Abraham, Nair, and Naskar 2000). High-yielding cassava varieties like H-226 and H-165 are used for industrial purposes. These varieties were developed through intervarietal hybridization by the Central Tuber Crops Research Institute in Trivandrum, Kerala, and released in 1971 (Abraham, Nair, and Naskar 2000). They were specifically bred for high-yielding purposes rather than culinary purposes (Abraham, Nair, and Naskar 2000). Irrigated cassava production is labor intensive, but relatively cheap labor in the area (\$1.29/man-day in 1998–2000) may enable labor-intensive weeding and irrigation (Howeler 2001).⁸

Similar to cassava production, irrigated sorghum production around the world may be associated with sufficiently large commercial demand for the product. In Mexico, sorghum has been consumed as fodder (Appendini and Liverman 1994) with potentially large commercial demand, while maize has remained human food. In Mexico's Bajío area, the world's highest sorghum yield of 14 tons/ha is achieved through ample irrigation and sufficient fertilizer (Leslie 2008). Elsewhere around the world, sorghum is mostly rainfed. This is possibly because of sorghum's general tolerance to drought and ability to grow on dry land, although it can also respond to adding water through irrigation (Eck and Musick 1979). Conditions are similar in SSA, where sorghum is still mostly a subsistence crop.

Cotton is another crop that is irrigated widely around the world. Cotton irrigation is found particularly in areas with high evaporative demand such as Egypt, Turkmenistan, and Turkey (Chapagain et al. 2006), where almost all cotton is irrigated (Table 2.2). Cotton irrigation is limited in the United States and Brazil where evaporative demand is low (Chapagain et al. 2006). Similar to production of other horticultural exports, cotton production in SSA has grown recently, albeit from low levels, particularly in West Africa (Haggblade and Hazell 2010). Cotton production in West Africa has been, however, mostly rainfed (Theriault and Serra 2014). In Mali and Burkina Faso, two of the largest cotton lint exporters in SSA, irrigated areas account for only 20 percent (Chapagain et al. 2006) and almost 0 percent (Dowd-Urbe 2014) of cotton production areas, respectively. Significant cotton productivity growth through irrigation may therefore be questionable in the short term for tropical SSA.

⁸ All dollars (\$) in this paper are US dollars.

Summary of Irrigation Patterns in the Tropics

Agricultural transformation is an important driver of poverty reduction and food security improvement in the world. Increased use of irrigation technology is often an important component of such transformation. Tropical SSA is one place where such transformation has been long overdue, given that poverty and food insecurity there have been widespread and persistent. As a result, governments in tropical SSA continue to be interested in the potential of irrigation to realize such transformation, reduce poverty, and improve food security. Such potential, however, needs to be carefully examined because production environments and types of crops grown there are very different from those in temperate zones. This paper spotlights major crops that are relevant to tropical SSA and briefly examines the key characteristics of past irrigation development patterns for these crops around the world, their potential determinants, and their poverty and food security impacts. Overall, the following general lessons are drawn.

First, climates in tropical SSA may limit the profitable private irrigation of many crops like vegetables and potatoes. Irrigation of these crops may still be observed, but their prices in the domestic market will remain high due to high production costs (or lower productivity), with relatively limited benefits to consumers, particularly the poor.

Second, agricultural R&D is an important determinant that can affect the adoption and expansion of irrigation for many tropical crops. Both for rice and for sugarcane, successful varieties have been increasingly developed locally through adaptive research by the National Agricultural Research Systems, supplemented by the International Agricultural Research System. High-yielding cassava varieties in Tamil Nadu also have contributed to irrigation expansion for these crops. Private R&D has been critical as well for certain crops like vegetables (such as hybrid tomato varieties) and banana.

Third, for some tropical crops (banana, sugarcane), irrigation is profitable only in a vertically coordinated system where economies of scale can be exploited, such as plantations. Their development, however, is more likely to benefit consumers of the markets for these crops (often importing developed countries), than domestic workers because employment effects may be limited due to the oligopsonic nature of these plantations in the local labor market. For other tree crops like oil palm, returns to irrigation are generally minimal in the tropics, even in plantations.

Fourth, irrigation of other staple food crops in tropical SSA such as cassava and sorghum will make sense only if there is commercial demand, such as industrial demand for cassava in Tamil Nadu and feed demand for sorghum in Mexico.

Fifth, irrigation in tropical SSA is likely to face competition from rainfed systems, which are also enabled by sufficient rainfall. Many tropical crops are still rainfed in countries where irrigation is widely used for crops like rice. For many rainfed tropical crops, returns from irrigation may still be relatively low and difficult to raise. R&D for maize (such as the development of hybrid varieties) and banana (for smallholders) may even raise productivity under rainfed conditions.

Of course, irrigation expansion depends on the farm-level profitability of irrigated systems, public investments into irrigation infrastructure, support for the effective development of irrigation equipment markets, and strengthening of collective action capacity for water resource management, widely examined in the literature. This section further illustrates that expansion of irrigation in tropical SSA is likely to be a complicated processes. The process depends on various factors that are often specific to crops being irrigated, including the relative returns between irrigated and rainfed systems, government efforts in strengthening public R&D, the emergence of commercial demand, profitability of the entire vertically coordinated supply system, and how each of them induces private-sector investment in irrigation facilities and further R&D. Understanding such processes helps us determine whether the irrigation has high returns and can contribute to poverty reduction and food security improvement in the short term; if so, for which crops; and what are key complementary policies. Given the discussion in this section, rice may have the greatest irrigation potential for achieving these goals in tropical SSA if complemented by, among other things, sufficient investment in rice R&D. Achieving these goals through irrigation expansion of other crops will require longer-term policies that induce the growth of commercial demand for the crops.

