15 Towards a Better Understanding of Biophysical Determinants of Yield Gaps and the Potential for Expansion of the Rice Area in Africa

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Introduction

Rice is grown in diverse environments in Africa, and this is reflected in farmers' yields. These range from less than 1 t/ha in low-input, rainfed systems to more than 9 t/ha in high-input, irrigated systems. As highlighted by Seck *et al.* (Chapter 2, this volume), Africa's rice production needs to be augmented substantially to reduce the current heavy reliance on imports.

Increasing rice production is possible through increasing rice yield per unit of land and through expansion of rice harvested area. To raise rice productivity per unit of land, there is a need to better understand which biophysical factors limit productivity in farmers' fields, and to what extent productivity could be increased via improved crop management. 'Potential yield' is defined as the **maximum** yield that can be obtained from a crop in a given environment as determined by simulation models with plausible physiological and agronomic assumptions (Evans and Fischer, 1999). Under irrigated conditions, potential yield is determined by climate (solar radiation and temperature), varietal characteristics and crop establishment methods including sowing date and density. Under rainfed conditions, potential yield is also affected by water availability.

Validated crop-simulation models are rarely available in Africa and, if they are, input values to run them, such as long-term weather data, are usually lacking. A proxy for potential yield can be the maximum yield obtained with good agricultural practices in an experimental field or in a high-yielding farmer's field. The 'yield gap' is defined as the difference between potential yield and average on-farm yield obtained by farmers (Becker *et al.*, 2003). Several 'yield gaps' can be defined (Fig. 15.1). Because of diminishing returns on investment, yields in farmers' fields do not in general exceed 80% of the potential yield estimated by validated simulation models.

A good understanding of potential yield and yield gaps enables us to identify opportunities for yield improvement in farmers' fields.

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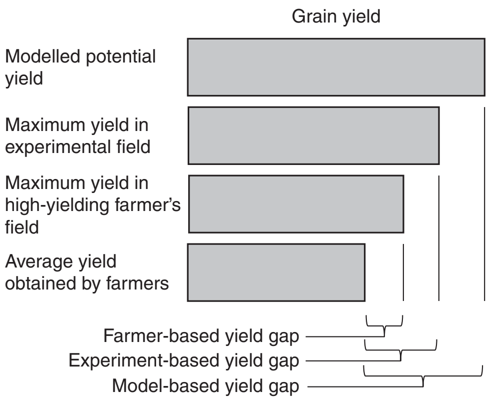

Fig. 15.1. Framework for estimation of yield gap based on three different potential yields (model-based, experimental field maximum and on-farm maximum). (Adapted from Lobell *et al.*, 2009.)

Closing these yield gaps may require adoption of alternative crop management practices or capital investment in, for example, bunding, land levelling or irrigation. To determine which of these alternative crop management or investments is needed, it is necessary to understand the biophysical determinants of rice productivity. What are the major yield-limiting factors (e.g. drought or excess water, nutrient deficiencies, and extreme temperature) and yield-reducing factors (e.g. insects, diseases, weeds, birds)? This type of information can be obtained via detailed studies in farmers' fields (often referred to as 'yield gap surveys'), as demonstrated by (e.g.) Wopereis *et al.* (1999) and Becker *et al.* (2003) for irrigated rice systems in West Africa. A complementary 'diagnostic survey' can provide information on, for example, production orientation (subsistence, market), household wealth, access to input and output markets, and access to rice knowledge and technologies. Combining information from the two surveys allows us to develop pathways to raise rice productivity in a sustainable manner.

In this chapter, we provide an overview of rice production systems in Africa and their distribution as a function of spatial variability of climate (agroecological zones) and soils on the continent. We also discuss the current status of knowledge with respect to spatial variability of disease epidemics. Climate factors such as temperature, humidity and rainfall strongly affect rice production through indirect effects on the incidence of pests and diseases. Next we discuss the current status of knowledge about rice yield gaps in Africa. We analyse the potential to enhance rice production in Africa by increasing rice harvested area (by bringing more land under cultivation or by increasing cropping intensity) and approaches to identify 'best-bet areas' for expansion. We conclude with a discussion of the challenges that hinder a better overview of determinants of yield gaps and areas with the best potential for sustainable expansion of rice harvested area in Africa.

Rice production systems

In Africa, five major rice production systems are distinguished: rainfed upland, rainfed lowland, irrigated lowland, deep water and mangrove swamp; the last two are of relatively minor importance in terms of surface area (Maclean *et al.*, 2002; Balasubramanian *et al.*, 2007; Seck *et al.*, 2012). New estimates of surface area under each rice production system are provided by Diagne *et al.* (Chapter 3, this volume).

Rice fields are usually flooded during part or all of the growing season, except in the case of rainfed upland rice. Surface-water regimes and water sources (e.g. irrigation, rainfall, water table) distinguish the rice-production systems.

- Irrigated lowland rice is generally grown in bunded fields with assured irrigation for one or two crops per year. Dam-based irrigation, water diversion from rivers, and pump irrigation from wells are major sources of irrigation water.
- Rainfed lowland rice is grown on level to slightly sloping, unbunded or bunded fields in lower parts of the toposequence and in inland valleys, which are defined as flat-floored, relatively shallow valleys and are widespread in the undulating landscape (see Rodenburg, Chapter 22, this volume). Fields are flooded by rains and groundwater for part of the rice-growing season, although in some seasons fields may not be flooded due to lack of rainfall. Rainfed lowland rice is also grown in flash-flood areas, where water level is suddenly increased during the

rice-growing season, causing short-term submergence. A fuzzy transition exists between rainfed and irrigated lowland rice production systems, where a water-management continuum exists ranging from strictly rainfed (no water control) to fully irrigated lowlands, which may evolve with investments in water-control measures.

