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Decomposing rice yield gaps into efficiency, resource and technology yield gaps in sub-Saharan Africa

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ABSTRACT

Meeting current rice demand in sub-Saharan Africa (SSA) requires narrowing yield gaps on currently available agricultural land. The objectives of this study were to decompose rice yield gaps into efficiency, resource and technology yield gaps and to identify priority areas for research and development in the major rice production systems (irrigated lowland, rainfed lowland, and rainfed upland) in SSA. Data were collected during the 2012–2015 wet seasons on soil properties, field operations and yields in 1529 fields at 34 sites in 20 countries using a standardized protocol. Stochastic frontier analysis using data on biophysical environment and fertilizer management practices together with a crop simulation model (ORYZA2000) was used to quantify the yield gap, and efficiency, resource, and technology yield gaps. Cluster analysis was performed to classify the site-production system combinations into yield gap groups. Actual rice yields were on average 3.8, 2.6 and 1.7 t/ha in irrigated lowland, rainfed lowland, and rainfed upland, respectively. The yield yap ranged from 2.0–10.0 t/ha across site-production system combinations while the efficiency, resource, and technology yield gaps varied between 0.9 to 5.7, 0.1 to 2.3 and 0 to 7.5 t/ha, respectively. On average, efficiency, resource, and technology yield gaps accounted for 23, 5 and 37 % of the benchmark yield (potential yield in irrigated lowland or water-limited potential yield in rainfed lowland and upland). Four yield gaps groups were identified and were related to the production systems, soil properties, and fertilizer application. Narrowing yield gaps requires the dissemination of integrated crop management practices in yield gaps groups with a large efficiency yield gap, whereas, in yield gaps groups with a large technology yield gap, the development of technologies to improve soil properties and fertilizer use should be given priority.

1. Introduction

Cereal consumption in sub-Saharan Africa (SSA) depends on massive imports (van Ittersum et al., 2016). This context is true for rice for which in 2016, rice production (milled equivalent) was 22.81 million tons while rice consumption was 34.83 million tons (FAOSTAT, 2019). From 2008 to 2018, rice consumption in SSA increased by 81 % while rice production increased by 55 % (FAOSTAT, 2019). The insufficient production of rice in SSA is partially due to the fact that farmers' yields are low (on average 2.2 t/ha in 2017) compared to the world average (4.6 t/ha in 2017) (FAOSTAT, 2019). The yield gap (the difference between the potential yield in irrigated lowland or water-limited potential yield in rainfed lowland and upland and the actual yield obtained by farmers) is large in SSA and was estimated at 5.5 t/ha for irrigated rice and 4.3 t/ha for rainfed rice (van Oort et al., 2017). Potential yield is defined as the maximum theoretical yield achieved by a specific crop genotype in a well-defined biophysical environment using crop simulation models assuming no other yield-limiting factors (e.g. nutrient deficiencies, toxicities) or yield-reducing factors (e.g. insects or other herbivores, diseases or weeds). Under irrigated conditions, the potential yield is determined by climate (solar radiation and temperature), varietal characteristics and crop establishment methods, including sowing date and density. Under rainfed conditions, the potential yield is also affected by water availability and refers to as water-limited potential yield (van Ittersum and Rabbinge, 1997; van Ittersum et al., 2013; van Oort et al., 2015a; Saito et al., 2017).

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Sustainable intensification, including the narrowing of existing yield gaps on currently available agricultural land, has been identified as one of the key strategies to meet future rice demand (Tilman et al., 2011). During the past two decades, several studies analyzed the yield gap in rice farming systems both at the global and local scales. On the global scale, the actual grain yield in parts of China is already approximating its potential yields while in West Africa, large yield gaps were reported (Neumann et al., 2010). In Southeast Asia, relative yield gaps were found to range from 9 to 71 % of the potential yield (Stuart et al., 2016). In SSA, larger relative yield gaps were reported in rainfed lowland and upland than in irrigated lowland system (Niang et al., 2017) and a large variation across sites in the range of 0.6–4.5 t/ha was demonstrated by Tanaka et al. (2017). Recently, the method of frontier analysis (Thiam et al., 2001) was coupled with crop modelling to decompose yield gap into efficiency, resource, and technology yield gaps in rice farming in Central Luzon (Silva et al., 2017). The efficiency yield gap refers to the difference between the technical efficient yield (maximum yield at a given level of inputs) estimated with the stochastic frontier analysis and farmers' actual yield (Fig. 1). Following this approach, differences in yield between farmers using the same level of inputs, in a well-defined biophysical environment, can be attributed to differences in crop management practices. The resource yield gap refers to the difference between the highest farmers' yields and the technical efficient yields under the assumption that input use in highest yielding fields is greater than in other fields (Fig. 1). The resource yield gap captures different resource allocation strategies pursued by farmers to sustain their livelihoods and cope with external shocks. The technology yield gap refers to the difference between potential yield or water-limited potential yield and maximum actual yield (Fig. 1) and indicates how much yield can be potentially increased in current highest yielding fields (Silva et al., 2017). Decomposing the yield gap is important to better understand by how much different types of yield gaps can be narrowed and if so, under which production, economic and environmental conditions (Tittonell and Giller, 2013). To our knowledge, such a systematic approach has not been applied at a relatively large scale in SSA. Previous studies in SSA focused on Ethiopia and Tanzania (van Dijk et al., 2017; Silva et al., 2019; Assefa et al., 2020). The objectives of this study were to decompose yield gaps in three rice production systems across 20 countries in SSA and identify priority areas for research and development.

