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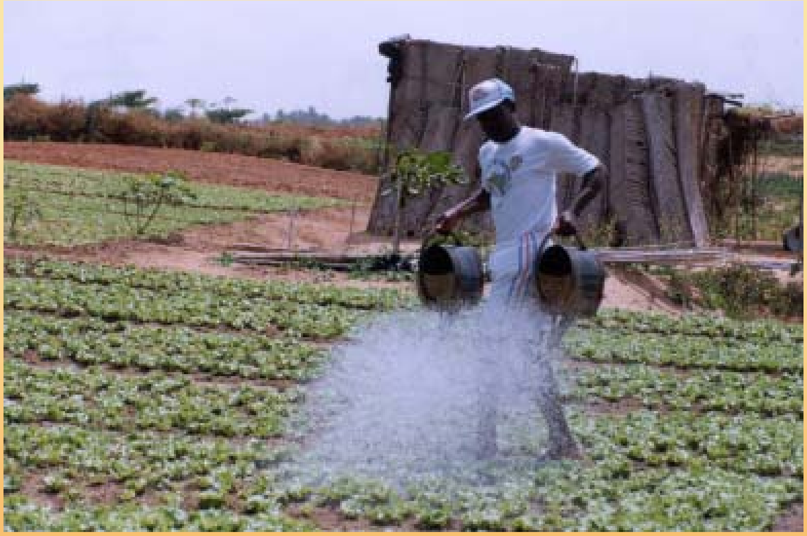

Improving Water and Fertilizer Use in Africa: Challenges, Opportunities, and Policy Recommendations

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Improving Water and Fertilizer Use in Africa:
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Background Paper Prepared for the African Fertilizer Summit

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by

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"To expand food production for a growing world population within the parameters of likely water availability, the inevitable conclusion is that humankind in the 21st century will need to bring about a 'Blue Revolution' to complement the so-called 'Green Revolution' of the 20th century. In the new Blue Revolution, water-use productivity must be wedded to land-use productivity. New science and technology must lead the way."

"The soil nutrient losses in SSA are an environmental, social, and political time bomb. Unless we wake up soon and reverse these disastrous trends, the future viability of African food systems will indeed be imperiled."

- Dr. Norman Borlaug, in his Travis P. Hignett Memorial Lecture on March 14, 2003, Muscle Shoals, Alabama (U.S.A.)

Improving Water and Fertilizer Use in Africa:
Challenges, Opportunities, and Policy Recommendations

Executive Summary

The increases in agricultural productivity that are needed to enhance rural incomes and achieve household food security throughout Africa will require substantial improvements in water and fertilizer use in both rainfed and irrigated areas. We also need to expand the use of irrigation by smallholders and develop small- and medium-scale irrigation schemes in locations where incremental benefits exceed incremental costs. The potential gains in agricultural production and farm incomes are substantial in areas where both water management and soil fertility can be improved. Complementary inputs including high-quality seeds, pesticides, energy, technical knowledge, farm implements, and financial credit must also be made available at affordable prices, and farmers must have access to reliable marketing opportunities.

The initial conditions for improving agricultural production in Africa are substantially different than those that existed in Asia at the time of the Green Revolution. Agroecological conditions are more challenging in Africa, the rural population is more disperse, and there are fewer opportunities for developing large-scale irrigation schemes. Greater effort will be required to disseminate new production technologies and ensure that all farmers have access to fertilizer and complementary inputs. The extensive poverty in rural areas and the risk aversion that comes with low incomes will limit farm-level expenditures on yield-improving inputs.

Appropriate near-term policies include subsidies on agricultural inputs and fair prices for agricultural products, to stimulate increases in agricultural production. Over time, direct subsidies might be replaced or complemented by crop loss insurance programs that provide downside risk protection. Public investments in education, research, and training will have greater long-term impact on agricultural production and rural livelihoods than input subsidies, but subsidies might be needed in many areas to "get agriculture moving" in a positive direction soon. Subsidies can be combined with agricultural training and extension programs to increase the likelihood that inputs will be used correctly and that measures of water and nutrient efficiencies will be optimized.

Public officials should assess the current state of agricultural production and marketing in their countries, with the goal of identifying primary constraints, risks, and opportunities. The analysis should be conducted from both public and private perspectives because public officials often have different views of constraints and risks than small-scale farmers who make decisions regarding inputs and outputs. Engaging farmers and representatives of farmer organizations in the evaluation process will enhance the value of the exercise. Donor agencies and international research centers can assist public officials by supporting studies that enhance understanding of farm-level production and marketing constraints, while also supporting policies and subsidies that reduce farm-level risks of applying fertilizer and investing in improvements in water management.

Improving Water and Fertilizer Use in Africa:
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1. Overview

As noted by Dr. Borlaug in 2003, substantial improvements in the use of water and fertilizer are needed to reverse the trend of nutrient mining in Africa and to place agriculture on a path of sustainable growth and development. Fertilizer is an essential input, given the inherent lack of nutrients in many African soils and the extensive nutrient mining that has occurred in the past. Many small-scale farmers lack the financial ability to obtain and apply fertilizer at times and in amounts that will maximize crop yields. The farm-level risk of applying fertilizer is greater in rainfed areas than in irrigated areas. Improvements in water supply and in farm-level water management can lead to greater use of fertilizer, with consequent increases in crop yields, farm income, and household food security.

The goal of this report is to provide background information for persons attending the Africa Fertilizer Summit in June 2006. Soil moisture and nutrients are essential inputs for agricultural production. Crop and livestock production are limited by inadequate availability of soil moisture and nutrients in many areas within Africa. Irrigation and water harvesting can be used to augment soil moisture in some areas. Organic and inorganic fertilizers can be applied to increase soil nutrients. The addition of irrigation water or fertilizer may fail to generate desired improvements in crop yields if either one of the inputs remains limiting. Public efforts to improve agricultural production must acknowledge the complementary relationships between water, fertilizer, and other inputs. This report focuses on water and fertilizer in the context of African agriculture.

2. Conceptual Framework

Soil moisture and nutrients are complementary inputs. The incremental productivity of soil moisture is a function of the amount of nutrients available, just as the incremental productivity of nutrients is a function of soil moisture. Incremental and total productivity are also determined by the time that these inputs are available to plants. Soil moisture and nutrients are needed at key stages of plant growth. If nutrients are available, but rainfall arrives late, productivity is impaired. Similarly, if soil moisture is available, but nutrients are limited, actual productivity will be less than potential.

The complementarity of soil moisture and nutrients is particularly pertinent in sub-Saharan Africa, where the farm-level cost of chemical fertilizer is high and rainfall is unreliable in many areas. High yields require ample fertilizer, high-quality seeds, and other costly inputs. Yet farm-level expenditures for fertilizer, seeds, and other inputs are risky in areas where rainfall is uncertain and crops fail frequently due to drought. This conundrum, in which farmers cannot afford to apply the inputs required to achieve high yields, explains a fundamental difference between crop production in Asia and Africa. In Asia, more than 50% of arable land is irrigated and the average annual application of fertilizer is about 40 kg per hectare of arable land. In Africa, less than 5% of farmland is irrigated and the average fertilizer application is less than 10 kg per hectare (Seckler, 1990).

Where fertilizer is applied in Africa, the use of nutrients by plants is often inefficient; that is, plants use only a portion of the nutrients applied. Inefficiency is caused partly by the lack of soil moisture at key stages of plant growth and partly by heavy rains that leach nutrients from the soil. Heerink (2005) suggests that in West Africa only 30% of the nitrogen from applied fertilizers is used by crops. Water is also used inefficiently. In the Sahel, only 10% to 15% of rainfall is used for plant growth partly because of the lack of adequate nutrients (Breman et al., 2001; Heerink, 2005). When plants cannot utilize rainfall, the water is lost through evaporation, surface runoff, or deep percolation. Farm-level water conservation measures such as constructing bunds and terraces can be helpful in retaining rainfall and improving the availability of soil moisture at key stages of plant growth. Nutrient and water use efficiency can be increased substantially in sub-Saharan Africa by improving the timing and availability of soil moisture and nutrients (Breman et al., 2001).

