3 Estimation of Cultivated Area, Number of Farming Households and Yield for Major Rice-growing Environments in Africa

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Introduction

Rice is an extremely versatile crop which can grow under a range of water regimes (in dry- and wetland conditions) and temperatures (at low and high altitudes and latitudes) (Seck *et al.*, 2012; Saito *et al.,* Chapter 15, this volume). The various rice environments are characterized mainly by the main source of water for the plant – for example, rainfall (direct rainfall and/or inflow), irrigation (water controlled through a system of canals, etc.), water table, uncontrolled flood water, and sea/brackish water. This has led to the distinguishing of rainfed upland, rainfed lowland, irrigated upland, irrigated lowland, mangrove-swamp and deep-water environments. Taking other environmental factors into account, a more detailed classification of rice environments is possible; for instance, 'high-altitude rainfed upland rice' versus 'low-altitude rainfed upland rice' (see Saito *et al.,* Chapter 15, this volume).

Figure 3.1 depicts in a schematic manner the three major rice-growing environments in Africa: upland (excluding hydromorphic fringes, see below), rainfed lowland (inclusive of hydromorphic fringes) and irrigated lowland (WARDA, 2004).

Upland environments are situated at the high end of the toposequence, where rice depends solely on rainfall as the water table is out of the reach of rice roots for much of the growing season. At the lower end of the toposequence, rice plants can reach the water table or profit directly from flood water. Along the toposequence, interactions exist between environments (e.g. water and nutrient flow from upland to lowland). These externalities influence the environmental sustainability of rice farming. Furthermore, interlinkages can blur the boundaries between rice environments, as in the hydromorphic zones, between the upland and lowland areas, which rather than being flooded for long periods have a water table close enough to the surface for rice roots to reach during the growing season. Another unclear transition exists between rainfed and irrigated lowlands, where a continuum of water management exists ranging from the strictly rainfed (no water control or only drainage), which may evolve (via investments in water control measures) to the fully irrigated lowlands. In this chapter, lowlands with partial water control (intensified lowland) are classified as rainfed lowland environments.

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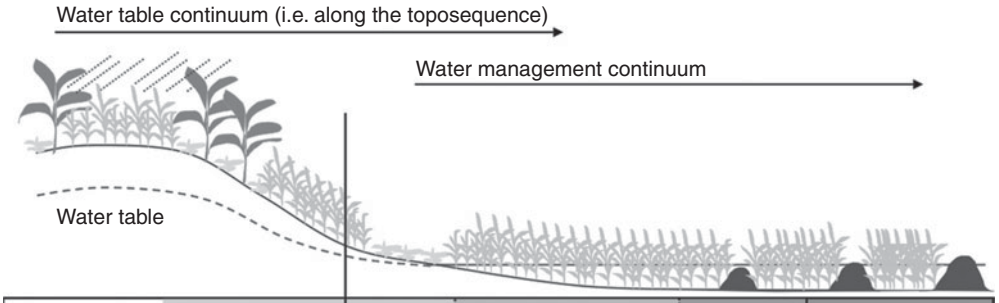

Ecology	Upland	Lowland fringe (hydromorphic)	Lowland	Intensified lowland	Irrigated lowland
Main water supply	Rainfall	Rainfall + water table	Rainfall + water table + unregulated flood water	Regulated flood water	Irrigation
Agroecological zone	Guinea savannah–humid forest zone	Guinea savannah–humid forest zone	Sudan savannah to humid forest zone	Sudan savannah to humid forest zone	Sahel to humid forest zone
Main stresses	Drought Weeds Pests and diseases P and N deficiency Soil erosion Soil acidity	Drought Weeds Pests and diseases P and N deficiency Soil erosion Soil acidity Fe toxicity	Drought/flooding Weeds Pests and diseases P and N deficiency Fe toxicity	Drought/flooding Weeds Pests and diseases P and N deficiency Fe toxicity	Weeds Pests and diseases Salinity Alkalinity P and N deficiency Fe toxicity

Fig. 3.1. Major rice environments and their attributes in Africa. (Adapted from WARDA, 2004, reproduced with permission from Africa Rice Center.)