2. Material and methods

2.1. Study sites

Data were collected during the 2012–2015 wet seasons by the Africa Rice Center (AfricaRice) and National Agricultural Research Institutes (NARIs) in 1529 farmers' fields at 34 sites in 20 countries: Benin, Burkina Faso, Cameroon, Chad, Côte d'Ivoire, Democratic Republic of Congo, Ethiopia, Ghana, Guinea, Madagascar, Mali, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Tanzania, The Gambia, Togo, and Uganda (Fig. 2). All the sites were identified by the NARIs as priority intervention areas.

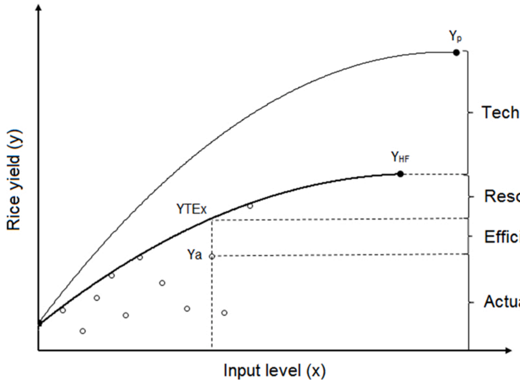

Fig. 1. Theoretical framework to decompose rice yield gap into efficiency, resource and technology yield gaps based on Silva et al. (2017). Yp is the potential yield as defined by van Oort et al. (2015a). Abbreviations are Ya: actual yield, YTEx: technical efficient yield and Y_{HF}: high-yielding farmers' yield.

Between 28 and 117 farmers' fields, thereafter, referred to as fields, were selected in each site. The fields were distributed in three rice production systems [irrigated lowland rice (IL), rainfed lowland rice (RL), and rainfed upland rice (RU)]. Across sites, 547 fields were in IL, 652 in RL and 330 in RU.

2.2. Data collection

Within each field, a 200 m^2 survey area was established at the beginning of the growing season and data on soil properties, field operations and yields were collected using a standardized protocol. The survey area was delineated using a tape measure. Soil samples (0–20 cm soil layer) were collected in the survey area in each field at the onset of the growing season. Nine cores from the survey area were pooled, air-dried, and sieved (2 mm). Soil samples were analyzed for pH (H_2O) and particle size distribution following standard wet analysis procedures (Niang et al., 2017).

Mid-infrared spectroscopy (MIRS) was used to predict soil organic carbon, soil total nitrogen, effective cation exchange capacity, and exchangeable potassium. The prediction accuracy by the MIRS was higher than 0.60 which was judged good enough to include the MIRS data in this study (Johnson et al., 2019). Crop management was made by farmers according to their usual practices. At maturity, rice grain yield was measured in three plots of 12 m^2 within the survey area in each field and reported at 14 % moisture content. Crop management data such as land preparation, planting material, and establishment method, and control of pests and diseases (weeds, diseases, insects and birds), except for fertilizer management practices, as well as differences between rice varieties were not considered in the study.

2.3. Data analysis

2.3.1. Stochastic frontier analysis

For each of the rice production system (IL, RL, and RU), stochastic frontier analysis (Thiam et al., 2001) was applied to evaluate the efficiency yield gap and resource yield gap for each field. Actual rice yield was the dependent variable. The independent variables included agro-ecological zones (AEZ), soil properties, and fertilizer application rates. The study used five AEZ delineated by HarvestChoice (2009) in order to capture the heterogeneity in the climatic conditions in SSA. The five AEZ were (1) highland defined as areas with elevation higher than 1200 m; (2) humid with length of growing period (LGP) > 270 days; (3) sub-humid with $180 < \text{LGP} < 270$ days; (4) semi-arid with $70 < \text{LGP} < 180$ days; and (5) arid with $\text{LGP} < 70$ days. Along the AEZ from humid to arid, solar radiation and temperature fluctuation increase while relative humidity and rainfall decrease (Tanaka et al., 2017). As only one IL site in Senegal belonged to the arid zone, data from this site were combined with the semi-arid zone.