In much of sub-Saharan Africa, water and labor have long been scarce resources, relative to land. Many farmers seek to maximize returns to their limited labor supply rather than maximizing returns to land, which is relatively abundant (Underhill, 1990). Rainfed farming systems, which require only moderate amounts of labor, are suitable for situations in which labor is scarce. Farmers might be reluctant to allocate labor to the operation and maintenance of an irrigation scheme, particularly if the allocation of water they will receive is uncertain. Rainfed cropping systems are commonplace in Africa partly because irrigation is not widely developed and partly because rainfed systems are consistent with the scarcity of labor, relative to land. Opportunities for improving crop yields by enhancing the use of fertilizer in rainfed settings are substantial (Underhill, 1990).

Agricultural intensification occurs in many areas when farmers seek to achieve household food security and generate financial returns from their limited resources. Many farmers wish to diversify cropping patterns and grow more than one crop per season if adequate resources are available. Intensification in much of Africa will require careful management of soil and water resources. Fertilizer is costly, and the risks of failure are high in regions where irrigation is unavailable or limited and rainfall is uncertain. Innovations in water harvesting and re-use, development of small-scale irrigation methods, and the use of water-saving irrigation systems that enable careful application of nutrients are needed to improve water and nutrient efficiency (Lal, 2000). Considerations for arid and semi-arid regions of Africa include water management techniques such as micro-catchments, water spreading and water harvesting, and water storage in small-scale farm ponds for supplemental irrigation (Lal, 1990).

3. Production Zones in Africa

Natural features such as climate, soils, and water supply vary greatly across the African continent. Political systems, market structure, and population density also vary substantially. Both the natural and socioeconomic dimensions of Africa influence the ability of farmers to produce crop and livestock products in a sustainable manner that enables them to achieve household food security and to generate income for expenditures or investment. Many authors have examined the relationship between water and fertilizer use in Africa. Some have concluded that water and nutrient constraints, in conjunction with the continent's natural endowment of vast deserts and large semiarid zones with low-fertility soils, pose a substantial challenge to farmers, researchers, and public officials striving to achieve sustainable improvements in agricultural productivity (Voortman et al., 2003). Without such improvements, Africa likely will remain home to a disproportionately large portion of the world's poor and malnourished residents.

The Food and Agriculture Organization of the United Nations (FAO) defines seven production regions within Africa, based on geographic and climatic homogeneity. The following description of the seven regions draws heavily from information presented in FAO Water Report 29, *Irrigation in Africa in Figures: Aquastat Survey, 2005* (Frenken, 2005).

Northern Region

The Northern Region includes Algeria, Egypt, Libyan Arab Jamahiriya, Morocco, and Tunisia. It is bordered in the north by the Mediterranean Sea and in the south by the Sahara, both of which have a strong influence on the climate (more moderate in the north and very dry in the south). Annual average precipitation in the region reaches only 96 mm (western Sahara excluded), ranging from 750 mm in the extreme northwest of Morocco to close to zero mm in southern Egypt. An estimated 65 million ha can be cultivated in the Northern Region. However, only 28 million ha (43%) are cultivated at present.

Sudano-Sahelian Region

The Sudano-Sahelian Region extends to the northern boundary of the Sahara and is bordered in the south by the Gulf of Guinea Region, which is more humid. The region includes Burkina Faso, Cape Verde, Chad, Djibouti, Eritrea, Gambia, Mali, Mauritania, Niger, Senegal, Somalia, and Sudan. The climate is generally dry, of Sahelian or Sudano-Sahelian type, and characterized by two seasons. The annual average precipitation is 311 mm, ranging from 25 mm in northern Sudan to more than 1,600 mm in southern Sudan. The average evapotranspiration is about 2,000 mm/year, but it can reach 8,000 mm/year in the Gash-Barka Basin in Eritrea. Half of the estimated 208 million ha that can be cultivated are in Sudan. In 2000, crops were cultivated on about 39 million ha, or almost 19% of the cultivable area.

Gulf of Guinea Region

The Gulf of Guinea Region is bordered in the north by the Sudano-Sahelian Region and in the south by the Atlantic Ocean. Countries in the region include Benin, Côte d'Ivoire, Ghana, Guinea, Guinea-Bissau, Liberia, Nigeria, Sierra Leone, and Togo. The climate is Sudanese in the north and wet tropical in the south. The annual average precipitation is 1,356 mm, with large variations between countries: from 1,039 mm/year in Benin to 2,526 mm/year in Sierra Leone.

Evapotranspiration increases from 1,500 mm/year in southern Togo to 5,200 mm/year in northern Nigeria. An estimated 55 million ha were cultivated in 2002, or 46% of the estimated 120 million ha that can be cultivated in the region.

Central Region

The Central Region includes Angola, Cameroon, Central African Republic, Congo, Democratic Republic of the Congo, Equatorial Guinea, Gabon, and Sao Tome and Principe. The climate of the region varies among countries, ranging from tropical dry or wet to equatorial. Average precipitation (1,425 mm/year) reaches both extremes in Sao Tome and Principe, ranging from 900 mm/year in the northeast to 6,000 mm/year in the southwest. Throughout the region, the average annual rainfall ranges from 1,010 mm/year in Angola to 3,200 mm/year in Sao Tome and Principe. Evapotranspiration varies from 1,200 mm/year to 2,200 mm/year. The estimated cultivated area in 2002 was about 21 million ha, or 12% of the 173 million ha that can be cultivated. The Central African Republic is the only landlocked country in the region.

Eastern Region

The Eastern Region is bordered in the northwest, north and northeast by the Sudano-Sahelian Region, in the east by the Indian Ocean, in the south by the Southern Region, and in the west by the Central Region. The region includes Burundi, Ethiopia, Kenya, Rwanda, Uganda, and the United Republic of Tanzania. The climate is dry in parts of Ethiopia and Kenya, equatorial in Uganda, tropical in western Burundi in the Imbo Plain near Lake Tanganyika, and moderate tropical in the highlands of Rwanda and Tanzania. The average annual precipitation, which occurs largely during one or two periods, is 920 mm, ranging from less than 100 mm in northeastern Ethiopia to 3,000 mm in some areas of Tanzania. An estimated 83 million ha can be cultivated, of which an estimated 31 million ha (37%) presently are cultivated.

Southern Region

The Southern Region is bordered in the northwest by the Central Region, in the northeast by the Eastern Region, and in the west, south, and east by the Atlantic and Indian Oceans, which meet at the Cape of Good Hope. Countries in the region include Botswana, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Zambia, and Zimbabwe. Mozambique, Namibia, and South Africa have access to the sea, while the other countries are landlocked. The main landscapes of the region are the fringing plains; the Kalahari scrub-desert with a total surface area of about 500,000 km^2 (covering a wide part of Botswana and extending towards Namibia and South Africa); and Africa's Great Rift. The climate is dry in the deserts, moderate at higher altitudes (Lesotho), and tropical to subtropical in the rest of the region. Rains fall mainly in the summer (October–April) except near the Cape of Good Hope in South Africa, where the climate is Mediterranean and rain falls in winter. The annual average precipitation in the region is 659 mm, ranging from less than 100 mm in the desert to more than 2,000 mm in northern Mozambique. The most humid country is Malawi (with an average precipitation of 1,810 mm/year), and the least humid is Namibia (285 mm/year). Evapotranspiration can exceed 3,700 mm/year in certain zones of Namibia.

Indian Ocean Islands Region

The Indian Ocean Islands include the Comoros, Madagascar, Mauritius, and Seychelles. In Madagascar, the climate varies from semi-arid to tropical humid; it is generally tropical humid in Seychelles and the Comoros, and subtropical to temperate maritime in Mauritius. The mean annual rainfall is 1,510 mm, ranging from 900 mm in the Comoros to 2,040 mm in Mauritius. At present, an estimated 3.8 million ha are cultivated, or about 46% of the 8.3 million ha that can be cultivated. Much of the cultivated land is in Madagascar.