4. POTENTIAL AND CHALLENGES IN FAVORABLE ENVIRONMENTS: BAKOLORI IRRIGATION SCHEME IN NORTHWESTERN NIGERIA

Discussions in previous sections suggest that irrigation use in Nigeria is likely to be concentrated in areas where water productivity is substantially high and that raising productivity in rice irrigation is critical for irrigation development in Nigeria. There is some growing interest in northern Nigeria lately given anecdotal evidence of higher rice yields (Enplan Group 2004) that are unusual in the country, where average rice yields are less than 2 tons/ha. In this section, we summarize the rice irrigation practices in the Bakolori irrigation scheme, located in northwest Nigeria. Similar to other public irrigation projects in Nigeria, Bakolori irrigation projects faced challenges in the past, but there has been anecdotal information that the rice yield there has remained high over time. To the authors' knowledge, representative surveys assessing the yields and profitability have not been conducted. We show that the yield is indeed high relative to African standards. We then briefly discuss whether the yield is high enough given agroecological conditions and draw an interesting lesson from other high-yielding regions around the world.

Bakolori Irrigation Scheme

The Bakolori irrigation scheme is located in the Talata Mafara Local Government Area of Zamfara State in northern Nigeria. The plan for the Bakolori irrigation scheme dates back to 1969 when FAO identified the Bakolori area for potential irrigation development (Yahaya 2002). The construction of the Bakolori irrigation scheme was started in 1975 by an Italian firm and was completed in 1978. The scheme was constructed as part of the Nigerian government's promotion of large-scale commercial farming. The Bakolori dam was constructed not only for irrigation downstream but also for the urban water supply in Sokoto city, about 140 kilometers downstream, and hydro-electric power for the region (Andræ and Beckman 1985, 105).

The Bakolori irrigation project has not always been successful, particularly during the early period. In an early period, local farmers were often expelled with insufficient compensation (Okolie 1995, 206). Irrigated wheat production, which was originally intended, was generally of poor performance. The causes for poor performance have not been empirically identified, but studies attribute it to factors including low wheat price and high fertilizer price (Andræ and Beckman 1985, 105). The climate in northern Nigeria is such that the period with a low enough temperature for wheat production is limited to October through February. Delaying wheat planting past November can lead to a substantial yield decrease (Kimmage 1991, Figure 7). However, many farmers grew sorghum or millet during the rainy season, and the harvest was often delayed to November. Production of wheat followed by sorghum, therefore, often did not allow high wheat yield.

Gradually, rice has become a major irrigation crop in Bakolori, possibly because rice production there faces fewer timing constraints than does wheat. Information about the Bakolori irrigation scheme has been scarce since the 1990s. Occasionally, studies have reported high rice yields achieved in the Bakolori irrigation scheme (Enplan Group 2004), but it has not been based on information from randomly selected farmers, which would give a more accurate productivity level.

Favorable Agroecological Environment

Bakolori is in the arid Sudan Savannah zone, where annual rainfall is approximately 500 to 600 mm. It is, however, endowed with some favorable environments. It is located along the Sokoto River, one of the largest tributaries to the Niger River. Bakolori is rich in Eutric Fluvisols (FAO et al. 2012), one of the types of soils considered most suitable for lowland rice production (Moormann and Breemen 1978). Among many agroclimatic parameters, Bakolori is particularly endowed with high solar radiation. High solar radiation is one of the key agroclimatic factors that facilitate plant growth and suppress pests and diseases, thus contributing to high yields (Barker, Herdt, and Rose 1985; Windmeijer and Andriess 1993).

Table 4.1 shows the solar radiation in Bakolori as well as other key locations in Nigeria. Bakolori is endowed with high solar radiation throughout the year compared to other locations in Nigeria. In particular, its solar radiation during the growing season and maturing stage in the dry season (March–May) is close to 7 kilowatt-hours (kWh) per square meter (m^2) per day, significantly higher than in Bida (6 kWh / m^2 / day) or Port Harcourt (less than 5 kWh / m^2 / day). The radiation level is higher than the levels in many major rice-producing countries in Asia and Latin America, which range around 5 for the major production season and 5 to 6 for the highest month, except Indian Punjab.

Table 4.1 Solar radiation and irrigated rice yield in Bakolori and elsewhere^a

Country/Location	Coordinates	Monthly solar radiation (kilowatt-hour per square meter per day)		Irrigated rice yield ^c
		Highest month	During major production season ^b	
Nigeria (Bakolori)	N12.5 E6	7.0	6.5 (January–May)	5.4 (dry season)
Nigeria (Bida)	N9 E6	6.3	5.4 (June–March)	3.0
Bangladesh (Dhaka)	N24 E90	5.9	5.1 (December–April)	4.3
Japan (Tokyo)	N36 E140	5.0	4.6 (May–September)	6.7
India (Punjab)	N31 E76	7.4	5.0 (July–April)	5.8
Indonesia (Jakarta)	S6 E107	6.3	5.2 (All year)	6.3
Philippines (Manila)	N14 E121	6.0	4.5 (May–February)	3.4
Sri Lanka (Colombo)	N7 E 80	6.1	4.9 (June–March)	3.7
Thailand (Bangkok)	N14 E100	6.3	5.0 (May–February)	4.0
Colombia (Cali)	N3 W77	4.6	4.4 (March–December)	5.6
<i>Countries with high solar radiations and rice yields</i>				
Egypt (Cairo)	N30 E31	7.7	6.4 (June–October)	9.5
Mali (Office du Niger)	N14 W6	6.9	5.7 (June–March)	5.0
Peru (Arequipa)	S16 W72	7.5	5.6 (February–June)	13.0
Turkey (Balikesir)	N39 E28	7.1	6.3 (May–September)	8.2
Turkey (Edirne)	N41 E27	6.6	5.8 (May–September)	8.2
Uruguay (Artigas)	S30 W56	6.9	5.7 (December–April)	8.0
United States (California)	N40 W122	8.3	7.1 (April–August)	8.1

Source: Authors' compilations from various sources.