- Deep-water rice production systems are found in the flood plains along the major rivers such as the Niger River, inland valleys, and coastal wetlands (Kawano and Sakagami, 2008). In the 'floating-rice' area, water depth remains high (up to 3 m) for an extended period (up to 5 months). In the 'deep-water' rice area, water remains in the fields for several months, but water is not as deep as in the floating-rice area. Rice varieties that are 140–180 cm tall are required for this system.
- Rice fields in the mangrove-swamp production system are located on tidal estuaries close to the sea. Rice can be grown during the period when freshwater floods wash the land and displace tidal flows. Tall rice varieties or varieties adapted to flash flooding are grown in this system.
- Rainfed upland rice is generally grown on level or sloping, unbunded fields. Flooding is rare in this system. In some cases (e.g. Uganda) supplementary irrigation may be used.

Distribution of Rice Production Systems in Relation to Agroecological Zones in Africa

You *et al.* (2009a,b) provide estimates of crop production, area and yield for 10 km ×10 km grid cells for 20 crops, including rice, based on downscaling from sub-national production, statistical or survey data by taking other spatial data such as land use, population density and crop suitability into account. Plate 6 shows the distribution of rice-production systems in Africa classified as: (i) rainfed, high-input/commercial; (ii) rainfed, low-input/subsistence; and (iii) irrigated, following the definition of global agroecological zones developed by the Food and Agriculture Organization of the United Nations and the International Institute for Applied Systems Analysis (FAO and IIASA, 2000). The distribution was calculated from sub-national production data in 2000; updated data are not yet available. Data on rice cultivation at sub-national scale are not available in Balasubramanian *et al.* (2007), Seck *et al.* (2012), FAOSTAT (http://faostat.fao.org/) or Diagne *et al.* (Chapter 3, this volume), and so could not be used in our assessment. Rice areas described in this chapter refer to areas where rice was cultivated in the particular system in 2000. If rice was grown and harvested more than once in the year, the physical area is not increased.

Rainfed, high-input/commercial systems use high-yielding varieties and some animal traction and mechanization (FAO and IIASA, 2000). Farmers apply some fertilizer and use pesticides. This system is not widespread in Africa, but can be found in countries such as Côte d'Ivoire, Madagascar and Uganda. The rainfed, low-input/subsistence system uses traditional varieties and mainly manual labour without (or with little) application of fertilizer or pesticides. This classification does not distinguish between rainfed lowland and upland rice systems.

The irrigated system refers to rice areas provided with either full or partial irrigation infrastructure. In general, modern varieties and relatively high fertilizer inputs are used, together with advanced management options such as soil- and water-conservation measures.

Rice is grown in 15 of the 16 agroecological zones distinguished in Africa (HarvestChoice, 2009) (Plate 7; Table 15.1). These agroecological zones are grouped according to temperature (tropical or sub-tropical), elevation (warm or cool) and moisture (arid, semiarid, sub-humid and humid) as explained in the footnote to Table 15.1. Thus, these groups include climate factors that strongly affect rice growth through direct effects on physiological processes and through indirect effects on the incidence of pests and diseases.

In West Africa, the terms 'Sahel', 'Sudan savannah', 'Guinea savannah' and 'Equatorial forest' are frequently used for agroecological zoning (e.g. Windmeijer and Andriesse, 1993; Defoer *et al.*, 2004). In this chapter, 'Sahel' is 'tropical – warm / arid'; 'Sudan savannah' is 'tropical – warm / semiarid'; 'Guinea savannah' is 'tropical – warm / sub-humid'; and 'Equatorial forest' is 'tropical – warm / humid'.

Table 15.1. Estimated share (%) of rice area by agroecological zone and production system in Africa in 2000. (Spatial analysis of data from HarvestChoice, 2009; You *et al.*, 2009a,b.)

Agroecological zone[a]	Rainfed, low-input/ subsistence rice system	Rainfed, high input/ commercial rice system	Irrigated rice system	Total
Tropical – warm / humid	11	1	4	16
Tropical – warm / sub-humid	36	2	11	49
Tropical – warm / semiarid	10	0.3	7	17
Tropical – warm / arid	0.3	0.1	1	2
Tropical – cool / humid	1	0.2	1	2
Tropical – cool / sub-humid	4	0.1	1	5
Tropical – cool / semiarid	0.2	0	<0.1	0.2
Tropical – cool / arid	<0.1	0	<0.1	<0.1
Sub-tropical – warm / humid	<0.1	0	0	<0.1
Sub-tropical – warm / sub-humid	<0.1	0	0.1	0.1
Sub-tropical – warm / semiarid	<0.1	0	<0.1	<0.1
Sub-tropical – warm / arid	<0.1	0	8	8
Sub-tropical – cool / humid	0	0	0	0
Sub-tropical – cool / sub-humid	<0.1	0	<0.1	<0.1
Sub-tropical – cool / semiarid	<0.1	0	0	<0.1
Sub-tropical – cool / arid	<0.1	0	<0.1	<0.1
Total	62	4	34	100

[a]'Tropical': monthly temperature adjusted to sea level greater than 18°C for all months; 'Sub-tropical': monthly temperature adjusted to sea level less than 18°C for one or more months.
'Cool': elevation greater than 1200 m in the tropical zone and greater than 800 m in the sub-tropical zone; otherwise classified as 'warm'.
'Arid': less than 70 days of growing period, which is defined as the period during the year when average temperatures are greater than or equal to 5°C and rainfall plus moisture stored in the soil exceed half the potential evapotranspiration; 'semiarid': 70–180 day growing period; 'sub-humid': 180–270 day growing period; 'humid': growing period more than 270 days.