4. Irrigated Systems and Water Harvesting

The seven production regions vary in terms of the volume of water withdrawn each year for agriculture, municipalities, and industry, as well as the proportions of withdrawal allocated to each sector. The largest volumes (93,889 million m^3 and 54,948 million m^3, respectively) are withdrawn in the Northern and Sudano-Sahelian Regions, where an estimated 85% and 95% of withdrawals are allocated to agriculture (Table 1).

When assessing the extent of irrigation and other forms of agricultural water management in Africa, the FAO report distinguishes between (1) irrigated areas, (2) cultivated wetland and inland valley bottom areas not equipped with irrigation facilities, and (3) cultivated flood recession areas not equipped with irrigation facilities. All three areas are included within the category of areas under water management (Frenken, 2005, Page 26). Throughout history, irrigation in Africa has consisted primarily of small-scale riverine systems, flood spreading, recession, and swamp planting (Field, 1990).

About 60% of the estimated 15.4 million ha under water management in Africa is in the Northern and Sudano-Sahelian Regions (Table 2). The proportion of Africa's irrigated area in those regions is greater than 66% (Table 3). Egypt accounts for 54% of the irrigated area in the Northern Region (Frenken, 2005). Most of the area irrigated in the Northern and Sudano-Sahelian Regions is equipped for full or partial irrigation. A moderate amount of spate irrigation is found in both regions. Spate irrigation is practiced primarily in the dry countries of Tunisia, Morocco, and Algeria in the Northern Region, and Somalia, Sudan, and Eritrea in the Sudano-Sahelian Region (Frenken, 2005). Equipped lowlands are found in all areas except the Northern Region and Indian Ocean Islands (Table 3). Flood recession irrigation is particularly important in the Gulf of Guinea Region (Table 2).

The proportion of cultivated area that is irrigated is smaller in Africa than in many areas of Asia. Less than 10% of the cultivated area is irrigated in all regions except the Northern Region and the Indian Ocean Islands (Table 4). These data reflect the variation in rainfall among the regions and the limited investment in irrigation schemes. The estimated irrigation potential for Africa is substantially larger than the area currently under irrigation. The FAO report has estimated the irrigation potential by major river basin (Frenken, 2005). The greatest potential exists in the Congo/Zaire, Nile, West Coast, Niger, and Zambezi River Basins (Table 5). More than 70% of Africa's irrigation potential exists in those five basins.

Most irrigation in Africa involves non-pressurized surface irrigation methods. The proportion of area with full or partial water control that is irrigated with surface systems ranges from 37% in the Southern Region to nearly 100% in the Sudano-Sahelian Region (Table 6). In most regions the proportion is greater than 80%. Sprinkler irrigation has been developed extensively only in the Southern Region, where pressurized systems are found on 52% of the area with full or partial water control. Localized irrigation, which includes drip irrigation systems, is not yet widely developed in Africa, The largest areas are found in the Northern and Southern Regions, where rainfall is limited and some of the countries are more prosperous than in other regions (Frenken, 2005).

An estimated 45% of the irrigated area in Africa is planted in rice and other cereals (Frenken, 2005). Industrial crops such as cotton and sugarbeets account for 15% of irrigated area, while irrigated fodder and vegetables are found on 14% and 12% of the area, respectively. Irrigated fodder is grown largely in the Northern Region, where many Egyptian farmers produce berseem for feeding livestock. About half the area planted in rice in Africa is found in Madagascar, while one-third is found in the Northern Region, primarily in the Nile Delta.

Substantial water resources are also used to produce livestock in Africa. Water is used directly for drinking by animals and to produce the crops consumed by livestock. Accounting for water use in the livestock sector is difficult, in part, because much of the feed consumed by livestock is a byproduct of agricultural production, such as crop residues. The incremental value of water in livestock production can be substantial when all of the socioeconomic aspects of livestock raising and marketing are considered (Peden et al., 2005). Hence, there is value in considering livestock production and water requirements when designing irrigation schemes and developing agronomic extension services.

Surface water is the primary source of irrigation water in most of Africa. In aggregate, surface water is used to irrigate about 78% of the area with full or partial water control (Table 7). The Nile River supports substantial irrigation in Sudan and Egypt, but many other river systems are less suitable for irrigation development. In the drier regions of Africa, where the need for irrigation is notable, river flows tend to be seasonal and to follow the rainfall pattern (Field, 1990). Surface water storage systems are needed to optimize the use of river water for irrigation in much of Africa, but the costs of construction and the potential environmental impacts might preclude development of surface water storage in some areas.

Groundwater is an important source of irrigation water in the Northern, Eastern, Southern, and Gulf of Guinea Regions. The true extent of groundwater irrigation is difficult to estimate accurately, given that most groundwater is extracted by individuals irrigating small parcels of land. The data from FAO (Table 7) indicate that about 2.5 million ha in Africa are irrigated with groundwater. Giordano (2006) reports that groundwater is used on about 1 to 2 million ha in Africa, contributing directly to the livelihood of 1.5% to 3% of the rural population. Groundwater also plays a critical role in the vital livestock sector as well as an important indirect role in the supply of domestic water to agricultural households.

There are substantial groundwater resources available in Africa, but much of the accessible groundwater is found in areas where surface water is abundant in major rivers and their tributaries (Zektser and Everett, 2004; Giordano, 2006). Efforts to develop greater use of groundwater include the distribution of low-cost treadle pumps and drip irrigation kits in Kenya, Tanzania, Zambia, and other countries (Polak and Yoder, 2006). Low-cost irrigation materials have enabled millions of small-scale farmers in Asia to gain access to shallow groundwater, with consequent gains in agricultural productivity, income, and household food security.

There is potential to develop additional surface water and groundwater supplies in southern Africa, but the costs and risks of development are substantial (FAO, 2003). Hence, most agricultural production will continue to come from rainfed areas. Crop yields in the region can be improved by increasing soil moisture through wider use of water-harvesting techniques. An estimated 70% to 85% of rainfall in some areas becomes surface runoff or deep percolation, is evaporated, or is used by weeds or failed crops. Water-harvesting technology can improve rainfall retention, increase crop yields, and ensure domestic water supplies (FAO, 2003).

The pace and success of irrigation development in sub-Saharan Africa, as in other regions, is dependent on supportive policies, institutions, and markets. For example, more than 70% of the land in Kenya is arid, and yet little irrigation is found there (Olouch-Kosura and Karugia, 2004). The country relies largely on rainfed agriculture. Six large-scale irrigation schemes have been constructed in Kenya, but only one is fully operational and two are partly operational. The schemes were built originally to support rice production, which once was subsidized heavily by the government (Olouch-Kosura and Karugia, 2004). Changes in government policies in the 1990s contributed to collapse of the irrigation schemes.

The Government of Ghana has been supporting irrigation development since the 1960s. Currently 22 major irrigation projects provide service to an estimated 11,000 ha of farmland, or about 0.2% of the area cultivated (Seini and Nyanteng, 2004). Most irrigation in Ghana involves rice and vegetables. In a survey of farmers conducted from 2000 through 2002, farmers reported that 14% of the land in vegetables is irrigated. About 15% of rice farmers reported using irrigation, and 35% of those farmers produce more than one crop each year. Only 4% of maize farmers and 2% of sorghum farmers reported using irrigation (Seini and Nyanteng, 2004). As in other African countries, irrigation is used primarily on rice and vegetables, while grains are produced largely in rainfed conditions.

5. The Variability of Rainfall

The reliability of soil moisture at critical stages of crop growth can be viewed as one of the most important agricultural inputs. The average amount of precipitation or irrigation water supply expected each year is an important summary statistic that is useful for planning purposes; however, the reliability of rainfall or of an irrigation supply is likely more important, given the uncertainty caused by variations in rainfall patterns and the potentially large costs imposed on farmers and society when soil moisture is lacking at critical growth stages.

Reliability is required to ensure food security and enable the development of non-agricultural societies. In some arid and semi-arid areas, soil depth and water-holding capacity are more important than soil nutrient reserves when choosing sites for crop or livestock development

(Pereira, 1977). Nutrients can be added to soil using organic or inorganic fertilizer, but water might not be available. In some areas of Africa, correlations of vegetation and rainfall variance are stronger than correlations involving vegetation and average rainfall (Pereira, 1977). Plant communities and societies tend to develop most successfully in areas where water supplies are reliable, either in the form of precipitation or a developed water supply project.