Notes: ^a Solar radiation is from National Aeronautics and Space Administration (2014). Solar radiation is obtained for coordinates closest to the cities or regions specified. For Asian countries, since rice is grown nationwide, capital cities are used. For Colombia, Egypt, Mali, Peru, Turkey, and the United States, major rice-growing regions are selected. ^b Production season for irrigated rice is at the country level, obtained from Food and Agriculture Organization of the United Nations (2014b) except for Bakolori. ^c Yield figures for Bangladesh, Indonesia, Philippines, Sri Lanka, and Thailand are from Seck et al. (2012). Most rice production is under irrigation in Egypt, Japan, Turkey, Uruguay, and the United States, and therefore national statistics are interpreted as irrigated rice yield. Similarly, the figure for Punjab in India is assumed to be the same as the irrigated rice yield. The figure for Japan is the average between 2011 and 2013, from United States Department of Agriculture (2014). Figures for Egypt, Turkey, Uruguay, and the United States are from Food and Agriculture Organization of the United Nations (2014a). The figure for Mali is from Nakano et al. (2013). The figure for Arequipa, Peru, is from Maclean, Hardy, and Hettel (2013, 170). The figures for India are from International Rice Research Institute (2014). The figure for Colombia is from 1985, based on Muñoz and Rosero (1988). Yield figures for Bakolori and Bida are based on the authors' fieldwork.

Therefore, based purely on solar radiation, Bakolori has the potential to achieve significantly higher rice yields than other regions within Nigeria and many major rice-producing countries in Asia as well as yields comparable to several countries with high rice yields, including Egypt, Peru, Turkey, Uruguay, and the United States, if the irrigation facility provides sufficient water access and appropriate varieties are available.

Rice Productivity in Bakolori Irrigation Scheme

Survey Method

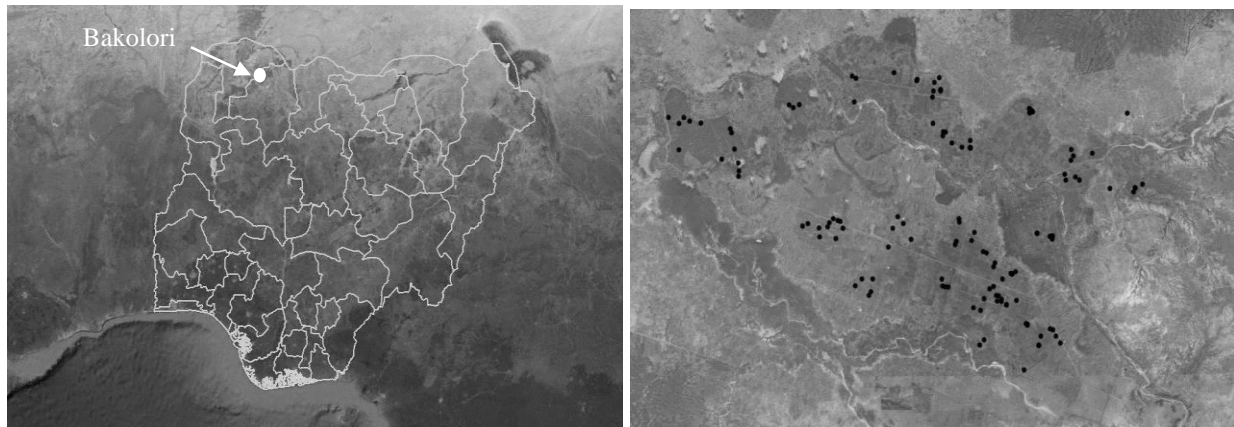
The Bakolori irrigation scheme is one of the largest schemes in Nigeria, with areas under effective irrigation area exceeding 5,000 ha and close to 19,000 registered farmers as of 2014 (Table 4.2). The scheme consists of 20 sections, each of which consist of 6 to 58 water user associations. The sections vary in area and number of registered farmers. In our survey, we used a sample framework that consists of the total list of farmers from rice-growing sections (all sections except sections AR, AL, and N SP R/N in Table 4.2). A stratified random sampling method was used. First, sample sizes N_j were assigned to each section proportional to its area. Second, every $\frac{1}{2}N_j$ th farmer on the list was selected from each section. We randomly sorted these $2N_j$ farmers within the section and asked the irrigation office to contact the first N_j farmers for the interview. A total of 110 farmers was interviewed. The last column in Table 4.2 shows the number of interviewed farmers in each section. Figure 4.1 shows the locations of the Bakolori irrigation scheme and plots cultivated by sampled farmers.

Table 4.2 Sections within the Bakolori irrigation scheme and number of interviewees in each section

Section name	Number of water user associations	Area (hectares)	Farmer	Samples in the survey
AL	7	95	376	0
AR	6	78	358	0
C	19	322	1,210	8
E Left	33	606	1,548	12
Right Up 1 and 2	26	471	1,569	11
F Left	15	192	262	4
G Left	17	226	486	5
G Rice A	58	575	2,667	14
G Rice B	14	131	417	3
G Right	15	345	437	3
F Right	17	157	317	4
E Down	20	235	1,180	5
L Rice 20	15	197	955	5
L Rice 10	9	158	976	4
M Rice B	21	173	927	4
M Rice A	47	478	2,250	11
N Rice R	12	259	632	6
N Rice D/G	21	358	1,136	8
N Rice D/K	32	148	1,414	3
N SP R/N	8	89	189	0
Total	412	5,294	18,945	110

Source: Authors' compilation based on information from Bakolori Irrigation Project office (2014).

Figure 4.1 Bakolori irrigation scheme and locations of plots for interviewed farmers



Source: Authors.

The survey was conducted in the first week of June 2014. Early June is typically immediately after the dry-season rice is harvested in the area, so farmers' recollections of harvest figures are likely to be quite accurate, and their recollections of input uses are likely to be reliable as the whole production season is about four months. Questionnaires were prepared in CSPro by the authors. Eleven locally hired enumerators (eight males and three females), who were selected based on their knowledge of rice production practices, survey experiences, and computer literacy, conducted the interviews using tablet laptops. All enumerators were selected outside the irrigation scheme to minimize the potential bias in harvest quantities reported.