Spatial analyses of agroecological zones and rice-distribution data (Plates 6 and 7) show that the largest proportion of rice area (49% of total) is within the tropical – warm / sub-humid zone, while 17% is within the tropical – warm / semiarid zone and 16% is in the tropical – warm / humid zone (Table 15.1). In the humid, sub-humid and semiarid zones, rainfed rice systems occupy a larger area than irrigated rice-production systems. Irrigated rice-production systems are dominant in the arid zone, with 8% (of the total rice area) in the sub-tropical – warm / arid zone and 1% in the tropical – warm / arid zone. Tropical – cool / humid and sub-humid zones (elevation greater than 1200 m) have 7% of the total rice area.

Rainfed low-input/subsistence rice farming is practised on 62% of the total rice surface area in Africa, while 34% is irrigated rice areas and 4% is rainfed, high-input/commercial systems. The latter includes not only tropical – warm / sub-humid in West Africa, but also 'Other zones including all the production systems' in the other regions (Table 15.2). The total area for irrigated rice is higher than the 26% reported by Diagne *et al.* (Chapter 3, this volume), probably as a result of the fact that the data were collected in different years and using different collection methods.

In West and East Africa, the tropical – warm / sub-humid zone has the largest share of rice area in both irrigated and rainfed, low-input systems, followed by tropical – warm / semiarid zone in West Africa and tropical – warm / humid zone (irrigated rice) and tropical – cool / sub-humid zone (rainfed, low-input) in East Africa (Table 15.2). The estimated share of irrigated rice in the tropical – warm / arid zone in West Africa is small (1%). In North Africa, the sub-tropical – warm / arid zone is restricted to Egypt. The rainfed, low-input system in tropical – warm / humid zone is predominant in Central Africa, including the Democratic Republic of Congo (DRC).

Table 15.2. Estimated distribution of rice area by region, agroecological zone and production system in Africa in 2000. (Spatial analysis of data from HarvestChoice, 2009; You *et al.*, 2009a,b.)

Agroecological zone	Production system	Rice area (×1000 ha) in 2000	Estimated share (%) of rice area in Africa
West Africa[a]			
Tropical – warm / sub-humid	Rainfed, low-input	1973	26
Tropical – warm / semiarid	Rainfed, low-input	619	8
Tropical – warm / sub-humid	Irrigated	423	6
Tropical – warm / humid	Rainfed, low-input	380	5
Tropical – warm / semiarid	Irrigated rice	366	5
Tropical – warm / sub-humid	Rainfed, high-input	101	1
Tropical – warm / arid	Irrigated	94	1
Other zones including all the production systems		138	2
Subtotal		4093	55
North Africa[b]			
Sub-tropical – warm / arid	Irrigated	610	8
Other zones including all the production systems		31	0.4
Subtotal		642	9
East Africa[c]			
Tropical – warm / sub-humid	Rainfed, low-input	584	8
Tropical – warm / sub-humid	Irrigated	423	6
Tropical – warm / humid	Irrigated	262	3
Tropical – cool / sub-humid	Rainfed, low-input	196	3
Tropical – warm / humid	Rainfed, low-input	157	2
Tropical – warm / semiarid	Irrigated	123	2
Tropical – cool / humid	Irrigated	94	1
Tropical – cool / sub-humid	Irrigated	90	1
Other zones including all the production systems		245	3
Subtotal		2174	29
Central Africa[d]			
Tropical – warm / humid	Rainfed, low-input	279	4
Tropical – warm / sub-humid	Rainfed, low-input	141	2
Other zones including all the production systems		170	2
Subtotal		590	8
Southern Africa[e]			
Subtotal		1	<0.1
Total		7500	100

[a]West Africa: Benin, Burkina Faso, Côte d'Ivoire, The Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone and Togo.
[b]North Africa: Algeria, Egypt, Morocco, Sudan (now Sudan and South Sudan) and Tunisia.
[c]East Africa: Burundi, Comoros, Eritrea, Ethiopia, Kenya, Madagascar, Malawi, Mozambique, Rwanda, Somalia, Tanzania, Uganda and Zambia.
[d]Central Africa: Angola, Cameroon, Central African Republic, Chad, Congo, DRC and Gabon.
[e]Southern Africa: Lesotho, Namibia, South Africa, Swaziland and Zimbabwe.

Distribution of Rice Production Systems in Relation to Soil Constraints

African soils generally have inherently poor fertility as they are old, often strongly weathered and leached (Bationo *et al.*, 2006). Furthermore, inadequate land-use and crop-management practices have led to increased soil erosion and depletion of nutrients and, consequently, a decline in rice productivity (Becker and Johnson, 2001a). In all rice-production systems, soil-related abiotic stresses may occur in rice (Defoer *et al.*, 2004; Balasubramanian *et al.*, 2007). In this section, we present a quantitative characterization of soil fertility within rice-growing environments in Africa. The approach follows that of Haefele and Hijmans (2007), who studied rainfed lowland rice in Asia, by combining spatial databases of soils and rice area. Soil information was derived from the digital version of the Soil Map of the World (FAO, 1995), and we used four soil groups with different levels of soil fertility and severity of soil constraints based on the interpretation of the modifiers of the soil fertility capability classification (FCC) system (Sanchez and Buol, 1985). The following are descriptions of the four soil-fertility groups (Haefele and Hijmans, 2007).