Extreme weather events, including droughts, excessive rains, and floods, often impair agricultural productivity in sub-Saharan Africa, causing sharp reductions in food availability and household food security. The rainfall pattern in sub-Saharan Africa is influenced by large-scale, intra-seasonal and inter-annual climate variability, which is influenced by the El Niño Southern Oscillation (Haile, 2005). Most of the severe droughts in sub-Saharan Africa in recent years have been linked to El Niño events.

Farmers in Burkina Faso have described climate variation as one of the factors that made farming more difficult and more risky during the previous 20 years (Ingram et al., 2002). Those farmers describe climate variability as including the increasing frequency of annual water deficits, late onset of the rainy season, premature end of rains, and unexpected rainfall distribution. In eastern Kenya maize yields range from zero to 1.7 tons per hectare, largely as a function of variability in weather conditions (Olouch-Kosura and Karugia, 2004). Most farmers use local, improved seed with little fertilizer because drought conditions cause the maize harvest to fail in about three of every ten years.

The riskiness of farming increases when farmers apply fertilizer, particularly in developing countries with uncertain rainfall and limited access to developed supplies of irrigation water. Sources of risk in farming include the likelihood that crop yields will be reduced by unfavorable weather conditions, unexpected weather events, late planting, and poor quality of key inputs, such as seeds and pesticides. Farmers also face demand-side risks including uncertainty about the markets for their products and prices they will receive. Fertilizer application increases farm-level expenditures in a manner that increases the potential financial loss when crops fail or market prices are lower than expected (Schnier et al., 1997).

Stige et al. (2006) examine linkages between historical climate information and aggregate crop and livestock production data generated during the past 40 years in many African countries. They observe strong associations involving the year-to-year variability in the El Niño Southern Oscillation and the yields of maize, sorghum, millet, and groundnuts. The observed association is "strongest for southern Africa, where productivity is expected to decline by 20% to 50% in extreme El Niño years." The authors observe similar, but weaker, relationships for millet and maize in western Africa. They note that sorghum and groundnut yields in northwest Africa appear to increase during El Niño years. The authors conclude that large swings in food production can be expected in Africa "if the global climate changes toward more El Niño-like conditions, as most climate models predict."

The potential impacts of global climate change, including greater swings in crop and livestock production, will have impacts at the farm level and in aggregate. Farmers will face greater uncertainty regarding yields, although El Niño-like events might be predictable to some degree. As noted by Stige et al. (2006), public agencies might endeavor to inform farmers of El

Niño-like events and encourage them to implement risk-minimizing strategies. For example, farmers might be advised to switch from maize to sorghum in some regions when El Niño conditions are expected. Several regions of Africa might experience substantial reductions in annual surface water supply as a result of climate change (de Wit and Stankiewicz, 2006). Adaptive planning might enable some countries to minimize the potentially negative impacts of reductions in rainfall and surface runoff.

6. Water, Fertilizer, and Crop Yields

Water and Fertilizer Interactions

Agricultural practices can be modified to enhance interactions between soil moisture and nutrients. In particular, adding organic matter to soils, preventing erosion, and increasing water retention through the use of bunds, tied ridges, and terraces will increase soil moisture content and enhance the effectiveness of fertilizer (Reardon et al., 1997). Tied-ridging, which involves the construction of perpendicular ridges with a depression in the center where water collects rather than running off, has improved farm crop income by 12% on a representative farm in Burkina Faso (Shapiro and Sanders, 1998).

Nutrient use efficiency is defined by some authors as the mass or value of crop produced per kilogram of nutrient applied or available in the soil (Rowe et al., 2006). The empirical value of nutrient use efficiency is influenced by many factors including soil acidity, soil organic matter, and soil moisture content (Giller et al., 2006). Farm management, input availability, and seasonal weather conditions will also influence the amount of crop produced per unit of fertilizer applied. In areas where the supply of supplemental fertilizer is limited, public officials might seek to maximize nutrient efficiency by implementing fertilizer distribution programs, improving the farm-level supply of complementary inputs, and providing agronomic extension services. Adding mulch to farm fields will increase moisture retention in the short-run and contribute to higher levels of soil organic matter over time. The higher levels of soil organic matter will improve soil water-holding capacity (Giller et al., 2006).

Empirical Evidence of Yield Effects

Several management practices to increase soil moisture retention have been tested by researchers and implemented by farmers throughout Africa. Water harvesting can be accomplished with simple bunds and barriers that collect or divert surface runoff into farm fields. More elaborate methods include tied-ridging of planted surfaces, contour furrows, excavated basins, underground tanks, and lined reservoirs (Mati, 2005; Oweis and Hachum, 2006). Yield effects of selected water-harvesting methods have been observed on experiment stations and in comparisons involving recommended practices and farm-level traditional production methods.

Tied-ridging enhances the effectiveness of precipitation by capturing rainfall and allowing greater time for infiltration. Such a practice can increase crop yields with or without complementary application of fertilizer. Jensen et al. (2003) obtained 34% and 42% increases in maize grain yields using only tied-ridging during normal to slightly dry rainfall conditions at two experimental sites in East Africa. When combining tied-ridging with nitrogen and phosphorus fertilizer, they obtained maize grain yields up to six times as large as those achieved using farmers' traditional practices (i.e., flat cultivation and no fertilizer). In general, the yield effect of tied-ridging was positive during dry and normal years (rainfall between 500 mm and 600 mm), but negative during wet years (rainfall between 700 mm and 900 mm). The authors note, however, that the negative effect can be offset somewhat by applying fertilizer.

The prospect of improving crop yields with tied-ridging, without adding fertilizer, is attractive in East Africa, given the high cost and risk associated with applying fertilizer in the region. Jensen et al. (2003) suggest that small-scale farmers are not likely to apply fertilizer to their tied-ridged maize fields unless they receive a considerable financial subsidy. Earth and stone dikes or barriers constructed to capture rainfall on small plots can also improve crop yields with or without supplemental fertilizer (Sanders et al., 1990).

The *teras* system of capturing water and sediment, practiced in eastern Sudan, is similar in concept to tied-ridging and other barrier methods of water harvesting. Bunds are constructed along three sides of a gently sloping field, with the upper end left open to allow inflow of surface runoff during rainfall events. The water provides soil moisture, and the sediment carries nutrients. Niemeijer (1998) has documented substantial increases in soil nutrients within the bunded areas of *teras* fields in the border region of eastern Sudan. The author suggests that this indigenous water-harvesting technique has enabled farmers in the region to sustain crop production for many years without fallowing land or applying organic fertilizer.

Bunding of crop fields to increase water retention also improves rice yields in West Africa. Becker and Johnson (2001) report significantly higher rice yields on bunded plots than on open plots during a 3-year study in Côte-d'Ivoire. In addition to an average increase in grain yields of about 40%, the authors observed a 25% decrease in weed biomass. The authors attribute 60% of the observed variation in rice grain yields to water control and the timing of agronomic practices such as weeding and the application of nitrogen fertilizer. According to the authors, the benefits of bunded rice fields, which include greater nitrogen use efficiency, likely will be greater in the well-drained inland valleys of the savanna and the bimodal rainfall forest, than in the high-rainfall monomodal forest zones.

The complementary interaction of water and fertilizer was demonstrated in a study of the yield effects of fertilizer on millet production in West Africa (Sivakumar and Salaam, 1999). The authors noted significant increases in millet yield and water consumption on experimental plots receiving fertilizer during four years of study in Niger. Water use efficiency, as measured in kilogram of yield per hectare, divided by water consumed, increased during all 4 years of the study. The average increase in water use efficiency attributable to the increase in fertilizer was 84%, suggesting that farmers obtained 84% additional yield per millimeter of water consumed by the millet plants.