Land Tenure within the Scheme

The farmers themselves own a majority of the cultivated area within the scheme. Leasing of plots by the irrigation office is observed only in sections F-left, F-right, E-left, M, and N. Even in these sections, however, the farmers own a majority of plots. For the plots leased by the scheme, lessees must apply every year for plots. The project manager directs the relevant intake officer (intake is sub-units within the section) to change allocate applicants to different plots every year.

Table 4.3 presents land tenure and land use practices from the survey. The information is for the plots where rice is mono-cropped, which accounts for most of the rice area within the scheme. Farmers own 84 percent of the area. Within this area, 83 percent has been inherited, while 17 percent has been purchased from previous owners. On average, current owners obtained the plots around 1998. Of the plots owned by farmers, 14 percent are subleased to other producers in the dry season, typically at the rate of \$50/ha. The subleasing market is still relatively rigid; on average sublessors have 2.2 potential lessees to choose from, but for 71 percent of the areas, only 1 lessee was available to the lessor. Typically the current lessors started subleasing around 2002. Future studies should investigate how the land market evolves in the Bakolori area in response to productivity change.

Table 4.3 Land use among mono-cropped rice area

Category	Value
% of area owned by the farmer	84 ± 9
% of area leased by the scheme	17 ± 9
Among the plots owned by the farmer	
Year obtained (average)	1998 ± 4
% of area inherited	83 ± 10
% of area purchased from previous owners	17 ± 10
Year purchased (average)	1998 ± 7
% of area subleased to other farmers in 2014 dry season	15 ± 9
Subleasing fee (2014 \$ per hectare) ^a	52 [0, 124]
% of subleased area with only one potential lessee ^a	71 [18, 100]
Number of potential sublessees per hectare (among subleased plot) ^a	2.2 [0, 10.5]
Year of first subleasing	2002 ± 9

Source: Authors' fieldwork.

Note: ^a These figures have large standard errors due to small samples and should be interpreted with caution.

Rice Productivity, Profitability, and Private-sector Investments

In the 2014 dry season, most rice plots were mono-cropped, and only in 6 percent of rice plots did farmers grow other crops (Table 4.4). Within these mono-cropped plots, only 32 percent of the areas that were irrigated during the dry season were mono-cropped in the rainy season. Of this 32 percent, 65 percent were irrigated in the rainy season, while the remaining 35 percent were rainfed. Popular varieties were FARO 44 (41 percent of the area) as well as popular local varieties called Bijin Bira (37 percent), Jirani Zawara (18 percent), and Jemila (4 percent). The share of Bijin Bira was considerably lower during the rainy season. Transplanting was practiced in only about 20 percent of the area; in the rest, broadcasting was used.

Table 4.4 Mono-cropping, varieties, irrigation, and use of transplanting

Categories	2014 dry season	2013 rainy season
% of mono-cropped rice area among all rice areas in 2014 dry season	100	32 ± 12
% of mono-cropped rice area among rice-grown plot	94 ± 6	93 ± 6
% cultivated with FARO 44 ^a	41 ± 12	63 ± 20
% cultivated with Bijin Bira	37 ± 12	7 ± 10
% cultivated with Jirani Zawara ^a	18 ± 9	16 ± 16
% cultivated with Jemila ^a	4 ± 5	5 ± 9
% of mono-cropped rice area		
Irrigated	100	65 ± 20
Transplanted	18 ± 9	18 ± 16

Source: Authors' fieldwork.

Note: ^a Area within the plot is weighted by the inverse of the number of varieties grown on the plot.

The average paddy yield in the 2014 dry season was 5.4 tons/ha, with a margin of 0.5 tons, indicating that the average paddy yield in the Bakolori irrigation scheme during the dry season was almost certainly 5 tons/ha or more (Table 4.5). The survey results thus confirm the anecdotal information that the rice yield in the Bakolori irrigation scheme is high by Nigerian standards and is comparable to irrigated rice yields in many Asian countries. Irrigated yields in the rainy season were slightly lower at 4.6 tons/ha although due to a small sample size the margins are large. In the rainy season, therefore, yield returns to irrigation may be somewhat lower, which also explains the lower use of irrigation in the rainy season mentioned above.

Table 4.5 Average paddy yields in Bakolori irrigation scheme

Categories	2014 dry season	2013 rainy season
Paddy yield on mono-cropped plot (tons per hectare)—irrigated	5.4 ± 0.5	4.6 ± 0.8
Rainfed (tons per hectare)		3.0 ± 1.7
Total (tons per hectare)	5.4 ± 0.5	4.0 ± 0.8

Source: Authors.

Rice Production Practices and Profitability

Table 4.6 summarizes the average profitability of rice production in the 2014 dry season in Bakolori, weighted by the size of rice plots. For the 2014 dry season, the farmgate paddy price was relatively high at 46 cents/kg, partly due to the high import tariff. This was higher than the prices observed a few years ago. For example, based on the Living Standard Measurement Survey-Integrated Survey of Agriculture (LSMS-ISA) 2010 data collected jointly by the World Bank and the National Bureau of Statistics, the price was around 33 cents/kg in the 2010 harvesting season. Gross revenue from irrigated rice production from the 2014 dry season was high partly because of the high paddy price, at \$2,489/ha. The average production cost was \$1,619/ha, leaving a net profit of \$858/ha.

Table 4.6 Profitability of irrigated rice production in Bakolori (\$ per hectare) in 2014 dry season

Categories	2014 dry season	\$ per farmer (average farm size = 0.28 hectare)
Cost		
Inputs (seeds, fertilizer, chemicals)	437 ± 70	123
Labor costs	841 ± 94	236
Machinery service costs	201 ± 25	57
Irrigation facility maintenance costs	17 ± 8	5
Empty bag ^a	45	13
Irrigation charge ^b	78	22
Subleasing fee ^c	8	2
Other miscellaneous (interest, fuels)	3 ± 5	1
Total costs	1,630 ± 147	458
Gross revenue	2,489 ± 236	700
Paddy price (cent per kilogram)	46	
Net profit	858 ± 182	241
Gross revenue under low price regime ^d	1,782	501
Paddy price (cent per kilogram)	33	
Net profit	152	43

Source: Authors.