The soil properties included in the model were soil clay content (%), soil total nitrogen content (%) and pH (H_2O). Other soil properties were not included in the model because of collinearities between soil total nitrogen, soil organic carbon and exchangeable potassium on the one hand and soil clay content and effective cation exchange capacity on the other hand (data not shown). Nitrogen (N) fertilizer application rate was considered as a continuous variable while phosphorus (P) and potassium (K) fertilizer applications were considered as dummy variables (either applied or not applied) because more than 50 % of farmers did not apply any P and K fertilizers. Linear, quadratic and interaction terms of a set of variables were included in the production frontier function to capture the non-linear effects of soil properties, nitrogen fertilizer application

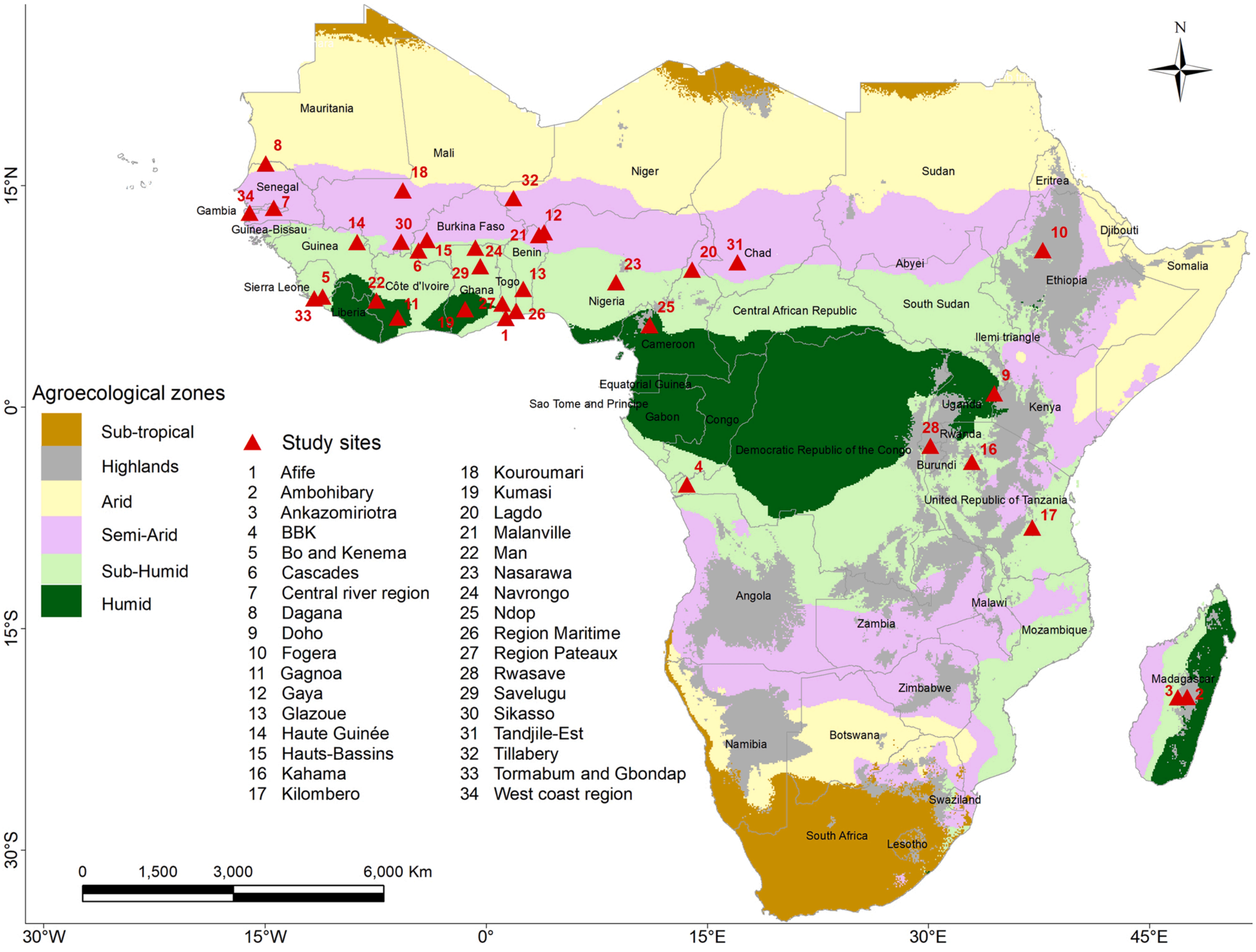

Fig. 2. Location of the 34 study sites in 20 sub-Saharan countries overlaid on the agro-ecological zone map (HarvestChoice, 2009). BBK: means Bas-Congo, Bandundu, Kinshasa and covers these three neighboring provinces.

rate as well as the interaction effects between AEZ and nitrogen fertilizer application rate. The interaction effects between AEZ and soil properties were not included since the response of rice plants to variation in soil properties was assumed to be similar across the agro-ecological zones. The continuous variables included in the production frontier analysis were mean-scaled and log-transformed before the analysis. The model was specified as time-invariant due to the limited number of fields in a given year at some sites. The formulation of the stochastic frontier model is as follows (Eq. 1).