Yield Gaps

For many years, researchers and extension service personnel throughout the world have reported gaps between the yields obtained on farms and those achieved on experiment stations. There are many reasons why farmers do not achieve the same yields as researchers, such as inadequate use of key inputs, poor timing of planting and other cultural practices, uncertainty regarding the measurement of inputs, and the profit incentive that requires consideration of incremental costs and benefits. Sub-optimal use of water and fertilizer can contribute to observed yield gaps, particularly in arid regions where farmers are unable to obtain or afford proper amounts of fertilizer. Empirical information regarding yield gaps is helpful in describing the potential gains that can be achieved by improving the aggregate use of water and fertilizer.

Yield gaps in the Gezira irrigation scheme in Sudan demonstrate the role of policies and prices in motivating farm-level use of fertilizer and other yield-improving inputs. The irrigated area of the Gezira scheme, which lies between the White and Blue sections of the Nile River, is about 880,000 ha. There are 102,000 tenant farmers in the scheme, managing an average land area of about 8 ha per household (Plusquellec, 1990). There is an officially imposed four-crop rotation in the scheme, in which cotton, the major cash crop, is grown in rotation with wheat, groundnut/sorghum, and fallow.

Farm-level yields of cotton and wheat in the Gezira scheme are only one-third to one-fourth the yields achieved at the Gezira Research Station (Table 8). In addition, the average cropping intensity is only 60%, which is substantially lower than the planned intensity of 75%. Plusquellec (1990) includes the “deterioration of soil fertility” in a list of issues generated by crop intensification and diversification, while not describing specifically the use of fertilizer. Rather, he describes the loss of water control due to inadequate operation and maintenance of the irrigation system. Declining crop prices have discouraged or prevented farmers from paying fees required to maintain the irrigation system. Loss of control has resulted in siltation and waterlogging in some areas, further reducing the farmers’ ability to pay for maintenance and repairs.

Yield gaps have been observed also in rainfed areas in Africa and where irrigation is accomplished primarily with small-scale systems. Most rice production in Tanzania occurs in rainfed conditions. An estimated 74% of the total paddy area is rainfed lowland rice, while 20% is upland rice, and 6% is irrigated (Kanyeka et al., 1995, cited in Isinika et al., 2004). Most production occurs on small-scale farms ranging in size from 0.5 ha to 2.4 ha. On farms with good water management, optimal plant spacing, and low to medium use of fertilizer and pesticides, yields range from 1.3 t/ha to 2.4 t/ha. By comparison, paddy yields at large-scale irrigated farms owned by the National Agricultural Food Corporation are as high as 8 t/ha (Isinika et al., 2004).

The Sasakawa-Global 2000 program has implemented more than 200,000 half-hectare production test plots in Africa since 1986 (Borlaug and Dowswell, 1995). The package of inputs used on the test plots includes (1) the best available commercial varieties, (2) good land preparation and optimal seeding dates, (3) good fertilizer application, including green manures and animal dung when available, and (4) moisture conservation and better water use if the plots are irrigated. Crop yields on the plots often are two to three times larger than yields on control plots where traditional production methods are used. Replicating test plot conditions on a large number of farm fields is challenging, but results suggest the magnitude of yield improvements that might be achieved with better use and coordination of key inputs, including high-quality seeds, fertilizer, and soil moisture.

A group of Swedish researchers has examined the range of crop yields achieved in sub-Saharan Africa by collecting farm-level production data from 3,000 farm households in 100 villages in eight countries: Ethiopia, Ghana, Kenya, Malawi, Nigeria, Tanzania, Uganda, and Zambia (Djurfeldt et al., 2004a). The authors define potential yield as the mean yield achieved by the 5% best performing farmers by crop and village, with outlier values excluded (Larsson, 2004, p. 116). They compare average yields with potential yields in each of the eight countries. Their results depict notable differences between the mean yields for most farmers and the mean yields for the 5% best performing farmers (Table 9). For maize, the mean yields for most farmers range from 0.9 t/ha to 1.8 t/ha, while potential yields range from 2.2 t/ha to 5.2 t/ha. Similar differences in mean yields are observed for paddy, while the differences for sorghum are smaller, but still notable. A summary comparison suggests that the observed yield gaps for maize, cassava, sorghum, and rice are greater than 50% (Table 10).

Larsson (2004), one of the Swedish researchers, attributes the large yield gaps observed in the eight countries partly to differences in agroecological conditions (soils, slope, etc.) and partly to economic and political considerations. He suggests that “the majority of smallholders either lack the resources for purchasing yield-improving inputs and/or consider marketing of food staples to be too risky (p. 116).” In particular, the sub-optimal use of fertilizer by most farmers explains the observed yield gaps. Public efforts to reduce both the farm-level prices of fertilizer and other inputs and the perceived risks of marketing food staples would encourage greater use of fertilizer, with consequent improvements in crop production, farm income, and household food security.

The data reported in Tables 9 and 10, particularly for maize, cassava, and sorghum, pertain largely to crop production in rainfed conditions. Only 7% of the land cultivated by farmers in the survey conducted by Djurfeldt et al. (2004a) is irrigated, and most of the irrigation is found on vegetables and rice. The irrigation systems generally are small-scale and managed by individual farmers or groups of households (Larsson, 2004). Hence, the data reported by Djurfeldt et al. (2004a) suggest that substantial gains in crop production can be achieved in rainfed settings by improving the use of key inputs. Regression analysis of the data suggests that chemical fertilizer, improved seeds and pesticides, and mechanical methods of land preparation (tractor and oxen ploughing) generally are associated with higher yields. In the case of maize, each factor adds about 500 kg to 700 kg in yield per hectare.

7. Policy Recommendations

Given the important role of agriculture in the livelihood of many rural residents of southern Africa, improvements in the productivity of land and water are needed to reduce poverty in the region. The Food and Agriculture Organization (2003) recommends a strategy that includes two major activities of public agencies (1) encouraging farmers and farmer groups to engage in productive agriculture by assisting them to achieve improvements in farm management and by improving the delivery of water services, and (2) expanding economic opportunities for farmers by addressing non-farm issues that provide disincentives for improving agricultural production. Public agencies must also invest in public goods that reduce both the farm-level cost of obtaining inputs and the post-harvest costs of transport and marketing.

Many authors have suggested that input subsidies are required in Africa to motivate farmers to use fertilizer and other productivity-enhancing inputs. A large number of such subsidies were eliminated in many countries in the 1980s and 1990s as required by economic structural adjustment programs administered by international financial institutions (Jayne et al., 2002). An alternative view is that larger investments in public goods are required to create the infrastructure needed to enable agriculture to thrive in the region. Pertinent public goods include roads, irrigation systems, electricity, educational institutes, and agricultural research and extension systems (Borlaug, 2003; Kelly et al., 2003). By enhancing Africa's physical and human capital, investments in infrastructure, public health, education, and research will increase the incremental productivity of standard agricultural inputs, such as land, irrigation water, and fertilizer.

In a sense, the path forward is clear, but also quite challenging. Most observers would agree that to get agriculture and economic development moving forward in Africa, the use of fertilizer needs to be expanded and improved in both rainfed and irrigated settings. There is also a need to expand the use of irrigation by smallholders and develop small- and medium-scale irrigation schemes in locations where incremental benefits exceed incremental costs. The potential gains in agricultural production and farm incomes are substantial in areas where both water management and soil fertility can be improved. The challenge is to provide these fundamental inputs, in addition to high-quality seeds, pesticides, energy, technical knowledge, farm implements, financial credit, and viable marketing opportunities
.

Substantial time and effort will be required to develop region-specific programs that promote the use of key inputs, while providing credit and ensuring viable market opportunities. Public investments in infrastructure and support for market mechanisms are needed. Also needed are public officials, technical specialists, and farmer representatives who can lead and sustain the effort to improve agricultural production and marketing in Africa over time and across the many ministries that must be involved in crafting innovative programs. As Borlaug and Dowswell (1995) suggest, there is a need for "venturesome scientists who can work across disciplines to produce appropriate technologies and who have the charisma and courage to make their case with political leaders" to achieve success over time.