Notes: ^a Typically NGN 100 per 100 kg bag. For 5.4 tons of paddy per hectare, it amounts to \$45/ha. ^b Irrigation charge is NGN 5,000/acre = approximately \$78/ha. ^c Calculated as $54 \times 0.15 \approx 8$ using figures in Table 4.3. ^d Using the zonal median price in the northwest zone in 2010, assessed by authors from Living Standard Measurement Survey – Integrated Survey on Agriculture 2010 (LSMS-ISA 2010) data.

The profit per farm household is, however, considerably smaller in magnitude because the average rice farm size within the scheme is approximately 0.28 ha, based on Table 4.2. The average profit per farm household for the 2014 dry season is \$241.

Labor accounted for the largest cost component of \$841/ha, which was approximately half of the total production cost. Inputs such as seeds, fertilizer, and agrochemicals together accounted for 25 percent, or \$418/ha. Machinery services including land preparation, harvesting, and milling accounted for 12 percent, or \$201 / ha.

Irrigated rice production in Bakolori is labor intensive. Table 4.7 summarizes the labor use (man-day / ha) for each crop husbandry activity as well as costs incurred. The labor uses combine both family labor and hired labor, where for simplicity, family labor is valued at the wage of hired labor. Total labor use was 180 man-days / ha for activities other than bird scaring (= 11 on nursery and 169 on main plot), and 76 man-days / ha for bird scaring. Overall labor wages were around \$4/man-day for activities excluding bird scaring, which is similar to the typical farm wages prevailing in most of northern Nigeria (Takeshima, Nin Pratt, and Diao 2013)⁹

Table 4.7 Labor use for rice production in Bakolori irrigation scheme in 2014 dry season

Items / Activities	Man-day per hectare	Cost (\$ per hectare)	Wages (\$ per day)
Nursery total	11 ± 11	24 ± 25	
Main plot total	245 ± 35	799 ± 90	
Excluding bird scaring	169 ± 24	702 ± 87	4.2
Land clearing	15 ± 5	43 ± 13	2.9
Harrowing/tilling	1 ± 1	2 ± 1	2.0
Leveling	15 ± 3	52 ± 11	3.5
Bunding	3 ± 2	10 ± 5	3.3
Planting	10 ± 3	65 ± 22	6.5
Gap filling	2 ± 2	11 ± 7	5.5
Fertilizer application	10 ± 3	33 ± 9	3.3
Manure application	1 ± 0	2 ± 3	2.0
Weeding	44 ± 9	120 ± 26	2.7
Chemical application	3 ± 1	14 ± 4	4.7
Irrigation assistance	28 ± 6	174 ± 46	6.2
Irrigation pump	1 ± 1	2 ± 4	2.0
Harvesting ^a /transport	36 ± 5	117 ± 13	3.3
Bird scaring	76 ± 16	97 ± 15	1.3
Total (surveyed)	256 ± 37		
Loading/off-loading ^b	5	18	
Total	261 ± 37	841 ± 94	3.2

Source: Authors.

Notes: ^a Includes threshing, drying, winnowing, and bagging. ^b Assessed from informal interactions with farmers.

Fertilizer use is relatively intensive (Table 4.8). A total of 99 percent and 94 percent of the rice areas received NPK and urea applications, with average quantities per hectare of 278 kg and 208 kg at a cost of \$164/ha and \$123/ha, respectively (nursery and main plots combined). This translates to approximately 144 kg/ha of nitrogen. This is almost two times higher than the 70kg/ha in typical rice irrigation in Nigeria (Takeshima and Bakare 2014). Seeding rates are also relatively high, with plots receiving on average 146 kg/ha of rice seeds when broadcast. Use of herbicides and pesticides is also common, used on 93 percent and 76 percent of the areas, respectively. Costs of these chemicals are, however, substantially lower than costs of fertilizer and seeds.

⁹ Wages for bird scaring are slightly lower as children instead of adult workers are employed.

Table 4.8 Use of seeds, fertilizer, and agrochemicals in 2014 dry season

Inputs	% using	Quantity (kilogram, liter per hectare)	Cost (\$ per hectare)
Seed (N)	9	9 ± 9	4 ± 4
Seed (M)	90	146 ± 23	89 ± 44
NPK (N)	9	9 ± 9	6 ± 6
NPK (M)	99	269 ± 44	158 ± 23
Urea (N)	5	3 ± 5	2 ± 3
Urea (M)	94	205 ± 31	121 ± 18
Nitrogen from NPK and urea		144 ± 21	
Urea Super Granule (USG)	5	8 ± 11	6 ± 8
Manure	8	243 ± 234	11 ± 12
Herbicide (N)	9	0 ± 0	1 ± 2
Herbicide (M)	93	4 ± 1	27 ± 5
Pesticide	76	2 ± 1	11 ± 3
Fungicide	4	0 ± 1	0 ± 1
Rodenticide	20	1 ± 1	0 ± 1
Total			437 ± 70

Source: Authors' fieldwork.

Note: NPK = nitrogen, phosphorous, potassium, N = nursery; M = main plot. Figures may not add up due to rounding.

Mechanization of certain activities has been widely observed (Table 4.9). Machinery was used on about 80 percent of the rice area for tillage and harrowing. Informal interactions indicate that most of the machinery is four-wheel tractors rather than power tillers. Ninety-six percent of threshing is also mechanized. This is much higher than the rest of the rice area in Nigeria, where use of tractors still accounts for only about one-third of the area (Takeshima and Bakare 2014). Of the area, 10 percent also received land clearing, which may be substantial given that land clearing is generally not needed in frequently cultivated areas such as this. Mechanized leveling was practiced on 3 percent of areas. Mechanization of planting, weeding, and harvesting is, however, almost absent. These patterns are generally consistent with the sequence of mechanization observed elsewhere in which mechanization of land preparation and threshing precedes that of other activities.