$$\ln Ya_i = \alpha_0 + \sum_{k}^{n} \beta_k \ln x_{ki} + \frac{1}{2}\sum_{k}^{n}\sum_{j}^{n} \theta_{kj} \ln x_{ki} \times \ln x_{ji} + v_i - u_i \tag{1}$$

where Ya_i is the actual yield of rice reported in the field i and x_i a vector of independent variables defined as before; v_i is the random variable associated with statistical noise; u_i is the non-negative random variable associated with technical inefficiency; and α_0, β_k, θ_{kj} are parameters to be estimated. β_k is an input-specific parameter and represents the responsiveness of rice yield in percent to a one percent increase of a particular input (in case $\theta_{kj} = 0$). θ_{kj} is a parameter that specifies both the quadratic terms of a variable (x_{ji}) and interaction between different variables (x_{ki} and x_{ji}) (Silva et al., 2017). The method of maximum likelihood was used for the simultaneous estimation of the parameters of the stochastic frontier model and the model performance indicators using the R package frontier (Coelli and Henningsen, 2013). Model performance indicators were sigma-squared (σ_s^2) and gamma (γ) and they were calculated following Eq. 2 and Eq. 3 (Coelli and Henningsen, 2013).

$$\sigma^2 = \sigma_u^2 + \sigma_v^2 \tag{2}$$

$$\gamma = \frac{\sigma_u^2}{\sigma^2} \tag{3}$$

where σ_u^2 is the variance of the non-negative random variable associated with technical inefficiency (u_i) and σ_v^2 is the variance of the random variable associated with statistical noise (v_i). Sigma square (σ^2) indicates the total amount of variance found in the model. Gamma (γ) indicates the dominant source of random error. If the value of γ is closer to 1, most of the unexplained variability in rice yield is attributed to the technical inefficiency. But, if the value of γ is closer to 0, most of the unexplained variability is attributed to the statistical noise (Coelli and Henningsen, 2013).

2.3.2. *Crop modeling*

A modified version of the ORYZA2000 model documented in van Oort et al. (2015b) was used to simulate potential yield for IL sites and water-limited potential yield for RL and RU sites. The model used the information on sowing dates, lengths of growing seasons, daily weather data and soil data. The genetic coefficients for all the varieties grown in farmers' fields were not available. Therefore, the potential yield and the water-limited potential yield were determined for each site – production system combination. One major rice variety grown in each site-production system combination was identified and its growing cycle duration and the average date of sowing used by farmers were used in the simulations. Daily weather data included minimum and maximum temperature, radiation, rainfall, wind speed, and early morning vapor pressure. For 22 sites, weather data were obtained from automated weather stations established at the sites. For 6 sites, weather data were obtained from the NASA POWER database (NASA, 2016). The NASA POWER data on the minimum and maximum temperatures were bias-corrected following van Oort et al. (2014) while solar radiation and rainfall data were used directly as previously described in Niang et al. (2017). The soil water characteristics used in the model simulation are presented in Table S1. Sand, silt, clay and soil organic carbon contents of the first five layers (1-m depth profile) of each rainfed lowland and upland field were extracted from the Africa Soil Information Service (AfSIS) database (http://africasoils.net). Using the average of the soil properties data over all fields of the same site within the same production system, saturated hydraulic conductivity (KST), volumetric water content at wilting point (WCWP), volumetric water content at field capacity (WCFC) and saturated volumetric water content (WCST) for each soil layer at each site were determined using the pedo-transfer functions proposed by Saxon and Rawls (2006). Rainfed rice yields depend strongly on groundwater depths for which there is no reliable data at a continental scale and at high temporal resolution even within international soil databases such as ISRIC-WISE (Batjes, 2012) and AfSIS (Hengl et al., 2015). Therefore, we made two assumptions: i) rainfed lowland, puddled, 25 cm high bunds and groundwater at 40 cm depth during the wet season, ii) rainfed upland, not puddled, no bund, and groundwater at 1000 cm depth during the wet season. Due to lack of weather data at 6 sites, the potential yield was simulated for 13 out of 15 IL sites while the water-limited potential yield was simulated for 15 out of 18 RL sites and 8 out of 9 RU sites.

2.3.3. *Determination of yield gap and efficiency, resource and technology yield gaps*

Yield gaps were expressed in absolute and relative terms. The absolute yield gap was calculated as the difference between the benchmark yield (potential yield in irrigated lowland or water-limited potential yield in rainfed systems) and actual farmers' yield and was referred to as the total yield gap hereafter. The relative yield gap was calculated as the ratio between the total yield gap and the potential yield (IL) or water-limited potential yield (RL and RU) and expressed in percentage. The technical efficient yield and efficiency yield gap were evaluated following Eq. (4) and Eq. (5) (Silva et al., 2017, Supplementary Material A).

$$\mathrm{YTEx_i} = \mathrm{Ya_i} \times \exp(-\mathrm{u_i})^{-1} \tag{4}$$

$$\mathrm{EYG_i} = \mathrm{YTEx_i} - \mathrm{Ya_i} \tag{5}$$

where YTExi is the technical efficient yield in field i, EYGi is the efficiency yield gap; $\mathrm{Ya_i}$ is the actual yield of rice reported in the field i and $\mathrm{u_i}$ is a non-negative random variable associated with the technical inefficiency (Eq. 4 and 5).