Within each environment, rice is produced as part of a wide range of production systems (Saito *et al.,* Chapter 15, this volume). The heterogeneity and the close interaction of rice production with other farm and off-farm activities highlight the need for technical components that can be readily used by producers to build more integrated production systems. The search for greater integration is above all a search for greater resource use efficiency through the creation of positive interactions within rice production systems, and between rice and other farm and non-farm activities. Seen in this way, the focus on integrated production systems encompasses many of the concerns associated with natural-resources management.

Country-based information on potential and actual rice cultivation areas in each rice environment is useful to prioritize rice research and development because of the differences in farming practices and productivity among environments. In this chapter, we estimate actual rice cultivation areas and farming population by rice environment in Africa as of 2009, based on survey data and secondary data from country publications and FAOSTAT (2012).

Methodology

The level of detail in the information available on rice cultivation areas in Africa varies among countries. Estimates of total annual rice harvested area are provided by FAOSTAT (2012) for most rice-producing countries in Africa. The United States Department of Agriculture (USDA) provides similar statistics for many African countries. Unfortunately, these total area estimates are not disaggregated by rice-growing environment.[1] Here, we use farm-household survey data from the rice statistics survey conducted by Africa Rice Center (AfricaRice) and its national (NARS) partners in 2009 (AfricaRice, 2010) to estimate the total cultivated rice area by rice-growing environment in Africa.[2] Because

of differences in the classification of rice-growing environments between countries, we use four environments in our study: irrigated, (rainfed) upland, (rainfed) lowland and 'other'. All rice-growing environments found in the countries and described using different terminologies which may vary from one country to another were reclassified into these four environments in order to obtain consistent estimates and meaningful comparison across countries (Table 3.1). For the purpose of the estimation, we classified the countries into four groups on the basis of the source of the data used to do the estimation (see Table 3.2 for the country groupings).

In the first two groups of countries (Table 3.2), the estimations of total rice area and number of farming households were based exclusively on data from the rice statistics survey database. For the first group, the data includes the population inflation weights used to obtain the national-level estimates from the sample estimates of the average total household rice area by environment and the distribution of rice-farming households by rice environment (see Appendix for details). These survey population weights[3] are missing from the survey data for the second group of countries. To obtain the national values from the sample estimates for the second group of countries, we used total national rice area from the 2009 rice statistics divided by the average household rice area to derive the total number of rice-farming households in the country. From this estimate and the average rice area by environment, we used the sample distribution of rice-farming households by rice environment to obtain estimates of the total number of rice-farming households and total rice areas by environment per country.

The third group comprises seven country members of the Coalition for African Rice Development (CARD), which were also part of the 2009 rice statistics survey. These countries also had missing survey population extrapolation weights. In addition, these countries did not have estimates of total rice cultivated area in their country reports. Thus, we used the information on rice area and production by rice environment for 2008 available in their National

Table 3.1. Classification of rice-growing environments by country in the rice statistics survey. (Modified from AfricaRice, 2011.)

Countries[a]	Irrigated	Lowland	Other
Benin, Burkina Faso, Cameroon, CAR, Côte d'Ivoire, DRC, Ghana, Guinea, Kenya, Madagascar, Nigeria, Rwanda, Tanzania	Irrigated lowland Upland with supplementary irrigation	Lowland Hydromorphic[b] Upland with groundwater[b]	Mangrove Other
The Gambia	Irrigated Upland with supplementary irrigation	Lowland Upland with groundwater	Mangrove
Mali	Irrigated	Lowland	
Senegal	Irrigated Upland with supplementary irrigation	Lowland Upland with groundwater	Mangrove
Sierra Leone		Inland-valley swamp Boliland[c]	Mangrove Other
Togo	Irrigated Upland with supplementary irrigation	Lowland Upland with groundwater	
Uganda	Irrigated Upland with supplementary irrigation	Lowland Hydromorphic[b] Upland with groundwater[b]	

[a]CAR, Central African Republic; DRC, Democratic Republic of Congo.
[b]Hydromorphic and upland with groundwater share the same definition, but the NARS partners differentiated them in the survey.
[c]Boliland is lowland where flooded conditions continue for 2–4 months in a year.

Table 3.2. Distribution of rice area by rice environment in Africa (2009).