Successful efforts to improve agricultural production will also acknowledge the heterogeneity of production conditions throughout Africa and the many ways in which residents have adapted to those conditions over time. There are many examples of successful agricultural intensification that can provide insight to researchers and public officials (Widgren and Sutton, 2004). In most cases, indigenous knowledge and local institutions play important roles in determining resource allocation and shaping the incentives for farm-level investments. Political economy, sociology, and cultural anthropology have much to contribute when designing programs to motivate improvements in the use of water and fertilizer.

When thinking about opportunities for improving agricultural production in Africa, many writers recall the Green Revolution that gave rise to large increases in crop yields and farm output in Asia. It is helpful to recall that Asia's Green Revolution involved at least four major components (1) a comprehensive program of state, private, and market-driven efforts to encourage improvements in agricultural productivity; (2) a package of farm inputs that included hybrid varieties, fertilizer, and pesticides; (3) substantial public subsidies involving both inputs and outputs; and (4) supportive agroecological environments. Governments chose to support agricultural intensification in selected regions where the likelihood of success was quite high, such as the Indian states of Punjab and Haryana. The overarching goal in participating countries was to achieve national food security, which could be reached by focusing efforts on just a portion of each country's cultivated area (Akande et al., 2004; Djurfeldt et al., 2004b).

The initial conditions for improving agricultural production in Africa are substantially different than those that existed in Asia at the time of the Green Revolution. Agroecological conditions are more challenging in Africa, the rural population is more disperse, and there are fewer opportunities for developing large-scale irrigation schemes. Greater effort will be required to disseminate new production technologies and ensure that all farmers have access to complementary inputs. The extensive poverty in rural areas and the risk aversion that comes with low incomes will limit farm-level expenditures on yield-improving inputs. Government subsidies can motivate greater use of key inputs, as they did before implementation of structural adjustment programs in many countries.

When designing policy interventions, public officials seeking to stimulate agricultural production in Africa must acknowledge the important roles of agroecological systems, human capital, and institutions. There is substantial potential for improving productivity in Africa by closing large yield gaps in both rainfed and irrigated areas. The yield gaps exist in part because farmers cannot obtain or afford key inputs due to financial constraints, inadequate infrastructure, or lack of a viable input market. Yield gaps are caused also by inadequate knowledge or training regarding the use of key inputs, poor timing of application, and unexpected losses due to pests and weather events. The risk of such losses prevents many small-scale farmers from making the investments necessary to optimize the use of limited water and nutrients. Public policies that minimize the risk of financial losses in bad years, while not constraining revenue earned in good years, would encourage greater use of water, fertilizer, and other costly inputs.

Appropriate near-term policies include subsidies on agricultural inputs and fair prices for agricultural products, to stimulate increases in agricultural production. Over time, direct subsidies might be replaced or complemented by crop loss insurance programs that provide downside risk protection. Public investments in education, research, and training will have a greater long-term impact on agricultural production and rural livelihoods than will input subsidies, but subsidies might be needed in many areas to "get agriculture moving" in a positive direction soon. Subsidies can be combined with agricultural training and extension programs to increase the likelihood that inputs will be used correctly and that measures to improve water and nutrient efficiencies will be optimized.

Many readers of these recommendations will note the lack of specific, detailed policy initiatives. Africa is a vast continent with substantial variability in agroecological conditions, crop production potential, demographics, and political systems. General tenets pertaining to policy intervention seem more appropriate than specific prescriptions. Public officials in any country might begin by assessing the current state of agricultural production and marketing, with the goal of identifying primary constraints, risks, and opportunities. The analysis should be conducted from both public and private perspectives. Public officials might have a very different view of constraints and risks than would small-scale farmers who make decisions regarding inputs and outputs. Engaging farmers and representatives of farmer organizations in the evaluation process will enhance the value of the exercise.

Analysis should include evaluation of opportunities to improve the use of water and nutrients in both rainfed and irrigated areas. Describing yield gaps in both areas and identifying causal factors will be helpful in determining the best ways to invest limited public funds in efforts to close the yield gaps. In some countries, public investments in irrigation might be sensible, while in others it will be wiser to invest in research, education, or training to improve production in rainfed areas.

In all countries, it will be wise to maintain a broad, comprehensive view of policy alternatives and interactions involving inputs, products, and marketing opportunities. Farmers will invest effort in improving yields only if they perceive an incremental gain that exceeds their incremental costs. When crop prices are low or the likelihood of crop failure is high, farmers have little incentive to use fertilizer and other costly inputs. They also have little reason to improve their human capital if their long-term perspective includes low crop prices, high input prices, and substantial risk regarding crop production.

Farmers make many micro-economic decisions involving inputs, outputs, and marketing. Each of those decisions is influenced by macro-economic conditions and the agricultural policy environment. Public officials can contribute tremendously to improving agriculture in Africa by learning as much as possible about the micro-economics of farming, and using that knowledge to design appropriate agricultural policies and ensure a supportive macro-economic environment. Donor agencies and international research centers can help move the process forward by supporting studies that enhance understanding of farm-level production and marketing constraints, while also supporting policies and subsidies that reduce the farm-level risk of applying fertilizer and investing in improvements in water management.

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References

Akande, T., G. Djurfeldt, H. Holmén, and A.C. Isinika. 2004. Conclusions and a look ahead. In: G. Djurfeldt, H. Holmén, M. Jirström, and R. Larsson (Eds.), 2004a. *The African Food Crisis: Lessons From the Asian Green Revolution*. CABI Publishing, Wallingford, Oxon, U.K., 266 pages.

Becker, M. and D.E. Johnson, 2001. Improved water control and crop management effects on lowland rice productivity in West Africa. *Nutrient Cycling in Agroecosystems* 59:119-127.

Borlaug, N.E., 2003. Feeding a world of 10 billion people: The TVA/IFDC legacy. The Travis P. Hignett Memorial Lecture, Muscle Shoals, Alabama.

Borlaug, N.E. and C.R. Dowswell, 1995. Mobilising science and technology to get agriculture moving in Africa. *Development Policy Review* 13(2):115-129.

Breman, H., J.J.R. Groot, and H. van Keulen, 2001. Resource limitations in Sahelian agriculture. *Global Environmental Change* 11(1):59-68.

Djurfeldt, G., H. Holmén, M. Jirström, and R. Larsson (Eds.), 2004a. *The African Food Crisis: Lessons From the Asian Green Revolution*. CABI Publishing, Wallingford, Oxon, U.K., 266 pages.

Djurfeldt, G., H. Holmén, M. Jirström, and R. Larsson. 2004b. African food crisis – the relevance of Asian Experiences. In: G. Djurfeldt, H. Holmén, M. Jirström, and R. Larsson (Eds.), 2004a. *The African Food Crisis: Lessons From the Asian Green Revolution*. CABI Publishing, Wallingford, Oxon, U.K., 266 pages.

Field, W.P. 1990. World irrigation. *Irrigation and Drainage Systems* 4(2):91-107.

Food and Agriculture Organization of the United Nations (FAO), 2003. A perspective on water control in southern Africa: Support to regional investment initiatives. Land and Water Division Discussion Paper 1, Rome.

Frenken, Karen (Ed.), 2005. Irrigation in Africa in Figures: AQUASTAT Survey, 2005. FAO Water Reports 29. Food and Agriculture Organization of the United Nations, Rome.

Giller, K.E., E.C. Rowe, N. de Ridder, and H. van Keulen, 2006. Resource use dynamics and interactions in the tropics: Scaling up in space and time. *Agricultural Systems* 88:8-27.

Giordano, Mark, 2006. Agricultural groundwater use and rural livelihoods in sub-Saharan Africa: A first-cut assessment. *Hydrogeology Journal* 14:310-318.

Haile, Menghestab, 2005. Weather patterns, food security, and humanitarian response in sub-Saharan Africa. *Philosophical Transactions of the Royal Society B* 360:2169-2182.

Heerink, N., 2005. Soil fertility decline and economic policy reform in Sub-Saharan Africa. *Land Use Policy* 22(1):67-74.

Ingram, K.T., M.C. Roncoli, and P.H. Kirshen, 2002. Opportunities and constraints for farmers of west Africa to use seasonal precipitation forecasts with Burkina Faso as a case study. *Agricultural Systems* 74:331-349.