- **Good, fertile soils with no major soil constraints:** topsoils not designated with any of the FCC modifiers h, k, e, a, i, s, c, O, n or b (see below). Absence of modifiers a, h and b indicates soil pH values in the optimum range between 6.0 and 7.3. Soils included here might be designated with the FCC modifiers x (volcanic materials) or v (vertic soil properties). Soils in this group have a range of indigenous soil fertility, but are generally less weathered than the next two soil groupings.
- **Poor soils with no major soil constraints:** topsoils are designated with no FCC modifier other than h (10–60% Al saturation of the effective CEC or pH between 5 and 6). Crop growth is not limited by any major soil constraint, although severe P deficiency may occur. However, the acid soil reaction and the high Al saturation indicate highly weathered soils with limited indigenous nutrient supply and low nutrient-retention capacity.
- **Very poor soils with considerable soil constraints:** topsoils are designated with one or several of the FCC modifiers k (<10% weatherable minerals in silt and sand fraction or exchangeable K <0.20 meq per 100 g soil), e (effective CEC <4 meq per 100 g soil), a (>60% Al saturation) or i (percentage of free Fe_2O_3 divided by percentage clay >0.15, and more than 35% clay or hues of 7.5 YR [yellow–red] or redder, and granular structure). Crop growth on these soils is potentially limited by combinations of low nutrient reserves (k), low CEC (e), Al toxicity (a) and high P fixation (i). Generally, these are highly weathered soils with very limited indigenous nutrient supply, low nutrient-retention capacity, frequent and often severe P deficiency, acidic to very acidic soil reaction (pH <5), and Fe and Al toxicities.
- **Problem soils:** topsoils are designated with the FCC modifiers s (saline soils), c (acid-sulfate soils), O (organic soils), n (sodic soils) or b (alkaline soils). Crop growth on these soils is likely to be limited by salinity (s), very low pH, P deficiency, and Fe, S or Al toxicity (c), nutrient deficiencies of N, Zn, K, P, Cu and Mo (O), or high pH and P, Fe, Zn deficiency (n, b).

Comparative distribution of rice areas by soil-fertility group for temperature zones (sub-tropical / tropical), elevation zone (warm / cool), moisture zone (humid / sub-humid / semiarid / arid), and production system (irrigated rice / rainfed, high-input / rainfed, low-input) is presented in Table 15.3.

The sub-tropical zone is characterized by either good or problem soils, with virtually nothing in between (Table 15.3). In contrast, problem soils are uncommon in the tropical zone, where poor and very poor soils predominate. The arid zone is also characterized by high percentages of good and problem soils. Good and poor soils are common in the semiarid zone, whereas the sub-humid zone has large areas of poor and very poor soils. Very poor soils are widespread in the humid zone.

Irrigated systems have higher percentages of good and problem soils than rainfed systems, and lower proportions of poor and very poor soils. About 67% and 25% of problem soils are designated with the FCC modifiers s (saline soils) and n (sodic soils), respectively, which are therefore more common than those designated with other FCC modifiers (c, O and b: 0.4–12%). When the distribution of rice areas by soil-fertility group is compared among Africa, South-east Asia and South Asia, the rainfed, low-input system in Africa tends to have poorer soils than the rainfed lowland systems in South Asia, but comparable soil fertility to rainfed lowland systems in South-east Asia.

Distribution of rice areas by soil-fertility group for the different regions, agroecological

Table 15.3. Comparative distribution of rice areas by soil-fertility group for temperature zone (sub-tropical / tropical), elevation zone (warm / cool), moisture zone (humid / sub-humid / semiarid / arid) and production system (irrigated rice / rainfed, high-input / rainfed, low-input). (Spatial analysis of data from FAO, 1995; HarvestChoice, 2009; You *et al.*, 2009a,b.)

	Estimated share (%)			
Zone / system	Good soils	Poor soils	Very poor soils	Problem soils
Temperature				
Sub-tropical	52	1	1	46
Tropical	21	32	43	5
Elevation				
Warm	23	30	38	9
Cool	22	20	55	3
Moisture				
Humid	7	19	73	1
Sub-humid	20	35	41	4
Semi-arid	35	38	16	10
Arid	53	1	4	42
Production system				
Irrigated rice	30	25	27	18
Rainfed, high-input	9	29	60	2
Rainfed, low-input	21	31	45	3
Rainfed lowland in South-east Asia[a]	25	18	47	10
Rainfed lowland in South Asia[a]	45	33	14	8

[a]Source: Haefele and Hijman (2007). Data on intermediate and shallow rainfed rice areas were combined.

zones and production systems is given in Table 15.4. Very poor soils are dominant in the humid and sub-humid zones. In the arid and semiarid zones, very poor soils account for less than 20%. High percentages of problem soils (>20%) are found in the irrigated rice system in the arid zone in West and North Africa, and more than 70% of them are designated with the FCC modifier s (saline soils). These findings are consistent with previous reports, which showed that rice productivity is limited by salinity in these areas (FAO, 2002; Defoer *et al.*, 2004). There is a high percentage of problem soils (26%) in the irrigated rice system in the tropical – warm / semiarid zone in East Africa, and 77% of these are designated with the FCC modifier n (sodic soils).

As soil tests commonly used for nitrogen are insufficiently reliable to be used as FCC parameters (Sanchez *et al.*, 2003; Haefele and Hijmans, 2007), nitrogen deficiencies could not be included as soil constraints in our spatial analysis. However, soils without major nutrient limitations will likely develop nitrogen deficiency in continuous cropping systems without nutrient inputs, and nitrogen deficiency may cause other nutrient deficiencies (Sanchez *et al.*, 2003). Many previous studies in both lowland and upland conditions across all agroecological zones in West Africa have shown substantial increases in rice yield in response to nutrient inputs via inorganic nitrogen fertilizer or legumes grown before rice cultivation, although response to nitrogen inputs is highly variable, depending on (e.g.) rice growing condition, variety used, production systems (e.g. Becker and Johnson, 1998, 2001a,b; Wopereis *et al.*, 1999; Akanvou *et al.*, 2000; Becker *et al.*, 2003). Indigenous soil nitrogen supply limited rice yield in most cases. See also Haefele *et al.* (Chapter 20, this volume).