Table 4.9 Mechanization of activities in 2014 dry season

Activities	% of area using machinery	Cost (\$ per hectare)
Land clearing	10 ± 7	9 ± 8
Tilling	83 ± 10	60 ± 12
Harrowing	85 ± 8	40 ± 11
Leveling	3 ± 4	2 ± 3
Planting	0 ± 0	0 ± 0
Weeding	0 ± 0	0 ± 0
Harvesting	0 ± 0	0 ± 0
Threshing ^a	96 ± 5	43 ± 7

Source: Authors' fieldwork.

Note: ^a Figures for threshing refer to the area corresponding to harvests.

While direct estimation of irrigation water use is difficult to obtain, we also assessed it roughly based on the number of weeks the plots were irrigated, typical frequency of irrigation per week, and typical number of hours inlets were left open during each round of irrigation. Based on this, rice plots during the 2014 dry season received approximately 290 (± 127) hours per ha of irrigation.

Use of Incomes

While the profits from rice production are modest due to small farm sizes, returns to family labor (incomes) may be significant given that a large share of production costs accrues to labor use, most of which is likely to be family labor. Most rice growers rely on rice farming as the largest source of total income, contributing to 74 percent of it (Table 4.10). More than half of the rice-farming income seems used for investments into productive assets, particularly farmland or production assets for nonfarm business. A fraction of rice income is also used to pay back the loan and for investment into human capital, other farming equipment, and consumptions goods such as food. Overall, however, the latter types of use are relatively minor.

Table 4.10 Investments from rice farm income

Categories	Value (margin of error)
% share of rice income in total income	74 \pm 6
Use of rice income	
% pay back the loan	9 \pm 7
% invest into productive assets	57 \pm 12
Farm equipment (machinery, tools)	8 \pm 7
Farmland	25 \pm 10
Livestock	6 \pm 6
Rice irrigation facilities (maintenance of canal, drainage)	4 \pm 5
Production assets for nonfarm business	14 \pm 8
% invest into human capital (education, health)	6 \pm 6
% invest into nonproductive assets (consumption goods)	15 \pm 9
% purchase more consumption goods (food)	14 \pm 9

Source: Authors' calculations.

It is interesting to assess how the high productivity has induced collective action and development of input markets, as hypothesized from the Asian Green Revolution and induced institutional innovation (Estudillo and Otsuka 2012; Ruttan and Hayami 1984). While we cannot establish the causality, the emergence of these markets and institutions around the Bakolori area still provides some insight.

Collective Action on Canal and Drainage Cleaning

Collective action on canal and drainage maintenance is relatively common (Table 4.11). Of the farmers, 97 percent and 64 percent voluntarily participate in the cleaning of canals and drainage within the sections on which their plots are located, and about half of farmers (52 percent and 48 percent) also clean canals and drainage in the upstream or downstream sections. On average, farmers started these activities in the mid-1990s. Fifty-three percent of farmers started canal-cleaning activities on their own initiative, while only 29 percent and 15 percent of farmers were initiated by the government, the irrigation scheme, or extension staff. Therefore, the farmers themselves have initiated a significant level of the collective action needed for maintaining the functions of irrigation facilities.

Table 4.11 Collective action of canal and drainage cleaning

Activity	% of farmers practicing	% own initiative	% initiated by the government or irrigation scheme	% initiated by the extension staff	Year started such activity
Cleaning canal in the same section	97 ± 4	53 ± 12	29 ± 11	15 ± 9	1997 ± 3
Cleaning drainage in the same section	64 ± 12	25 ± 11	25 ± 10	14 ± 8	1996 ± 3
Cleaning canals in the upstream section	52 ± 12	18 ± 10	18 ± 9	14 ± 8	1995 ± 3
Cleaning drainage in the downstream section	48 ± 12	16 ± 9	16 ± 9	15 ± 9	1994 ± 3

Source: Authors' calculations.

Growth of Private Sector (Input Supplies, Service Provision)

The number of input dealers known to each farmer seems to have increased to the level where there is relatively sufficient competition (Table 4.12). On average, each rice farmer seems to know ten dealers or service providers in the areas supplying seeds, fertilizer, and agrochemicals or providing tractor services and power tiller services. About 80–90 percent of farmers perceive that the number of input suppliers has increased in the past five years, with improved timeliness in their availability. Shares are slightly lower for tractor service providers and power tiller service providers, although at least half of farmers feel improvements.

Table 4.12 Average perceptions of the growth of inputs and service providers

Types of agents	Number of suppliers known to each farmer	% of users who have seen increase in service providers in the past five years	% of users who have seen improved timeliness in service providers in the past five years
Seed seller	11 ± 4	89 ± 11	93 ± 10
NPK fertilizer seller	9 ± 2	81 ± 10	78 ± 10
Urea fertilizer seller	9 ± 2	89 ± 8	83 ± 10
Herbicide seller	9 ± 3	97 ± 5	93 ± 7
Pesticide seller	10 ± 3	82 ± 10	82 ± 10
Tractor service provider	8 ± 2	68 ± 11	58 ± 12
Power tiller service provider	9 ± 6	59 ± 26	55 ± 26

Source: Authors' calculations.

Similarly, farmers typically know 22 commission agents, 13 rice traders, and 7 rice mills and parboilers in the area (Table 4.13). About 80 percent of farmers perceive an increase in the number of commission agents and traders in the past five years. A majority of them think that the numbers have more than doubled in the past five years. Similarly, about 60 percent of farmers perceive increases in the number of rice mills and parboilers in the area in the past five years. Though these need to be validated with further surveys on these service providers, at least farmers are feeling growing competitiveness of service provisions in output markets.

Table 4.13 Average perceptions of the growth of output and postharvest service providers

Type of agent	Number of suppliers known to each farmer	% of users who have seen more than double increase in service providers in the past five years	Increase but less than double	No change
Commission agents	22 ± 9	52 ± 12	30 ± 11	2 ± 2
Rice traders	13 ± 4	57 ± 12	24 ± 11	9 ± 7
Rice mill	7 ± 3	33 ± 12	25 ± 11	11 ± 8
Parboiler	7 ± 3	25 ± 11	33 ± 12	8 ± 7

Source: Authors' calculations.