Except for N, P and K fertilizer applications, other crop management practices were not included in the stochastic frontier model. This limitation might result in over-estimation of the efficiency yield gap if other crop management practices are major determinants of rice yield. The resource yield gap was calculated for each field as the difference between the high-yielding farmers' yield (YHF) at the site to which the field belongs and the technical efficient yield of the field (YTExi). The high-yielding farmers' yield at the site was defined as the mean across fields of actual yields above the 90th percentile. We considered that the resource yield gap of the field was not available when high-yielding farmers' yield of the site was lower than the technical efficient yield of the field. This happens when the highest rice yields in the fields of a particular site were very low compared to the yields in the fields in other sites due to low soil fertility and input use. The technology yield gap was calculated for each site as the difference between potential yield (IL) or water limited potential yield (RL and RU) and high-yielding farmers' yield of the site.

High-yielding farmers' yield, Yp and Yw were estimated per site. We tested whether there was a significant difference in the efficiency yield gap, resource yield gap and technology yield gap among sites of a given production system using the non-parametric Kruskal-Wallis test as the data on efficiency, resource, and technology yield gaps in each of the three production systems were not normally distributed (results of normality test not shown). We first performed the Levene test for the homogeneity of variance. When the variances were not homogenous, we accounted for the heterogeneity of variances by weighting the data by the site variance. The resource yield gap due to N – the most limiting nutrient for rice in SSA (Saito et al., 2019) – was assessed in each site-production system combination by comparing the N rate among the lowest (mean across fields with an actual yield below the 10th percentile), average (mean across fields with an actual yield between the 10th and 90th percentile) and highest-yielding farmers. Significant differences in N rate among the different farmers' categories at each site were tested using analysis of variance (ANOVA) since in all sites, data on N rate were normally distributed (results of normality test not shown). A hierarchy cluster analysis (Ward's method) was performed to identify homogenous groups of site-production system combinations using mean efficiency yield gap and mean technology yield gap. The mean resource yield gap was not included in the cluster analysis because it was small (<1 t/ha), except for 2 RL sites. The sites for which the technology yield gap was not available were excluded from the cluster analysis.

3. Results

3.1. *Overview of rice yield, soil properties and fertilizer application in rice farming in sub-Saharan Africa*

There was a large variation in average rice yield across sites in all the three production systems with a range of 2.25–5.76 in IL, 1.07–5.25 in RL, and 1.00–2.55 t/ha in RU. There was also a large variation in rice yield between fields in some of the sites with the standard deviation ranging from 0.71 to 1.70 t/ha in IL, 0.35–2.52 t/ha in RL, and 0.36–1.53 t/ha in RU. Average rice yield across all sites was 3.78 in IL, 2.60 in RL and 1.65 t/ha in RU (Table 1).

Site mean soil pH ranged from 5.2 to 6.5 in IL, 4.6 to 7.1 in RL and 4.0 to 6.3 in RU with a standard deviation of 0.3 – 0.7 in IL, 0.3 – 0.9 in RL and 0.3 – 0.8 in RU, indicating a large variation across sites and between fields in some of the sites (Table 1). Average soil pH across all sites was 5.7 in IL, 5.5 in RL and 5.3 in RU (Table 1).

There was a large variation in soil clay content across sites with the range from 8 to 77 % in IL, 11 to 47% in RL and 7 to 41% in RU and a large variation between fields in some of the sites (Table 1). Average soil clay content across all sites was 31 % in IL, 24 % in RL and 21 % in RU (Table 1).

Across sites, soil total nitrogen ranged from 0.04 to 0.33 % in IL, 0.05 to 0.48 % in RL and 0.05 to 0.25 % in RU with a low variation between fields in the same sites (Table 1). Average soil total nitrogen was 0.12 % in IL, 0.15 % in RL and 0.12 % in RU (Table 1).

The average rates of nitrogen fertilizer used by farmers were 83, 78, and 35 kg N/ha in IL, RL, and RU, respectively (Table 1). Across site-production system combinations, phosphorus fertilizer was applied by 44 % of the farmers and potassium fertilizer was applied by 39 % of the farmers (Table 1).

3.2. *Production frontier*

The coefficients estimated for the variables of the production frontier are shown in Table 2. In IL, the expected percentage increase in mean yield from sub-humid zone to semi-arid zone was about 10.7 % while the expected percent decrease in mean yield from sub-humid zone to humid zone was about 41.2 %. There was no significant difference in the mean

Table 1
Average rice yield, soil pH, soil clay content, soil total nitrogen, nitrogen fertilizer rate (N), percentage of farmers applying phosphorus fertilizer (P) and potassium fertilizer (K) in 34 sites in three production systems (irrigated lowland, rainfed lowland, rainfed upland) and five agro-ecological zones (AEZ) in sub-Saharan Africa. Standard deviations are in brackets.