At the landscape level (e.g. watershed), natural resources (particularly water and soil resources) are strongly correlated with their position in the toposequence (Andriesse and

Table 15.4. Estimated share of rice physical area by region, agroecological zone, production system and soil-fertility group. Estimated share with >1% of total rice physical area is presented.

		Estimated share (%)			
Agroecological zone	Production system	Good soils	Poor soils	Very poor soils	Problem soils
West Africa					
Tropical – warm / sub-humid	Rainfed, low-input	19	40	40	1
Tropical – warm / semiarid	Rainfed, low-input	34	43	15	9
Tropical – warm / sub-humid	Irrigated	13	54	27	6
Tropical – warm / semiarid	Irrigated	40	37	11	13
Tropical – warm / humid	Rainfed, low-input	12	19	68	1
Tropical – warm / sub-humid	Rainfed, high-input	12	33	52	3
Tropical – warm / arid	Irrigated	59	0.3	19	22
North Africa					
Subtropical – warm / arid	Irrigated	52	1	1	46
East Africa					
Tropical – warm / sub-humid	Rainfed, low-input	25	30	38	7
Tropical – warm / sub-humid	Irrigated	20	24	43	13
Tropical – warm / humid	Rainfed, low-input	10	20	70	0.5
Tropical – warm / humid	Irrigated	4	32	63	0.5
Tropical – cool / sub-humid	Rainfed, low-input	35	18	40	7
Tropical – warm / semiarid	Irrigated	30	18	26	26
Tropical – cool / humid	Irrigated	5	25	69	0.3
Tropical – cool / sub-humid	Irrigated	15	30	54	1
Central Africa					
Tropical – warm / humid	Rainfed, low-input	2	4	93	1
Tropical – warm / sub-humid	Rainfed, low-input	13	7	77	2

Fresco, 1991; Windmeijer and Andriesse, 1993). In inland valley systems, soil fertility tends to improve as one moves down the slope to the valley bottom, calling for soil-fertility recommendations at the plot level that differ with toposequence position, such as proposed for farming systems in South-east Asia (e.g. Homma *et al.*, 2003). Such variations strongly affect rice-cropping systems, farmers' crop and varietal choices, and rice productivity (Andriesse and Fresco, 1991; Audebert *et al.*, 1999; Touré *et al.*, 2009). These variations could not be captured in the work reported in this chapter.

Mapping Potential Epidemics of Rice Diseases

Climate factors such as temperature, humidity and rainfall strongly affect rice production through indirect effects on the incidence of pests and diseases. Savary *et al.* (2012) developed global risk maps of potential epidemics involving five rice diseases, using a simple generic model 'EPIRICE'. Diseases considered were leaf blast, brown spot, bacterial blight, sheath blight and tungro virus (which occurs only in Asia). The following is a summary of the results for Africa.

- High potential risk areas for leaf blast epidemics in Africa include West Africa (e.g. Guinea, Liberia, Nigeria, Sierra Leone), Central Africa (e.g. Cameroon, Gabon), and East Africa (e.g. western Tanzania, Madagascar, the Ethiopian highlands).
- Potential epidemics of brown spot and bacterial blight in Africa have similar patterns, and high-risk areas for both are in the humid and sub-humid zones of West Africa.
- Simulation predicted potential sheath blight epidemics in the humid and sub-humid zones of West Africa, Central Africa (e.g. Cameroon, Gabon), and in eastern Madagascar.
- Tungro virus has not been reported in Africa as there is no vector. However, tungro

potential epidemics were simulated in humid and sub-humid zones in West Africa and Madagascar, indicating that, should the vector become established in these areas, there is a potential risk of tungro occurring.

Although Savary *et al.* (2012) indicate that more research is needed to improve the EPIRICE model, this fairly crude information suggests where major epidemics may be expected and thus where research efforts need to be focused. The humid and sub-humid zones of West Africa are areas at risk of epidemics of all the diseases included in the analysis. Madagascar is also prone to rice disease epidemics. Such areas will need more attention to develop integrated crop-health management strategies for avoiding disease epidemics. At the landscape level (e.g. watershed), the occurrence and intensity of biotic stresses also differs within the toposequence (Defoer *et al.*, 2004), so the results of the model will need to be validated through field observations on disease incidence and impact on yield.

Analysing Rice Yield Gaps in Rice-growing Environments in Africa

While agroecological zoning and soil mapping in relation to rice distribution provide useful information, these approaches are not directly linked to rice productivity. In this section, we describe crop models for estimating potential yield, and review previous 'yield gap surveys' in major rice-production systems in Africa.

Estimating potential yield using crop-simulation models

Combining crop-simulation models, which simulate crop phenology, growth and yield, with geographic information systems (GIS) is a potentially powerful approach to estimate potential yield as well as characterize rice-growing environments in Africa. However, past simulation efforts for rice in Africa have focused mainly on the potential yield of irrigated lowland rice in arid and semiarid environments in West Africa (tropical – warm / arid and tropical – warm / semiarid zones), where diurnal and seasonal variation in temperature is a major determinant of rice production (Dingkuhn and Sow, 1995). Dingkuhn and Sow (1995) identified areas where there is potential risk of spikelet sterility occurring due to extreme (high and low) temperatures. In addition to this model (ORYZA_S), several other models have been used for simulating potential yield of irrigated and rainfed lowland rice in Africa (Sheehy *et al.*, 2004; Hijmans and Serraj, 2008).