Note: No one indicated decreases; all remaining do not know the changes in the numbers.

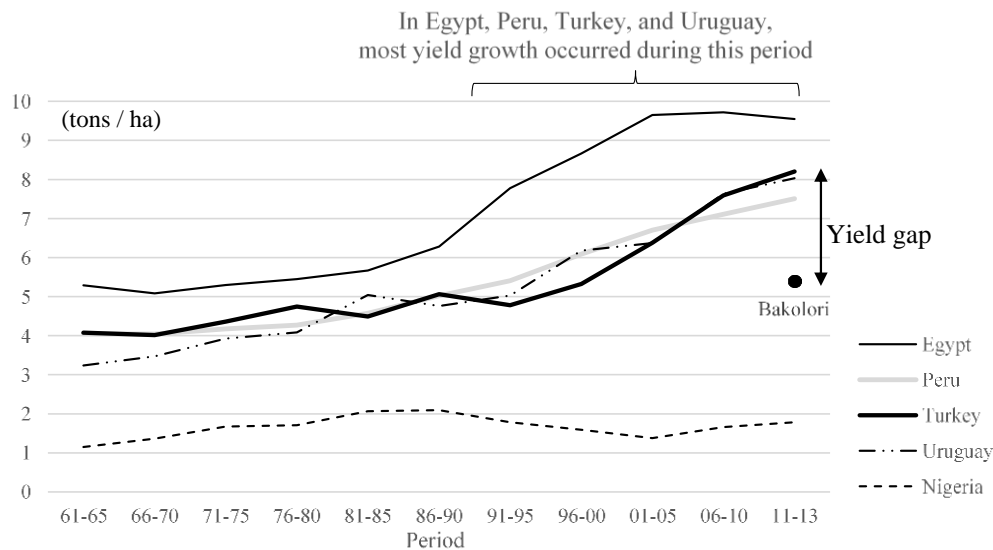
Last, a significant number of farmers supply seeds. It was discovered that about half of the farmers are growing rice seeds for sale, although only 2 percent are growing certified rice seeds. There is likely to be a significant demand around the area for seeds, including those that are not certified. On average (including those not growing seeds), 14 percent of harvests (with a margin of ± 4) within the scheme are sold as seeds. These seed growers are likely to be selling seeds not only within the irrigation scheme but to farmers in other areas. This is possibly because irrigation facilitates the production of seeds of fairly good quality (varietal purity, genetic uniformity), although this needs to be confirmed in future studies.

There are, however, some aspects of the market that are relatively underdeveloped, compared to similarly productive irrigation schemes found in Ghana (Takeshima et al. 2013). For example, use of informal credit is not widely observed, even though the high yields in the area can potentially raise the returns to intensive uses of inputs, which often require upfront payments at the beginning of the production season. The absence of informal credit may be in part because in the Muslim culture that is common in northern Nigeria, credit arrangements are subject to various restrictions, although various alternative forms of transactions may exist (Udry 1990). Similarly, while land preparation and threshing are almost entirely mechanized, harvesting activities are still predominantly manual. Use of irrigation is also low during the rainy season compared to the dry season, which contrasts with the trends in Asia in early periods where rainy-season irrigation generally spreads faster than dry-season irrigation (Chandler 1979, Table 3; Huke 1982, cited in Barker, Herdt, and Rose 1985). Future research needs to investigate why these developments have not been observed in Bakolori.

Lessons for High Potential Area (Bakolori)—Experiences in Egypt, Turkey, Uruguay, and Peru

Overall, rice irrigation in Bakolori is much higher yielding than in the rest of Nigeria. However, the current yield levels given the input uses still pose challenges. In particular, as was argued in Otsuka and Yamano (2005) and Takeshima (2014a), insufficient domestic R&D in African countries including Nigeria has been one of the major constraints for agricultural rice productivity growth. Just as average rice yields in Nigeria are much lower than those in other countries, irrigated rice yields in Bakolori are still much lower than those in countries with similarly favorable endowments of solar radiation, as discussed above, including Egypt, Peru, Turkey, and Uruguay. Important to note, all four of these countries have had substantially increased rice yields in the past 20 to 30 years alone. Their yields increased from 5 to 6 tons/ha in the late 1980s and 1990s to 7.5 to 10 tons in 2013 (Figure 4.2). Their yield growth during this period accounts for about one-third of current yields and is drastically different from relatively stagnated yield trends earlier.

Figure 4.2 Rice yield growth in countries with high solar radiation and high yields (Egypt, Peru, Turkey, and Uruguay)



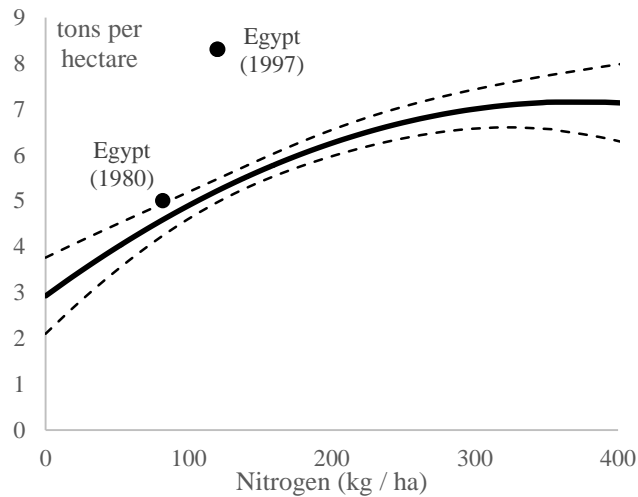
Source: Food and Agriculture Organization of the United Nations (2014a) and authors' calculations for Bakolori.