Site name	Country	No. of fields	AEZ	Yield (t/ha)	Soil pH (H_2O)	Soil clay content (%)	Soil total nitrogen (%)	N fertilizer rate (kg/ha)	Field with P fertilizer (%)	Field with K fertilizer (%)
Irrigated lowland										
Dagana	Senegal	39	Arid	2.99 (1.37)	6.0 (0.4)	46 (12)	0.05 (0.01)	112 (51)	18	0
Rwasave	Rwanda	49	Highlands	3.41 (1.70)	5.2 (0.2)	31 (8)	0.33 (0.14)	46 (20)	92	94
Doho	Uganda	28	Humid	3.11 (1.67)	5.7 (0.4)	25 (10)	0.20 (0.10)	0 (0)	0	0
Gagnoa	Côte d'Ivoire	51	Humid	2.25 (1.02)	5.4 (0.5)	18 (8)	0.15 (0.13)	31 (46)	59	59
Central river region	The Gambia	70	Semi-arid	3.64 (0.71)	5.8 (0.4)	52 (12)	0.14 (0.07)	33 (44)	47	47
Gaya	Niger	7	Semi-arid	2.77 (1.27)	5.5 (0.4)	16 (6)	0.09 (0.02)	86 (60)	71	71
Kouroumari	Mali	43	Semi-arid	5.25 (1.56)	6.5 (0.7)	44 (15)	0.04 (0.01)	67 (44)	91	19
Malanville	Benin	71	Semi-arid	5.07 (1.35)	5.6 (0.6)	25 (16)	0.08 (0.05)	89 (53)	79	79
Tillabery	Niger	63	Semi-arid	5.76 (0.92)	5.4 (0.6)	29 (10)	0.08 (0.03)	156 (73)	98	95
Afife	Ghana	46	Sub-humid	3.26 (1.37)	5.9 (0.3)	77 (10)	0.18 (0.04)	87 (50)	96	96
Kahama	Tanzania	8	Sub-humid	3.16 (0.99)	5.8 (0.6)	14 (3)	0.09 (0.02)	8 (15)	13	0
Lagdo	Cameroon	21	Sub-humid	2.95 (1.19)	6.1 (0.4)	39 (20)	0.11 (0.04)	36 (32)	71	71
Navrongo	Ghana	16	Sub-humid	4.09 (1.70)	5.9 (0.6)	18 (8)	0.10 (0.05)	69 (45)	100	100
Region Maritime	Togo	29	Sub-humid	3.92 (1.04)	5.5 (0.7)	29 (15)	0.11 (0.04)	15 (17)	48	48
Savelugu	Ghana	6	Sub-humid	5.13 (1.35)	5.7 (0.3)	8 (3)	0.08 (0.03)	102 (71)	83	83
Rainfed lowland										
Ambohibary	Madagascar	36	Highlands	3.82 (1.71)	5.5 (0.3)	21 (4)	0.33 (0.12)	1 (2)	0	0
Fogera	Ethiopia	26	Highlands	3.53 (1.22)	6.5 (0.5)	47 (8)	0.18 (0.05)	3 (9)	12	0
Ndop	Cameroon	50	Highlands	5.25 (2.15)	4.8 (0.2)	38 (8)	0.48 (0.23)	116 (116)	42	42
Kumasi	Ghana	32	Humid	2.06 (1.09)	6.0 (0.9)	22 (10)	0.15 (0.12)	76 (101)	38	38
Gaya	Niger	17	Semi-arid	3.09 (1.36)	5.5 (0.5)	26 (18)	0.11 (0.05)	151 (117)	94	94
Sikasso	Mali	60	Semi-arid	2.32 (1.10)	5.2 (0.6)	32 (10)	0.09 (0.03)	65 (67)	60	48
Tandjile-Est	Chad	9	Semi-arid	2.56 (0.58)	5.8 (0.3)	11 (5)	0.15 (0.10)	0 (0)	0	0
Bo and Kenema	Mali	55	Sub-humid	1.90 (0.87)	5.1 (0.6)	20 (10)	0.19 (0.07)	25 (56)	15	15
Cascades	Burkina Faso	23	Sub-humid	2.70 (1.43)	4.7 (0.8)	44 (15)	0.11 (0.05)	10 (10)	57	52
Glazoue	Benin	28	Sub-humid	1.07 (1.09)	5.9 (0.6)	11 (4)	0.07 (0.04)	7 (9)	43	43
Kahama	Tanzania	55	Sub-humid	2.53 (1.17)	5.7 (0.4)	18 (7)	0.09 (0.02)	13 (25)	2	0
Kilombero	Tanzania	10	Sub-humid	3.12 (2.52)	7.1 (0.6)	16 (3)	0.08 (0.03)	33 (23)	0	0
Ladgo	Cameroon	40	Sub-humid	2.97 (2.11)	6.0 (0.7)	22 (15)	0.07 (0.02)	5 (16)	20	20
Nasarawa	Nigeria	46	Sub-humid	1.99 (1.00)	4.6 (0.9)	17 (12)	0.10 (0.08)	4 (18)	0	0
Navrongo	Ghana	11	Sub-humid	2.47 (1.49)	6.1 (0.3)	18 (10)	0.09 (0.04)	40 (47)	64	64
Region Pateaux	Togo	28	Sub-humid	3.09 (0.96)	4.9 (0.6)	11 (4)	0.08 (0.02)	19 (18)	61	61
Savelugu	Ghana	76	Sub-humid	1.12 (0.87)	5.7 (0.5)	17 (10)	0.05 (0.01)	28 (32)	47	47
Torm and Gbondap	Sierra Leone	50	Sub-humid	1.19 (0.35)	4.8 (0.2)	41 (8)	0.29 (0.13)	0 (0)	0	0
Rainfed upland										
Ankazomiriotra	Madagascar	22	Highlands	1.84 (0.76)	5.1 (0.3)	20 (6)	0.15 (0.03)	1 (6)	0	0