Hijmans and Serraj (2008) used the ORYZA2000 model (Bouman *et al.*, 2003) to determine relative yield reduction of rainfed lowland rice attributable to drought stress, using the weather database of the US National Aeronautics and Space Administration (NASA) Langley Research Center Atmospheric Sciences Data Center POWER (Prediction Of Worldwide Energy Resource) Project, and estimated planting date for each degree resolution, and some soil parameters including water table depth and percolation rate, with global coverage. The results showed that although variation in relative yield reduction is large across areas with similar total rainfall during the rice-growing season, relative yield reduction is negatively related to total rainfall during the rice-growing season. Rainfed lowland rice production is considered possible only with total rainfall above 450 mm. When total rainfall during rice growing season is 750–850 mm, relative yield reduction (median value) is about 50%. East African countries (except for Madagascar) tend to have a larger yield reduction than West African countries (except for areas where rice cannot be grown without irrigation, such as in the tropical – warm / arid zone).

If suitable crop-simulation models are developed or adapted for Africa, high-quality long-term climate data at coarse resolution for use as input for such models are commonly lacking. This will constrain GIS-based assessment of growth environments using crop models. Satellite-based climate data, such as Hijmans and Serraj (2008) used, can be useful as an alternative for the assessment. However, while ground-based and NASA satellite-based data were correlated, there were differences in climatic parameters between them (Yang *et al.*, 2007; White *et al.*, 2008; Bai *et al.*, 2010).

These differences are due to the fact that both data sources have inherent errors and uncertainties. Errors related to ground-based parameters include poor maintenance of climate-observation facilities, resulting in inadequate data. Uncertainties related to satellite-based parameters include pixel size, sensor resolution, navigation time, algorithm accuracy and geographical coincidence of instantaneous information recorded by a satellite with measurements on the ground (Bai *et al.*, 2010). If there are no long-term ground-based data or a lot of missing data, the use of relationships between ground-based and NASA satellite-based data may be a means for estimating missing ground-based data to be used in crop-simulation models.

Yield gaps and determinants in major rice production systems

Becker *et al.* (2003) reported that average on-farm yields of irrigated lowland rice in different agroecological zones in West Africa range from 3.4 t/ha to 5.4 t/ha, and potential yields range from 6.9 t/ha to 9.8 t/ha. The potential yield is highest in the Sahel zone (Senegal) and lowest in the humid forest zone (Côte d'Ivoire). The yield gaps range from 3.2 t/ha to 5.9 t/ha, showing considerable scope for increasing yields.

Becker and Johnson (1999) conducted surveys in irrigated systems of the forest zone of Côte d'Ivoire. Yields varied between 0.2 t/ha and 7.3 t/ha, with average yields of 3.2 t/ha under partial irrigation and 4.2 t/ha in fully irrigated systems. Age of seedlings at transplanting, timeliness of operations and application of P fertilizer explained 60% of observed variability.

Wopereis *et al.* (1999) highlighted the low recovery rates of fertilizer N applied to the crop in farmers' fields in irrigated systems in Burkina Faso, Mali and Senegal. Farmers can, therefore, improve efficiency and profitability by improving the recovery rate of applied nutrients, especially N, through better crop management in general, without major increases in investment in fertilizers. The most important constraints that resulted in low N recovery rates were (Wopereis *et al.*, 1999): timing of N fertilizer application not coincident with critical growth stages of the rice plant; use of relatively old (>40 days) seedlings at transplanting; unreliable irrigation water supply; weed problems; and late harvesting (Senegal River delta). Haefele *et al.* (2000, 2001) showed that rice yields in farmers' fields in Mauritania and Senegal could be raised by 2 t/ha through improved weed and soil-fertility management.

Potential yields of irrigated lowland rice in Madagascar are estimated at about 11.4–14.9 t/ha (Sheehy *et al.*, 2004), while on-farm yields range from 2.6 t/ha to 9.9 t/ha (Tsujimoto *et al.*, 2009), which suggests yield gaps range from 1.5 t/ha to 12.3 t/ha. While yield-gap studies have not been carried out for irrigated lowland rice in other East and North African countries, trials managed by researchers achieved more than 11 t/ha in Egypt and Kenya, and more than 9 t/ha in Mozambique (Matsushima *et al.*, 1994; Namba, 2003, 2005; Menete *et al.*, 2008). Thus, potential rice yields in Egypt, Kenya and Madagascar seem to be higher than those in West Africa.

Studies in West Africa show average farm yields for rainfed lowland rice range from 1.0 t/ha to 2.2 t/ha (Becker and Johnson, 2001b). Given that potential yields of rainfed lowland rice are assumed to be similar to those of irrigated lowland rice, the yield gaps are 4.8–7.6 t/ha (Becker and Johnson, 2001b; Becker *et al.*, 2003). Becker and Johnson (2001b) studied the effects of improved water control and crop management on lowland rice productivity in West Africa. Retaining flood water with field bunds increased rice yield by about 40% and improved weed control (about 25% less weed biomass in bunded than in open plots). Application of mineral fertilizer N increased rice yields by almost 20% in bunded fields, but resulted in no increase in open fields. Land levelling together with bunding facilitated improved water management which decreased weed growth and increased nutrient use efficiencies.

Rice yield measurements for rainfed upland rice, including intensive and extensive systems, showed a range in farmers' fields of 0.8–1.6 t/ha (Becker and Johnson, 2001a). While potential yields have not been estimated for upland rice in Africa, trials managed by researchers have given rice yields of 4.0–5.6 t/ha with nutrient input and also with supplementary irrigation in two of five studies (Dingkuhn *et al.*, 1998; Oikeh *et al.*, 2008; Ekeleme *et al.*, 2009; Saito and Futakuchi, 2009; Kamara *et al.*, 2010). Thus, yield gaps also appear to be high under rainfed upland conditions, but not as large as those under irrigated and rainfed lowland conditions. Becker and Johnson (2001a) showed that increased cropping intensity and reduced fallow duration were associated with yield reduction: intensification-induced yield loss was about 25% (a drop from an average of 1.5 t/ha to 1.1 t/ha) and was mainly related to increased weed infestation and declining soil quality.