		Distribution of area by rice environment (ha)				
Group[a]	Country	Irrigated	Upland	Lowland	Other	All
Group 1	Guinea	52,526	532,329	381,756	39,211	1,005,822
	Nigeria	86,079	557,256	1,032,935	219,427	1,895,697
	Senegal	94,185	36,178	43,948	0	174,311
	Sierra Leone	0	453,531	117,720	28,266	599,517
Group 2	Benin	4,798	10,407	23,552	0	38,757
	Burkina Faso	13,328	16,022	61,743	0	91,093
	Cameroon	25,212	60,926	19,635	0	105,773
	Kenya	17,521	449	414	0	18,384
	Togo	3,689	4,345	27,876	0	35,910
	Mali	335,269	174,747	134,851	0	644,867
	Madagascar	782,487	78,439	322,688	0	1,183,614
	Côte d'Ivoire	37,110	615,325	314,863	973	968,271
Group 3	CAR	377	18,310	2,731	373	21,791
	DRC	71,910	248,485	28,021	23,378	371,794
	The Gambia	27,916	19,350	25,231	7,013	79,510
	Ghana	24,496	8,126	129,533	2,485	164,640
	Rwanda	14,433	0	0	0	14,433
	Tanzania	254,679	9,382	677,806	571	942,438
	Uganda	361	65,790	72,109	0	138,260
Group 4	Mozambique	72,684	36,182	73,954	0	182,820
	Liberia	7,433	143,662	82,013	0	233,108
	Ethiopia	6,313	3,852	2,811	155	13,131
	Zambia	6,724	4,696	11,775	6	23,201
	Chad	51,579	51,961	37,734	2,075	143,349
	Niger	5,023	4,279	4,727	797	14,826
	Guinea-Bissau	8,479	38,025	47,521	11,042	105,067
	Mauritania	7,261	1,630	4,779	0	13,670
	Egypt	518,520	12,935	12,810	31,203	575,468
	Morocco	6,392	160	172	1,076	7,800
	Algeria	63	43	35	8	149
	Angola	4,023	4,153	6,036	0	14,212
	Burundi	18,585	1,258	7,778	0	27,621
	Comoros	12,001	4,314	6,266	0	22,581
	Republic of Congo	207	1,028	1,008	469	2,712
	Gabon	80	253	258	84	675
	Malawi	17,951	9,678	28,338	52	56,019
	Somalia	1,890	1,142	710	102	3,844
	South Africa	378	114	572	0	1,064
	Sudan[b]	2,529	2,285	1,438	206	6,458
	Zimbabwe	117	55	145	0	317
Total Africa		2,594,608	3,231,102	3,748,292	368,970	9,942,974
Total Africa (%)		26	32	38	4	100

[a]Group 1: countries with all data including sampling weights; Group 2: countries with full information on total rice area and farmers' distribution across rice-growing environments from rice statistics survey data 2009; Group 3: countries with full information on total rice area from NRDS 2008 data, distributions across rice-growing environments and average rice area by environment from rice statistics survey data 2009; Group 4: countries with total rice in 2009 from FAOSTAT (2012), farmers' distribution and average area by rice-growing environment predicted using spatial econometrics.

[b]Including what is now South Sudan.

Rice Development Strategies (NRDS) and followed the same estimation procedure as for the countries in the second group.

Countries in the fourth group are the remaining rice-producing countries in Africa which were not covered by the 2009 rice statistics survey.[4] For this group, we first used the 2009 rice statistics survey data of the first three groups of countries and the GIS coordinates at the third level of administrative sub-division in the country to estimate a spatial forecasting model based on the universal kriging interpolation method (Calder and Cressie, 2009). We then used the estimated model parameters to predict the average total household rice area and proportion of rice-farming households in each rice-growing environment for all the countries in the fourth group. And, finally, we used the 2009 total country rice harvested areas from FAOSTAT (2012), which we multiplied by the predicted averages and proportions to estimate the total rice area and number of rice-farming households in 2009 for each rice environment for each country in this fourth group (see Appendix for more details).

Rice yields per rice environment were estimated for countries covered by the 2009 rice statistics survey (Groups 1, 2 and 3). These yields were obtained by dividing total rice production by the total rice-cropped area of the household.