Important to note, much of this yield growth has been associated with varietal improvements realized through substantial domestic R&D on breeding. In Egypt, domestically bred Giza varieties have spread rapidly since the 1980s (Badawi 1997). Giza 176, released in 1989, spread to 30 percent of the rice area in 1991, while Giza 177, released in 1994, spread to 15 percent of the area in the next year (Badawi 1997). This is associated with a considerable increase in yields given nitrogen level. Figure 4.3 illustrates the rough approximation of nitrogen response curves in Bakolori estimated from the survey data and compares it with yields and nitrogen uses in Egypt in 1980 and 1997. While yields given nitrogen in Egypt in 1980 were quite similar to current levels in Bakolori, by 1997, they had increased significantly, with 8 tons/ha of rice produced with 120 kg/ha of nitrogen. In Bakolori today, the same nitrogen level would typically produce only 5 tons/ha. Such a discrepancy in performance can be attributed in one way to the fact that Egypt has invested substantially in varietal improvement since 1980, while Nigeria has done little. Egypt has 12 rice breeders (Diagne et al. 2011), while Nigeria has only 2 (Takeshima 2014a).

Turkey and Uruguay have experienced similar yield growth associated with significant adoption of domestically bred rice varieties recently. Turkey's rice yield had already been high, around 6 tons by the mid-1990s. However, the yield has further increased to 8 to 9 tons per hectare recently. This increase often has been attributed to, among others, a successful domestically bred variety, Osmancık-97. Osmancık-97 was a cross between the Italian variety Rocca (the most popular in the mid-1990s; Gaytancıoğlu and Sürek 2000) and EUROPA (unknown origin), developed at the Thrace Agricultural Research Institute in Edirne. In 2012, Osmancık-97 accounted for 80 percent of rice production in Turkey (Beşer and Sürek 2012).

In Uruguay, three varieties, El Paso 144, INIA Tacuari, and INIA Olimar, account for 95 percent of the rice area (Ferrando, Mañay, and Scavino 2012). All three of them are locally bred crosses that gradually have replaced introduced varieties since the 1990s (Instituto Nacional de Investigación Agropecuaria [INIA] 2011). El Paso 144 has resistance to pathogens and was released in 1985. INIA Tacuari has high cold tolerance and was released in 1992. INIA Olimar is high yielding and was released in 2002 (Ferrando, Mañay, and Scavino 2012).

Figure 4.3 Approximated relationship between yield and nitrogen use for dry-season irrigated rice production in Bakolori (confidence interval of mean yield)



Source: Authors. Figures for the fertilizer use rate for rice in Egypt are from Food and Agriculture Organization of the United Nations, International Fertilizer Industry Association, and International Fertilizer Development Center (1999) cited in Tran (2001, Table 4).

Note: The curve is estimated by simply regressing the yield on nitrogen use and its square term because of the small sample size in the data.

Key Implications of Rice Irrigation in Bakolori Irrigation Scheme

Overall, while the Bakolori irrigation projects experienced a sad history in the past, the infrastructure that was developed in the 1970s has turned out to be critical for the rice irrigation that has developed over the years. This has implications for the long-run returns from investment in irrigation infrastructure. While some irrigation infrastructure may have low returns or impose negative externalities in surrounding areas in the short run, it can bring positive benefits in the long run depending on the introduction of new varieties and improvements to other technologies such as machinery. One needs to assess the returns to public investment in irrigation more carefully. Based on randomly selected farmers within the projects, we confirm that the average yield from dry-season rice irrigation in Bakolori is almost certainly greater than 5 tons/ha. It is meaningful to know that high yield comparable to or higher than the irrigated environment in Asia is realized in some locations in Nigeria where the average rice yield has hovered around or less than 2 tons/ha for several decades.

However, international perspectives suggest that even in Bakolori, yields are not high enough. Important to note, the yield gap is associated with gaps in the domestic R&D efforts in Nigeria and other comparable countries like Egypt, Turkey, and Uruguay, all of which have successfully developed and released domestically bred varieties, which seem to have been widely adopted by farmers in ways that have further raised rice yields since the 1980s.

5. SUMMARY

This paper briefly provides three perspectives that can be useful in the future assessment of irrigation potential in Nigeria: (1) factor endowments, (2) challenges inherent in the tropics, and (3) some successes realized despite the remaining challenges.

First, certain aspects of factor endowments and their evolutions in Nigeria are relatively unique; population (and to some extent agricultural population) is growing fast, the water to labor ratio is declining quickly, and the expansion potential for agricultural areas is increasingly exhausted. Nigeria is becoming a relatively water-stressed country compared to countries in Latin America, central Africa, West Africa, and even Asia other than South Asia. Labor is relatively abundant compared to water. In the long term, shares of irrigated areas may rise above some of the more land-abundant countries like the United States or Australia but will not reach the level of Asia. A successful expansion of irrigation, if it occurs, may be more labor based in the short to medium term. Agricultural R&D is likely to be a critical factor that affects general water productivity in farming, which determines whether water is used more intensively in the agricultural sector or is diverted to nonagricultural sectors.

Second, irrigation expansion in Nigeria is likely to face constraints that are common in the tropical regions. It is affected by the climate, agricultural R&D efforts, growth of commercial demand, and the successes of vertical coordination such as plantations. In the short to medium term, rice may have the greatest irrigation potential for achieving poverty reduction and food security improvement if complemented by, among other things, sufficient investments in rice R&D. Achieving these goals through irrigation of other crops will require more complicated processes.

Third, a relatively high irrigated rice yield in the Bakolori irrigation scheme in northwestern Nigeria shows that it is possible in parts of Nigeria to realize high yields that are comparable with those of more advanced countries. However, given nitrogen use levels and high solar radiation in the area, substantial yield gaps still exist. This gap appears to be associated with insufficient domestic rice R&D in Nigeria. Countries like Egypt, Turkey, and Uruguay are similarly endowed with high solar radiation in their rice production areas and have realized some of the world's highest rice yields. In these countries, one-third of current yields have come from yield growth in the past 20 to 30 years, all associated with the release of domestically bred rice varieties.

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