Few of these yield-gap surveys quantified losses due to biotic stresses with the exception of weeds. More information on potential losses due to biotic stresses in rice fields in Africa can be found in Chapters 16 (weeds), 17 (diseases), 18 (insect pests) and 19 (birds).

There is a dearth of up-to-date information on magnitude and determinants of yield gaps across major rice-production regions in Africa. The yield-gap surveys mentioned above were mainly conducted in the 1990s and crop models available at the time were only validated for irrigated growing conditions in West Africa. Diagne *et al.* (Chapter 4, this volume) provide information on losses due to biotic and abiotic stresses based on farmer perceptions of the occurrence and relative importance of the stresses from a survey conducted in 2009 in several African countries.

In 2011, the Africa Rice Center (AfricaRice) launched the Africa-wide Rice Agronomy Task Force, a collaborative effort of (initially) 15 African countries, to be expanded gradually to include at least all of AfricaRice's member countries. The Task Force has launched a collective effort to analyse major determinants of rice productivity in different rice systems through yield-gap and diagnostic surveys.

Potential for Sustainable Expansion in Rice Harvested Area

In terms of the potential for expansion of cultivated area and increased production, lowlands or wetlands show the greatest promise, with an estimated total of 239 million ha across sub-Saharan Africa (Andriesse, 1986). Less than 5% of the lowlands are currently planted with rice (Balasubramanian *et al.*, 2007). Wetlands can be defined as areas where the soil is saturated with water either permanently or seasonally. The wetlands of sub-Saharan Africa include coastal plains, including deltas, estuaries and tidal flats; inland basins, comprising extensive drainage depressions; river flood plains, consisting of recent alluvial deposits bordering rivers; and inland valleys. Inland valleys are known as *dambos* in East and Central Africa, *fadamas* in northern Nigeria and Chad, *bas-fonds* or *marigots* in francophone countries, and 'inland valley swamps' in Sierra Leone (Andriesse, 1986).

There is a large untapped potential for irrigation in Africa, extending to about 24 Mha or 1.8 times greater than the existing irrigation area (You *et al.*, 2011; Fig. 15.2). Nigeria has the largest potential for large- and small-scale irrigation investments, with about 5.7 Mha, followed by Benin, Guinea, Mozambique, Uganda and Tanzania, which each have more than 1 Mha potential. There is an estimated further 2 Mha of irrigated land that could be rehabilitated. Algeria, Egypt, Somalia and Sudan (now Sudan and South Sudan) share more than 70% (about 1.5 Mha) of disused irrigated area (i.e. that could be rehabilitated) (You *et al.*, 2009c); with the exception of Egypt, rice production is not popular in these countries. Water scarcity is a constraint to rice production in Egypt. Double cropping of rice is often possible with the introduction of irrigation, which can augment the rice harvest area. However, introducing intensive rice cultivation using irrigation may increase water scarcity in the future. Proper land-development and crop-management practices are essential for sustaining productivity of irrigated lowland rice systems.

The above assessment of irrigation potential could be used to guide the distribution of investment funds across countries (You *et al.*, 2009c, 2011). But, as the next step, in-depth local-level assessments are essential. AfricaRice has started using remotely sensed imagery and advanced algorithms to map inland valleys at national level. This technology allows more precise estimation of the total area of inland valleys using a standardized method and also mapping of their exact location. The methodology that has been developed and is being evaluated uses a digital elevation model (DEM). The DEM is generated using stereo-pair images collected by the Advanced Spaceborne Thermal Emission and