Results

The estimated rice areas disaggregated by country and by rice environment are shown in Table 3.2. The estimated total number of rice-farming households by rice-growing environment are presented in Table 3.3, but will not be discussed as the trends are the same as for the area estimates. The total rice area harvested in Africa in 2009 is estimated at 9,942,974 ha. Countries with high total rice areas (500,000 ha or more) are Nigeria (1,895,697 ha), Guinea (1,005,822 ha), Madagascar (1,183,614 ha), Côte d'Ivoire (968,271 ha), Tanzania (942,438 ha), Mali (644,867 ha), Sierra Leone (599,517 ha) and Egypt (575,468 ha). The disaggregation by rice environment shows rainfed lowland (3,748,292 ha) and upland (3,231,102 ha) to be the dominant environments with 38% and 32% of the total rice areas, respectively. The total area under irrigation is estimated at 2,594,608 ha, which represents about 26% of the total rice area on the continent. The other rice-growing environments are estimated to occupy only 4% of the total rice area.

The total cultivated rice area estimated for 2009 in this study is 4.5% higher than the estimated 9,514,792 ha for 2008 (Seck *et al.*, 2012). This may be due to differences in the reference years or that Seck *et al.* (2012) used a different methodology to estimate the total area.[5] When the estimates from the two studies are compared country by country, the most important **increases** in the estimated total rice areas are for Côte d'Ivoire (568,271 ha, +142%), The Gambia (45,510 ha, +134%), Cameroon (55,772 ha, +112%), Mozambique (72,820 ha, +66%), Senegal (48,982 ha, +39%), Mali (162,315 ha, +34%) and Tanzania (232,437 ha, +33%). Substantial **decreases** in the estimated total rice area are also recorded in three of the major rice-producing countries in Africa: Sierra Leone (400,483 ha, –40%), Nigeria (486,304 ha, –20%) and Egypt (169,923 ha, –23%).

Table 3.4 presents average paddy rice yield per rice environment as obtained from the survey data of countries in Groups 1, 2 and 3. These yields were obtained at the household level by dividing total household rice production by total household rice-cropped area and then averaged across the country.

Highest country average household rice yields (per season) were in Rwanda, Mali, Cameroon, Senegal and Nigeria. These relatively high yields are due to the high yield in irrigated growing environment, except for Nigeria and Cameroon where lowland yields exceed irrigated ones. The highest national average yields were recorded in Rwanda (4.43 t/ha), Mali (4.01 t/ha) and Senegal (3.90 t/ha) for irrigated environments and in Cameroon (3.20 t/ha) and Nigeria (3.02 t/ha) for lowlands. Countries with lowest rice yields across rice environments include the Central African Republic, the Democratic Republic of Congo and Sierra Leone.

Table 3.5 gives estimates for rice yields in irrigated environments in the Sahel–savannah and sub-humid agroecological zones. Sahel–savannah irrigated zones occur throughout The Gambia and Mali, and in the extreme north of Benin; the Sahel

Table 3.3. Number of rice-farming households by rice environment in Africa (2009).