(*continued on next page*)

Table 1 (*continued*)

Site name	Country	No. of fields	AEZ	Yield (t/ha)	Soil pH (H_2O)	Soil clay content (%)	Soil total nitrogen (%)	N fertilizer rate (kg/ha)	Field with P fertilizer (%)	Field with K fertilizer (%)
Man	Côte d'Ivoire	64	Humid	1.26 (0.46)	5.2 (0.6)	21 (7)	0.22 (0.13)	0 (0)	0	0
Sikasso	Mali	6	Semi-arid	1.28 (0.71)	5.3 (0.5)	26 (13)	0.06 (0.03)	63 (34)	83	33
West coast region	The Gambia	70	Semi-arid	1.41 (0.68)	5.9 (0.6)	11 (7)	0.07 (0.03)	11 (18)	39	39
BBK*	DRC	42	Sub-humid	1.00 (0.36)	4.6 (0.8)	41 (11)	0.25 (0.15)	0 (0)	0	0
Glazoue	Benin	25	Sub-humid	1.53 (1.53)	6.3 (0.4)	7 (3)	0.05 (0.01)	50 (57)	76	76
Haut-Bassins	Burkina Faso	19	Sub-humid	2.55 (1.36)	4.0 (0.4)	27 (6)	0.06 (0.03)	12 (11)	58	58
Haute Guinée	Guinée	70	Sub-humid	1.48 (0.76)	5.7 (0.6)	22 (9)	0.15 (0.13)	9 (16)	34	34
Navrongo	Ghana	12	Sub-humid	2.51 (1.25)	6.0 (0.4)	14 (10)	0.08 (0.05)	15 (27)	33	33

BBK: means Bas-Congo, Bandundu, Kinshasa and covers these three neighboring provinces.

Table 2

Coefficients for the variables of the frontier production function for irrigated lowland, rainfed lowland and rainfed upland rice systems in sub-Saharan Africa.

Variable	Irrigated lowland	Rainfed lowland	Rainfed upland[a]
Production frontier			
Intercept	6.75	8.14**	7.54
Agro-ecological zone[b]			
Semi-arid zone	10.69*	8.81	−12.30
Highland zone	7.83	55.54*	–
Humid zone	−41.23***	−19.71	–
Soil total nitrogen	−0.11*	0.29***	−0.23
Soil clay content	−0.02	0.11	0.56***
Soil pH (H_2O)	−4.85	−7.08**	−7.55
Total soil nitrogen^2	−0.11	−0.29***	−0.10
Soil clay content^2	−0.11**	−0.23*	−0.19
pH (H_2O)^2	2.27	3.83***	4.76
Nitrogen fertilizer rate	0.59*	0.28	−0.51
Nitrogen fertilizer rate^2	0.01	0.02	0.04
Phosphorus fertilizer application	14.39*	−0.13	−0.22
Potassium fertilizer application	1.09	0.42	0.30
Semi-arid x nitrogen fertilizer rate	−0.98	−9.03*	−0.12
Highland x nitrogen fertilizer rate	3.50	−10.54*	–
Humid x nitrogen fertilizer rate	−10.37***	−3.56	–
Soil total nitrogen x nitrogen fertilizer rate	−0.03	0.11***	−0.02
Soil clay content x nitrogen fertilizer rate	0.01	0.04	0.17***
Soil pH x nitrogen fertilizer rate	−0.24*	−0.08	0.29
Model evaluation			
Sigma-squared	0.62***	0.84***	1.00***
Gamma	0.98***	0.83***	0.93***

Significance codes are: '***' 0.1 %, '**' 1%, '*' 5%.

[a] In rainfed upland of highland and humid zones, farmers did not apply any nitrogen fertilizer. Results from these zones are not included in the stochastic production function.