Isinika, A.C., G.C. Ashimogo, and J.E.D. Mlangwa, 2004. From Ujamaa to structural adjustment – agricultural intensification in Tanzania. In: G. Djurfeldt, H. Holmén, M. Jirström, and R. Larsson (Eds.), 2004. *The African Food Crisis: Lessons From the Asian Green Revolution*. CABI Publishing, Wallingford, Oxon, U.K., 266 pages.

Jayne, T.S., J. Govereh, A. Mwanaumo, J.K. Nyoro, and A. Chapoto, 2002. False promise or false premise? The experience of food and input market reform in eastern and southern Africa. *World Development* 30(11):1967-1985.

Jensen, J.R., R.H. Bernhard, S. Hansen, J. McDonagh, J.P. Moberg, N.E. Nielsen, and E. Nordbo, 2003. Productivity in maize based cropping systems under various soil-water-nutrient management strategies in a semi-arid, alfisol environment in East Africa. *Agricultural Water Management* 59(3):217-237.

Kelly, V., A.A. Adesina, and A. Gordon, 2003. Expanding access to agricultural inputs in Africa: a review of recent market development experience. *Food Policy* 28(4):379-404.

Lal, R., 1990. Low-resource agriculture alternatives in sub-Saharan Africa. *Journal of Soil and Water Conservation* 45(4):437-445.

Lal, R., 2000. Soil management in the developing countries. *Soil Science* 165(1):57-72.

Larsson, R., 2004. Crisis and potential in smallholder food production – evidence from micro level. In: G. Djurfeldt, H. Holmén, M. Jirström, and R. Larsson (Eds.), 2004. *The African Food Crisis: Lessons From the Asian Green Revolution*. CABI Publishing, Wallingford, Oxon, U.K., 266 pages.

Mati, B.M., 2005. Overview of water and soil nutrient management under smallholder rain-fed agriculture in East Africa. Working Paper 105, International Water Management Institute. Colombo, Sri Lanka.

Niemeijer, D., 1998. Soil nutrient harvesting in indigenous water harvesting in eastern Sudan *teras*. *Land Degradation & Development* 9:323-330.

Olouch-Kosura, W. and J.T. Karugia, 2004. Why the early promise for rapid increases in maize productivity in Kenya was not sustained: Lessons for sustainable investment in agriculture. In: G. Djurfeldt, H. Holmén, M. Jirström, and R. Larsson (Eds.), 2004. *The African Food*

Crisis: Lessons From the Asian Green Revolution. CABI Publishing, Wallingford, Oxon, U.K., 266 pages.

Oweis, T. and A. Hachum, 2006. Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. *Agricultural Water Management* 80(1):57-73.

Peden, D., A. Freeman, A. Astatke, and A. Notenbaert, 2005. Investment options for integrated water-livestock-crop production in sub-Saharan Africa. Final Report to the International Water Management Institute, Colombo, Sri Lanka.

Pereira, H.C., 1977. Land-use in semi-arid southern Africa. *Philosophical Transactions of the Royal Society of London* 278:555-563.

Plusquellec, H., 1990. The Gezira Irrigation Scheme in Sudan: Objectives, Design, and Performance. Technical Paper Number 120, The World Bank, Washington, D.C.

Polak, P. and R. Yoder, 2006. Creating wealth from groundwater for dollar-a-day farmers: Where the silent revolution and the four revolutions to end rural poverty meet. *Hydrogeology Journal* 14:424-432.

Reardon, T., V. Kelly, E. Crawford, T. Jayne, K. Savadogo, and D. Clay, 1997. Determinants of farm productivity in Africa: A synthesis of four case studies. Technical Paper Number 75, SD Publication Series, Bureau for Africa, U.S. Agency for International Development, Washington, D.C.

Rowe, E.C., M.T. van Wijk, N. de Ridder, and K.E. Giller, 2006. Nutrient allocation strategies across a simplified heterogeneous African smallholder farm. *Agriculture, Ecosystems and Environment*, forthcoming.

Sanders, J.H., J.G. Nagy, and S. Ramaswamy, 1990. Developing new agricultural technologies for the Sahelian countries: The Burkina Faso Case. *Economic Development and Cultural Change* 39(1):1-22.

Schnier, H.F., H. Recke, F.N. Muchena, and A.W. Muriuki, 1997. Towards a practical approach to fertilizer recommendations for food crop production in smallholder farms in Kenya. *Nutrient Cycling in Agroecosystems* 47:213-226.

Seckler, D., 1990. Private sector irrigation in Africa. In: S. Barghouti and G. Le Moigne (Eds.), 1990. Irrigation in Sub-Saharan Africa: The Development of Public and Private Systems. Technical Paper Number 123. The World Bank, Washington, D.C.

Seini, A.W. and V.K. Nyanteng, 2004. Smallholders and structural adjustment in Ghana. In: G. Djurfeldt, H. Holmén, M. Jirström, and R. Larsson (Eds.), 2004. *The African Food Crisis: Lessons From the Asian Green Revolution*. CABI Publishing, Wallingford, Oxon, U.K., 266 pages.

Shapiro, B.I. and J. H. Sanders, 1998. Fertilizer use in semiarid West Africa: Profitability and supporting policy. *Agricultural Systems* 56(4):467-482.

Sivakumar and Salaam, 1999. Effect of year and fertilizer on water-use efficiency of pearl millet (*Pennisetum glaucum*) in Niger. *Journal of Agricultural Science* 132:139-148.

Stige, L.C., J. Stave, K. Chan, L. Ciannelli, N. Pettorelli, M. Glantz, H.R. Herren, and N.C. Stenseth, 2006. "The effect of climate variation on agro-pastoral production in Africa. *Proceedings of the National Academy of Sciences* 103(9):3049-3053.

Underhill, H.W., 1990. Small scale irrigation in Africa in the context of rural development. Cranfield Press, Bedford, United Kingdom, 90 pages.

Voortman, R.L., B.G.J.S. Sonneveld, and M.A. Keyzer, 2003. African land ecology: Opportunities and constraints for agricultural development. *Ambio* 32(5):367-373.

Widgren, M. and J.E.G. Sutton, 2004. *Islands of Intensive Agriculture in Eastern Africa*. Eastern African Studies, Great Britain, 160 pages.

de Wit, M. and J. Stankiewicz, 2006. Changes in surface water supply across Africa with predicted climate change. *Science* 311:1917-1921.

Zektser, I.S. and L.G. Everett (Eds.), 2004. Groundwater resources of the world and their use. IHP-VI. Series on Groundwater Number 6. UNESCO, Paris.

Table 1.
Estimated annual water withdrawals for agriculture, municipalities, and industry in seven regions of Africa

Region	Volume Withdrawn (million m3)	Proportion of African Withdrawals (%)	Allocation Among Sectors		
			Agriculture (%)	Municipalities (%)	Industry (%)
Northern	93,889	43.7	85	9	6
Sudano-Sahelian	54,948	25.6	95	4	1
Gulf of Guinea	12,395	5.8	71	20	9
Central	1,993	0.9	56	32	12
Eastern	14,215	6.6	88	11	1
Southern	21,657	10.1	70	24	6
Indian Ocean Islands	15,717	7.3	94	4	2
Africa	**214,814**	**100.0**	**86**	**10**	**4**

Source: Frenken, 2005. Page 24, Table 9.

Table 2.

Estimated areas under water management in seven regions of Africa

Region	Area Under Water Management (hectares)	Area Under Water Management (%)	Category of Water Management: Irrigated (%)	Wetlands and Valleys (%)	Flood Recession (%)
Northern	6,339,756	41.2	100	0	0
Sudano-Sahelian	2,945,290	19.1	89	2	9
Gulf of Guinea	1,443,777	9.4	39	14	47
Central	455,939	3.0	29	71	0
Eastern	849,338	5.5	73	27	0
Southern	2,253,837	14.6	91	8	1
Indian Ocean Islands	1,117,653	7.3	99	0	1
Africa	**15,405,590**	**100.0**	**87**	**7**	**6**

Source: Frenken, 2005. Page 27, Table 11.