		Distribution of rice-farming households by rice-growing environment (number)				
Group[a]	Country	Irrigated	Upland	Lowland	Other	All
Group 1	Guinea	39,911	522,917	297,555	26,518	886,901
	Nigeria	16,557	135,186	262,379	42,448	456,570
	Senegal	93,468	30,315	44,960	0	168,743
	Sierra Leone	0	400,906	97,307	24,880	523,093
Group 2	Benin	8,594	20,033	43,765	0	72,392
	Burkina Faso	13,256	25,750	123,251	0	162,257
	Cameroon	21,778	63,229	23,503	0	108,511
	Kenya	7,107	273	195	0	7,575
	Togo	3,631	5,603	29,517	0	38,751
	Mali	162,425	146,654	59,399	0	368,478
	Madagascar	669,254	107,771	389,329	0	1,166,354
	Côte d'Ivoire	27,480	493,906	287,929	1,297	810,612
Group 3	CAR	633	36,470	6,554	633	44,290
	DRC	61,199	261,946	40,774	21,466	385,385
	The Gambia	13,060	5,803	8,708	2,281	29,852
	Ghana	6,580	2,709	32,353	621	42,263
	Rwanda	55,648	0	0	0	55,648
	Tanzania	125,563	3,044	251,506	380	380,493
	Uganda	1,098	109,127	133,852	0	244,077
Group 4	Mozambique	37,986	23,287	42,094	0	103,367
	Liberia	4,644	104,174	56,688	0	165,506
	Ethiopia	3,836	2,207	1,554	251	7,848
	Zambia	3,887	3,001	5,799	534	13,221
	Chad	38,326	38,268	23,366	1,441	101,401
	Niger	1,901	2,205	1,577	316	5,999
	Guinea-Bissau	8,593	34,193	30,393	9,650	82,829
	Mauritania	5,943	1,092	3,087	0	10,122
	Egypt	864,200	9,097	9,097	27,291	909,685
	Morocco	9,541	106	106	848	10,601
	Algeria	50	28	22	6	106
	Angola	2,250	2,802	3,535	0	8,587
	Burundi	20,757	569	4,727	0	26,053
	Comoros	6,457	2,910	4,213	0	13,580
	Congo	138	750	822	382	2,092
	Gabon	49	173	170	55	447
	Malawi	10,276	5,857	14,111	2,708	32,952
	Somalia	1,484	796	493	74	2,847
	South Africa	173	73	299	0	545
	Sudan[b]	2,046	1,607	1,000	151	4,804
	Zimbabwe	60	36	80	0	176
Total Africa		2,349,839	2,604,873	2,336,069	164,231	7,455,012
Total Africa (%)		32	35	31	2	100

[a]Group 1: countries with all data including sampling weights; Group 2: countries with full information on total rice area and farmers' distribution across rice-growing environments from rice statistics survey data 2009; Group 3: countries with full information on total rice area from NRDS 2008 data, distributions across rice-growing environments and average rice area by rice-growing environment from rice statistics survey data 2009; Group 4: countries with total rice area from FAOSTAT (2009), farmers' distribution and average area by rice-growing environment predicted using spatial econometrics.

[b]Including what is now South Sudan.

Table 3.4. Average rice yield (t/ha) by rice environment for countries in Groups 1, 2 and 3 (2009).

	Irrigated			Upland			Lowland			Other		
Country	n	Mean	SD	n	Mean	SD	n	Mean	SD	n	Mean	SD
Benin	41	2.07	0.9	75	1.51	0.8	159	1.83	0.8	0	–	–
Burkina Faso	51	2.21	1.4	99	1.73	1.2	455	1.71	1.1	0	–	–
Cameroon	227	1.94	1.2	659	2.95	1.4	245	3.20	1.4	0	–	–
Côte d'Ivoire	39	1.68	0.7	665	1.22	0.6	389	1.61	0.7	2	1.10	0.1
The Gambia	62	2.16	2.0	25	1.70	1.8	39	1.28	0.6	11	1.30	0.0
Ghana	78	1.60	0.7	32	1.01	0.4	394	1.16	0.6	8	1.00	0.4
Guinea	53	1.24	0.4	601	1.12	0.4	357	1.10	0.4	32	1.09	0.3
Kenya	226	1.53	0.9	13	1.25	0.5	9	1.29	1.1	0	–	–
Madagascar	446	1.69	1.0	70	1.04	0.7	257	1.71	0.9	0	–	–
Mali	618	4.01	1.4	558	2.33	1.0	226	2.85	1.8	0	–	–
Nigeria	244	2.24	1.6	1815	1.44	0.8	3448	3.02	2.1	973	2.55	1.2
CAR	7	0.49	0.2	407	0.57	0.3	71	0.53	0.2	7	0.53	0.2
DRC	57	1.34	0.4	244	1.00	0.4	36	0.88	0.3	20	1.13	0.4
Rwanda	168	4.43	2.2	0	–	–	0	–	–	0	–	–
Senegal	370	3.90	1.7	358	1.12	0.7	868	1.22	0.6	0	–	–
Sierra Leone	0	–	–	780	0.55	0.4	218	0.56	0.4	41	0.77	0.4
Tanzania	305	1.40	0.6	8	0.63	0.3	527	1.13	0.6	1	1.08	0.0
Togo	68	2.06	0.8	104	1.40	0.8	549	1.82	0.9	0	–	–
Uganda	4	1.85	0.8	480	1.72	1.0	588	1.79	1.0	0	–	–
All countries in Groups 1, 2 and 3[a]	3064	2.22	1.0	6993	1.23	0.2	8835	1.89	0.7	1095	2.07	0.5

n, sample size matching the criteria; SD, standard deviation, –, not applicable.
[a]The yield for all countries in Groups 1, 2 and 3 is the average country yield weighted by the estimated area per country.