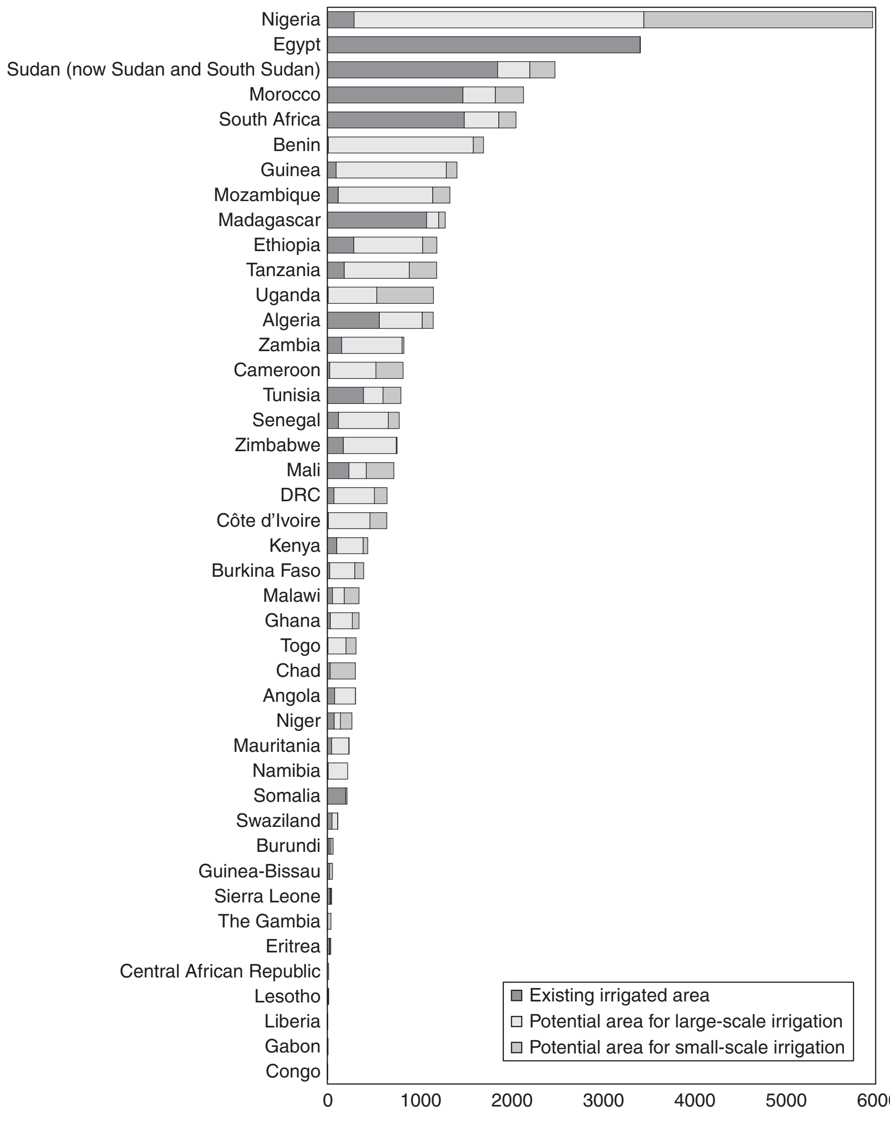

Fig. 15.2. Existing irrigated area and irrigation potential in Africa. (From You *et al.*, 2011, with permission from Elsevier.) The countries in footnotes in Table 15.2 are included except for Comoros and Rwanda. Definitions of large-scale and small-scale irrigation refer to You *et al.* (2011).

Reflection Radiometer (ASTER) instrument – a joint project of NASA and the Ministry of Economy, Trade and Industry (METI) of Japan – on-board the Terra satellite. These images, which have a spatial resolution of 30 m and 1 m accuracy, are freely available for download. The algorithm follows two steps: first, the streams are determined from the DEM using a standardized procedure in ArcGIS; second, a calculation procedure creates transects along each section of the stream. The elevation of the stream is assessed (in metres above sea level) and the areas along the transect that have the same elevation (±2 m) are identified as the inland valley. The procedure has been applied for Benin and Togo, and validated with a digital map of inland valleys from the IMPETUS (An Integrated Approach to the Efficient Management of Scarce Water Resources in West Africa) project (Giertz *et al.*, 2008). The first findings are shown in Plate 8 (A–D). Initial results show the majority of inland valleys to be well mapped, but modifications are required in the algorithm to improve mapping of first-order inland valleys.

Expansion of upland rice areas for increasing rice production may be possible in Africa, through replacing (or rotating with) other upland crops or growing rice in more favourable uplands, where there is sufficient rainfall (low risk of drought for rice cultivation) or supplementary irrigation available. Even in these cases, crop-rotation systems with other crops such as legumes, fallowing or crop–livestock systems is essential for sustainable production, as continuous rice cropping tends to reduce rice yield and sustainability. (See also Haefele *et al.*, Chapter 20, this volume.)

Conclusions

The rice-growing environments in Africa are highly diverse. Rainfed, low-input systems account for more than 60% of the total rice area. In West and East Africa, which have larger rice areas than the other regions, the tropical – warm / sub-humid zone is predominant for irrigated rice and rainfed, low-input rice production systems, whereas in North Africa irrigated rice is grown in the sub-tropical – warm / arid zone. Extreme temperature is an important abiotic constraint to rice production in tropical – warm / semiarid and arid zones in West Africa (high and low temperature) and in the highlands of East Africa (low temperature). In rainfed systems, drought risk is likely to be high in East Africa; the spatial and temporal effects of drought, flooding or a combination of the two needs to be analysed by taking into account local geo-morphological and hydrological information, as well as farmers' rice-cropping practices. Potential yields tend to be higher in East and North Africa than in West Africa. A high percentage of problem (mainly saline and sodic) soils is found in irrigated rice systems in arid and semiarid zones; however, soil constraints in general are more common in humid and sub-humid zones than in arid and semiarid zones across West, Central and East Africa. Epidemics of major diseases are expected to occur in humid and sub-humid zones in West Africa and Madagascar. This information is a first step towards determining research priorities and targeting development and diffusion of rice technologies for each region or country.

The mapping of potential pest epidemics did not cover biotic stresses such as *Rice yellow mottle virus*, or potential outbreaks of insect pests. In the upland production system, stem borers, rice bugs, nematodes and termites are important biotic stresses, while in lowland systems, African rice gall midge and *Rice yellow mottle virus* are also important. Rodents and birds are other major biotic stresses occurring across rice-production systems (Balasubramanian *et al.*, 2007; de Mey and Demont, Chapter 19, this volume; Diagne *et al.*, Chapter 4, this volume). Moreover, problems with weeds are extremely common across major rice-production systems (Rodenburg and Johnson, 2009; Rodenburg and Johnson, Chapter 16, this volume; Diagne *et al.*, Chapter 4, this volume). However, knowledge of the spatial and temporal extent and severity of these biotic stresses is still limited. Thus, further research is needed to determine where, when and how rice production might be affected by biotic constraints in Africa in the future.

In this chapter, we describe the GIS-based characterization of rice-growing environments and potential irrigation areas at the continental or regional level, and promising results for the identification of inland valleys through satellite imagery. However, these will need to be complemented with data and analyses of socio-economic factors such as distance to markets, road conditions and land-tenure issues (Erenstein *et al.*, 2006; You *et al.*, 2011).

More work is clearly needed in developing crop-simulation models that work for African growth conditions. Combined with locally collected data on crop management practices, such models are expected to facilitate estimation of exploitable yield- and water-productivity gaps, identification of risks of outbreaks of pests and diseases, and identification of regions with the greatest potential for enhanced rice production and expansion of rice-cropped area – all issues that are of great importance to Africa's food security.

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Figure 15.2 is reprinted from *Food Policy*, volume 36, L. You, C. Ringler, U. Wood-Sichra, R. Robertson, S. Wood, T. Zhu, G. Nelson, G. Zhe and S. Yan, 'What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach', pages 770–782, Copyright (2011), with permission from Elsevier.

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