Table 3.

Areas under irrigation by type of irrigation and region of Africa

Region	Area Under Irrigation		Category of Water Management		
			Full or Partial Control	Spate Irrigation	Equipped Lowlands
	(ha)	(%)	(ha)	(ha)	(ha)
Northern	6,339,756	47.2	6,230,706	109,050	0
Sudano-Sahelian	2,619,950	19.5	2,098,238	299,520	222,192
Gulf of Guinea	565,257	4.2	360,088	0	205,169
Central	132,439	1.0	125,652	2,800	3,987
Eastern	616,143	4.6	593,103	0	23,040
Southern	2,063,427	15.3	1,962,902	0	100,525
Indian Ocean Islands	1,107,903	8.2	1,107,903	0	0
Africa	**13,444,875**	**100.0**	**12,478,592**	**411,370**	**554,913**
Proportion (%)	**100**		**93**	**3**	**4**

Source: Frenken, 2005. Page 27, Table 12.

Table 4.

Cultivable, cultivated, and irrigated areas, by region in Africa

Region	Cultivable Area (ha)	Cultivated Area (ha)	Proportion of Cultivable Area (%)	Area with Any Irrigation (ha)	Proportion of Cultivated Area (%)
Northern	65,320,000	28,028,178	42.9	6,339,756	22.6
Sudano-Sahelian	208,256,000	38,764,012	18.6	2,619,950	6.8
Gulf of Guinea	119,860,000	54,964,000	45.9	565,257	1.0
Central	173,060,000	21,303,000	12.3	132,439	0.6
Eastern	82,853,400	30,869,000	37.3	616,143	2.0
Southern	113,678,650	32,950,000	29.0	2,063,427	6.3
Indian Ocean Islands	8,307,000	3,795,000	45.7	1,107,903	29.2
Africa	**771,335,050**	**210,673,190**	**27.3**	**13,444,875**	**6.4**

Source: Frenken, 2005. Page 13, Table 1.

Table 5.
Estimated irrigation potential in Africa, by major river basin

Basin	Irrigation Potential (ha)	Proportion of Africa's Potential (%)	Regions
Congo/Zaire	9,800,000	23.1	Central, Eastern, Southern
Nile	8,000,000	18.8	Northern, Sudano-Sahelian, Central, Eastern
Niger	2,816,510	6.6	Northern, Gulf of Guinea, Central, Sudano-Sahelian
Zambezi	3,160,380	7.4	Central, Southern, Eastern
Lake Chad	1,163,200	2.7	Northern, Central, Sudano-Sahelian, Gulf of Guinea
Rift Valley	844,010	2.0	Sudano-Sahelian, Eastern
Senegal	420,000	1.0	Gulf of Guinea, Sudano-Sahelian
Volta	1,487,000	3.5	Gulf of Guinea, Sudano-Sahelian
Orange-Sengu	390,000	0.9	Southern
Shebelle-Juba	351,460	0.8	Sudano-Sahelian, Eastern
Limpopo	295,400	0.7	Southern
Okavango	208,060	0.5	Central, Southern
South Interior	54,000	0.1	Central, Southern
North Coast	2,199,050	5.2	Northern, Sudano-Sahelian, Eastern
West Coast	6,268,650	14.7	Sudano-Sahelian, Gulf of Guinea, Central, Southern
South Coast	1,584,200	3.7	Southern
Cenetral East Coast	1,927,460	4.5	Sudano-Sahelian, Eastern, Southern
Madagascar and Islands	1,534,990	3.6	Indian Ocean Islands
Africa	**42,504,370**	**100**	
Source:	Frenken, 2005. Page 26, Table 10.		

Table 6.
Irrigation methods by region of Africa

Region	Area with Full or Partial Control (ha)	Surface Irrigation (ha)	Surface Irrigation (%)	Sprinkler Irrigation (ha)	Sprinkler Irrigation (%)	Localized Irrigation (ha)	Localized Irrigation (%)
Northern	6,230,706	4,925,733	79.1	923,583	14.8	381,390	6.1
Sudano-Sahelian	2,098,238	2,090,384	99.6	7,654	0.4	200	0.0
Gulf of Guinea	360,088	311,348	86.5	47,220	13.1	1,520	0.4
Central	125,652	120,221	95.7	5,430	4.3	1	0.0
Eastern	593,103	522,520	88.1	68,571	11.6	2,012	0.3
Southern	1,962,902	732,710	37.3	1,022,358	52.1	207,834	10.6
Indian Ocean Islands	1,107,903	1,086,413	98.1	19,468	1.8	2,022	0.2
Africa	**12,478,592**	**9,789,329**	**78.4**	**2,094,284**	**16.8**	**594,979**	4.8

Source: Frenken, 2005. Page 28, Table 13.

Table 7.
Source of water for irrigation, by region of Africa

Region	Area with Full or Partial Control (ha)	Surface Water (ha)	Surface Water (%)	Groundwater (ha)	Groundwater (%)	Mix of Surface and Groundwater (ha)	Mix of Surface and Groundwater (%)
Northern	6,230,706	4,138,685	66.4	1,839,494	29.5	25,000	0.4
Sudano-Sahelian	2,098,238	1,986,450	94.7	111,788	5.3	0	0.0
Gulf of Guinea	360,088	230,432	64.0	122,285	34.0	7,371	2.0
Central	125,652	125,652	100.0	0	0.0	0	0.0
Eastern	593,103	446,920	75.4	146,183	24.6	0	0.0
Southern	1,962,902	1,715,995	87.4	246,849	12.6	58	0.0
Indian Ocean Islands	1,107,903	1,102,528	99.5	5,375	0.5	0	0.0
Africa	**12,478,592**	**9,746,662**	**78.1**	**2,471,974**	**19.8**	**32,429**	0.3

Note: An estimated 227,527 ha in the Northern Region are irrigated with treated wastewater.
Source: Frenken, 2005. Page 29, Table 14.

Table 8. Crop yields on farm fields and a research station in the Gezira Irrigation Scheme, 1982 to 1983

Crop	Farm Fields (t/ha)	Research Station (t/ha)	Ratio of Station to Farm
Cotton	0.95	3.10	3.26
Wheat	0.85	3.57	4.20
Sorghum	1.20	4.75	3.96
Groundnut	1.43	5.24	3.66

Source: Plusquellec, 1990.

Table 9. Mean yields of maize, sorghum, and paddy reported by Djurfeldt et al. (2004a) in their study of crop production in eight countries, 2000 to 2002

	Maize		Sorghum		Paddy	
Country	Three Seasons Mean Yield (t/ha)	5% Best Performing Farmers' Yield (t/ha)	Three Seasons Mean Yield (t/ha)	5% Best Performing Farmers' Yield (t/ha)	Three Seasons Mean Yield (t/ha)	5% Best Performing Farmers' Yield (t/ha)
Ethiopia	1.2	4.0	1.1	2.4	n	n
Ghana	1.2	5.2	0.5	1.3	1.0	2.8
Kenya	1.6	4.7	n	n	n	n
Malawi	0.9	2.2	n	n	0.7	1.9
Nigeria	1.8	3.4	1.2	2.0	2.2	3.4
Tanzania	1.0	2.6	n	n	1.6	4.2
Uganda	1.5	4.4	n	n	1.5	4.5
Zambia	1.1	2.8	0.6	1.7	n	n

Notes: Yields above 10 t/ha for maize, 3 t/ha for sorghum, and 8 t/ha for paddy have been excluded when calculating mean values.
The letter 'n' denotes no data, or not applicable.

Source: Tables 7.2 through 7.4 in Larsson, 2004.

Table 10. Summary of yield gaps observed by Djurfeldt et al. (2004a), in 2000 to 2002

Crop	Mean Yield (t/ha)	Potential Yield (t/ha)	Yield Gap (%)
Maize	1.3	3.4	-60.3
Cassava	5.4	14.0	-57.6
Sorghum	0.9	1.8	-53.5
Rice	1.4	3.6	-58.9

Source: Table 7.5 in Larsson, 2004.