Table 3.5. Average rice yield (t/ha) by irrigation environment for countries in Groups 1, 2 and 3 (2009).

	Sahel–savannah irrigated systems			Sub-humid irrigated zones		
Country	n	Mean	SD	n	Mean	SD
Benin	13	2.12	1.0	28	2.05	0.9
Burkina Faso	23	2.78	1.0	28	1.74	1.5
Cameroon	48	2.95	1.6	179	1.68	1.0
The Gambia	62	2.16	2.0	0	–	–
Mali	618	4.01	1.4	0	–	–
Nigeria	109	2.23	1.7	135	2.24	1.6
Senegal	365	3.91	1.7	5	1.96	1.2
All	1238	3.65	1.7	375	1.92	1.3

n, sample size matching the criteria; SD, standard deviation; –, not applicable.

agroecological zone occurs in northern Cameroon, the Senegal River valley and Casamance regions in Senegal, the northern states of Nigeria (Borno, Jigawa, Kano, Katsina, Kebbi, Sokoto, Yobe and Zamfara) and Boucle du Mouhoun, Central, North and Sahel regions of Burkina Faso. Sub-humid irrigated zones are irrigated zones located outside the Sahel–savannah.

Notes

[1] Balasubramanian *et al.* (2007) provide estimates of country total rice areas disaggregated by rice-growing environments.
[2] The estimation methodology is detailed in the Appendix.
[3] 'Survey population weights' are coefficients associated with sampled units which are used to extrapolate from the sample to the whole population of farmers. In essence, the coefficient gives the number of farmers represented by each sample farmer.
[4] Liberia and Mozambique, which are included in this group, were covered by the 2009 rice statistics survey, but data analyses were not conducted.
[5] Seck *et al.* (2012) used a simpler procedure to estimate the distribution of total rice area by rice-growing environment for these countries: the percentage distribution of area by environment of a similar neighbouring country for each country of this group in combination with the estimated total rice area in 2008 for that country as given by FAOSTAT (2012).

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Appendix 3.1 Methodology for Estimating Total Rice Cultivated Area by Rice-growing Environment

In this appendix we describe the methodology used to estimate a country's total cultivated rice area and number of rice-farming households in 2009 by rice environment. The estimated total area for the whole continent was obtained by aggregating the country estimates.

For a country with a population of farmers (i.e. farming households) of size N and J rice environments each with N_j number of rice farmers, let a_{ij} denote the total rice area in environment j of a farmer i and d_{ij} be a dummy binary indicator taking the value 1 if the farmer grows rice in environment j and zero otherwise, $i = 1, \ldots, N$ and $j = 1, \ldots, J$. Let also A_j denote the country's total cultivated rice area in environment j, f_j the proportion of farmers in the country growing rice in environment j and $\bar{a}_j$ the average total household cultivated rice area in environment j. Then we have for $j = 1, \ldots, J$, $N_j = \sum_{i=1}^{N} d_{ij}$, $A_j = \sum_{i=1}^{N} a_{ij} = \sum_{i=1}^{N} d_{ij} a_{ij}$, $f_j = \frac{N_j}{N}$ and $\bar{a}_j = \frac{A_j}{N_j}$. The country's total rice area A is thus given by $A = \sum_{j=1}^{J} A_j$.

From these expressions, we can obtain from a (possibly multistage stratified) random sample of rice-farming households consistent estimates of the country's total number of farmers growing rice

in environment j and the corresponding total rice area in environment j. More precisely, we have $\widehat{N}_j=\sum_{i=1}^{n} w_i d_{ij}$ and $\widehat{A}_j=\sum_{i=1}^{n} w_i d_{ij} a_{ij}$, where w_i $i=1,..,n$, are the survey population weights such that $\sum_{i=1}^{n} w_i=N$.[1] Similarly, the country's proportion of farmers growing rice in environment j and the average total household rice area in environment j are consistently estimated by $\hat{f}_j=\frac{1}{\sum_{i=1}^{n} w_i}\sum_{i=1}^{n} w_i d_{ij}$ and $\widehat{\bar{a}}_j=\frac{1}{\sum_{i=1}^{n} w_i d_{ij}}\sum_{i=1}^{n} w_i d_{ij} a_{ij}$, respectively.

For the countries in the second and third groups where we did not have the survey population weights, we have estimated $\widehat{A}_j$ and $\widehat{N}_j$ by $\widehat{A}_j=\widehat{N}_j\times\widehat{\bar{a}}_j$, and $\widehat{N}_j=N\times\hat{f}_j$, respectively, where $\hat{f}_j=\frac{1}{n}\sum_{i=1}^{n} d_{ij}$ is the sample proportion of farmers growing rice in environment j and $\widehat{\bar{a}}_j=\frac{1}{n\hat{f}_j}\sum_{i=1}^{n} d_{ij} a_{ij}$ is the sample average of the total household rice area under environment j. We estimate N, the total number of rice-farming households in the formulae above, by dividing the total cultivated rice area obtained from the 2009 survey country reports (for the second group) and the NRDS (for the third group) by the sample average of total household rice area across all rice environments.

In the 2009 rice statistics survey, the area information was collected for all of the plots of each household. Unfortunately, the information on the rice environment of each household plot was not collected. Instead, the rice environment information was collected at the household level by asking the household to indicate by order of importance all the environments where it was growing rice. Hence, we cannot know the a_{ij} quantities in the formulae above from the rice statistics survey data. Only the d_{ij} quantities are available from the rice statistics survey. This makes it impossible to estimate A_j from the formulae above. To circumvent the problem of non-availability of the rice-growing environment-specific household cultivated area variables, we use the household-level rice environment information and the total household cultivated rice area $a_i=\sum_{j=1}^{J} a_{ij}$, which can be computed from the rice statistics survey data (since the information on the size of each household rice cultivated plot was collected) and proceed as follows.

Let $j_i^*=argmax\{a_{ij};j=1,\ldots J\}$ designate the household's most important rice-growing environment in terms of area occupied (the first rice-growing environment listed by the household) and let d_{ij}^* be the dummy binary indicator taking the value 1 if $j=j_i^*$ and 0 otherwise. We can then approximate A_j, the country's total rice area in environment j, by the quantity $A_j^*=\sum_{i=1}^{N} d_{ij}^* a_i$. It is clear that $A_j^*=A_j$ if every household grows rice in only one environment. Also, A_j^* is close to A_j if the area of a household's minor (secondary) rice-growing environment is small (i.e. if a_{ij} is small for $j\neq j_i^*$). The reality is very close to these two conditions as the vast majority of African rice farmers generally grow rice in small plots located in the same environment (Seck *et al.*, 2012). This turned out to be overwhelmingly the case in the 2009 rice statistics survey data, where less than 10% of farmers grew rice in more than one rice-growing environment. Moreover, this percentage becomes insignificant after grouping the various rice-growing environments into the four major environments (Table 3.A.1). Hence, A_j^* is a very good approximation of A_j when using the data from the 2009 rice statistics survey. To obtain an estimate $\widehat{A}_j^*$ of A_j^* and the coresponding approximate quantities it suffices to replace in the estimation formula above d_{ij} by d_{ij}^* and a_{ij} by a_i.

Spatial interpolation: kriging

Let $\{(Z_s):s\in D\subset R^2\}$ be a spatial process specified as follow: $Z_s=m(s)+X_s$ where $m(s)=E(Z_s)<\infty$ is the trend of the process and $X_s=(Z_s-E(Z_s))$ the fluctuation (Calder and Cressie, 2009).

Let $\{s_i:i=1,\ldots,n\}$ be the geostatistical data, i.e. a set of known locations of the process: $s_i=(x_i, y_i)$ with x_i being the longitude and y_i the latitude at location s_i. For this chapter, s_i represents data points at the third sub-division level for Benin, Burkina Faso, Cameroon, CAR, Côte d'Ivoire, Guinea, Kenya, Rwanda, Sierra Leone, Togo and Uganda. The second sub-division was used for DRC, The Gambia, Ghana, Madagascar, Nigeria and Tanzania, whereas the first sub-division level was used for Mali and Senegal according to the availability of data. For countries of the fourth group, we randomly selected within each country 25 locations where further predictions will be made. In total, $n=695$ locations were obtained from the above cited 19 countries on which models are based to predict values at the other

Table 3.A.1. Estimation details for countries of Group 1.

	Estimated area (ha)	Standard error	95% Confidence interval	
Senegal				
Irrigated	94,185	2,734	88,813	99,557
Upland	36,178	1,242	33,736	38,621
Lowland	43,948	1,090	41,809	46,086
Total estimated	174,311	4156	166,160	182,462
Guinea				
Irrigated	52,526	3,584	45,320	59,731
Upland	532,329	13,142	506,522	558,137
Lowland	381,756	9,862	362,362	401,150
Others	39,211	4,061	30,940	47,482
Total estimated	1,005,822	17,618	971,252	1,040,392
Nigeria				
Irrigated	86,079	4,868	76,503	95,655
Upland	557,256	12,063	533,600	580,911
Lowland	1,032,935	21,240	991,292	1,074,577
Others	219,427	12,823	194,267	244,586
Total estimated	1,895,697	28,071	1,840,668	1,950,723
Sierra Leone				
Upland	453,531	13,154	427,713	479,348
Lowland	117,720	5,824	106,255	129,185
Others	28,266	3,602	21,059	35,474
Total estimated	599,517	14,842	570,397	628,636

850 locations where no data are available. The country predicted value is the average value of the predicted values at sampled locations.

The mean part of the model can be specified as a function of given covariates and/or coordinates, but we specified it as a polynomial function of the coordinates: $m(s) = \beta_0^* + \beta_1^* x + \beta_2^* y$,

where $(\beta_0^*, \beta_1^*, \beta_2^*) = \arg\min \sum_{i=1}^{n} (z_{s_i} - \beta_0 - \beta_1 x_i - \beta_2 y_i)^2$ are coefficients of the linear trend.

For the sake of kriging, X_s was assumed to be a random process with an existing Gaussian variogram $2\gamma(h) = V(Z_{s_i} - Z_{s_j})$, $h = d(s_i, s_j)$ being the Euclidian distance between s_i and s_j, with the parameter γ estimated as (see Calder and Cressie, 2009):

$$\hat{g}_h = \begin{cases} 0 & if\ |h| = 0 \\ C_0 + C_1 \left(1 - \exp\left(\frac{-3h^2}{a^2}\right)\right) & if\ |h| > 0 \end{cases} \text{; where } a = range,\ C_0 = nugget\ effect = V(Z_s),\ C_0 + C_1 = sill$$

The range is the longest distance with correlated values of the process; the nugget effect represents the semivariance of the process on microscale, i.e. very close to 0 (Kastelec and Košmelj, 2002) and the sill is the maximum semivariogram value. The range, nugget effect and sill parameters were estimated by maximum likelihood using the package geoR (Ribeiro and Diggle, 2001). The predicted values of Z are obtained as weighted linear combinations of the available data: $\hat{Z}_{s_0} = \sum_{i=1}^{n} \lambda_i Z_{s_i}$ where s_0 is an unobserved location. The weights λ_i are obtained by minimizing the mean square error: $\min(Z_{s_0} - Z_{s_0})^2$ subject to the condition of an unbiased estimator $\sum_{i=1}^{n} \lambda_i = 1$ (Calder and Cressie, 2009).

We used this spatial interpolation method to predict the proportion of rice-farming households in irrigated, upland and lowland environments (the proportion of farmers in other environments, where applicable, is deduced from the first three) and the average total household area in each of the four environments for each country of the fourth group.

Note

[1] We note that $W_i = \frac{N}{n}$ for a simple random sample. But most countries have used a two-stage stratified random sampling procedure (see AfricaRice, 2010, and the country reports cited therein for details of the countries' sampling procedures and survey populations).