[b] The sub-humid zone was considered as a reference for the agro-ecological zones.

yield between highland zone and sub-humid zone. The linear effect of soil clay content on rice yield was not significant, but the quadratic effect of soil clay content on rice yield was negative indicating that rice yield decreased at high soil clay content level. There was a positive linear effect of nitrogen fertilizer rate on rice yield. Phosphorus fertilizer application increased rice yield. Compared to the sub-humid zone, rice yield response to an increase in nitrogen fertilizer rate was lower in the humid zone. There was a negative interaction effect between soil pH and nitrogen fertilizer rate on rice yield, indicating that rice yield increased more with an increase in nitrogen fertilizer rate when soil pH was lower. There was a negative linear effect of soil total nitrogen on rice yield (Table 2).

In RL, the expected increase in mean yield from sub-humid zone to highland zone was about 55.5 %, while there was no significant difference in mean yield between semi-arid, humid and sub-humid zone (Table 2). Linear and quadratic effects of soil total nitrogen on rice yield were significant and these showed that rice yield increased with an increase in soil total nitrogen, but beyond a certain level of soil total nitrogen, rice yield decreased. Also, we found a significant positive interaction between soil total nitrogen and nitrogen fertilizer rate. When the relationship between soil total nitrogen and rice yield was assessed for different nitrogen fertilizer application rates, there were optimum levels in soil total nitrogen for higher yield in nitrogen-fertilized conditions (Fig. 3). The linear and quadratic effects of soil pH on rice yield were significant and these showed that rice yield decreased with an increase in soil pH, but beyond a certain level, rice yield increased (Table 2). The linear effect of soil clay content on rice yield was not significant, but the quadradic effect of soil clay content on rice yield was negative. Compared to the sub-humid zone, rice yield response to an increase in nitrogen fertilizer rate was lower in the semi-arid and highland zones (Table 2).

In RU, soil clay content had a positive effect on rice yield (Table 2). There was a significant positive interaction effect between soil clay content and nitrogen fertilizer rate on rice yield.

3.3. *Yield gaps*

Total yield gap, efficiency, resource and technology yield gaps are presented in Fig. 4 and Appendix (Table S.2). Average total yield gaps on the different sites varied from 2.54 to 9.98 t/ha t/ha overall, with the range between 2.54 and 9.79 t/ha in IL, 2.75 and 9.98 t/ha in RL and 3.38 and 7.70 t/ha in RU (Fig. 4). Average total yield gap across sites was 4.96 in IL, 5.28 in RL and 5.57 t/ha in RU (Fig. 4). Relative yield gaps on the different sites varied from 31 to 88 % overall, with the range between 31 and 76 % in IL, 43 and 88 % in RL, and 57 and 86 % in RU (Fig. 5). The average relative yield gap across sites was 55 % in IL, 67 % in RL and 75 % in RU (Fig. 5). Sites with greater levels of nitrogen fertilizer inputs had lower relative yield gaps in irrigated lowland. In rainfed lowland and rainfed upland, the site mean relative yield gap was independent of the site mean nitrogen fertilizer input (Fig. 5).

The site mean technical efficient yield varied from 4.29 to 7.81 t/ha in IL, 2.07 to 9.18 t/ha in RL and 2.12 to 3.83 t/ha in RU (Fig. 6). On average, the technical efficient yield was 6.07 in IL, 4.28 in RL and 2.83 t/ha in RU. Sites with higher actual yield had a higher technical efficient

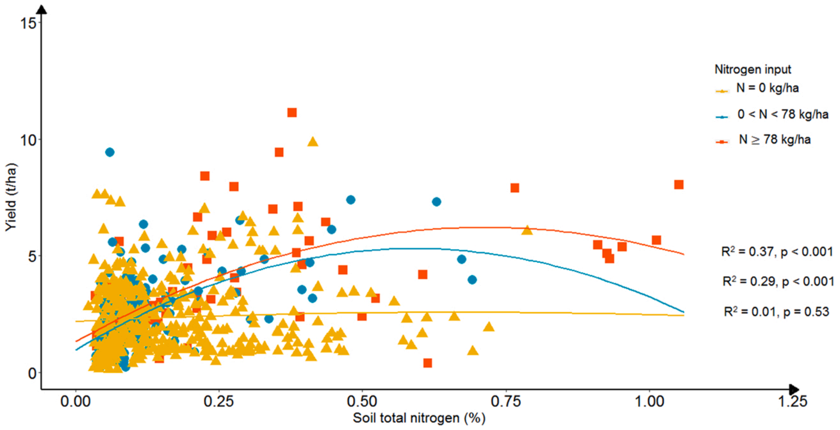

Fig. 3. Relationship between soil total nitrogen and rice yield at different nitrogen (N) fertilizer inputs in rainfed lowland. The yellow, blue and red lines represent the quadratic relationship between soil total nitrogen and rice yield for fields with 0, between 0 and 78, and ≥ 78 kg/ha of nitrogen inputs, respectively. Models performance metrics (R^2 and p-value) are presented for yellow, blue and red lines (bottom, middle, top). The value of 78 kg/ha represents the mean of N fertilizer input across rainfed lowland sites. The relationship is presented only for rainfed lowland where there was a linear and quadratic relationship between soil total nitrogen and rice yield, and there a positive interaction effect between soil total nitrogen and nitrogen fertilizer input on rice yield (Table 2) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

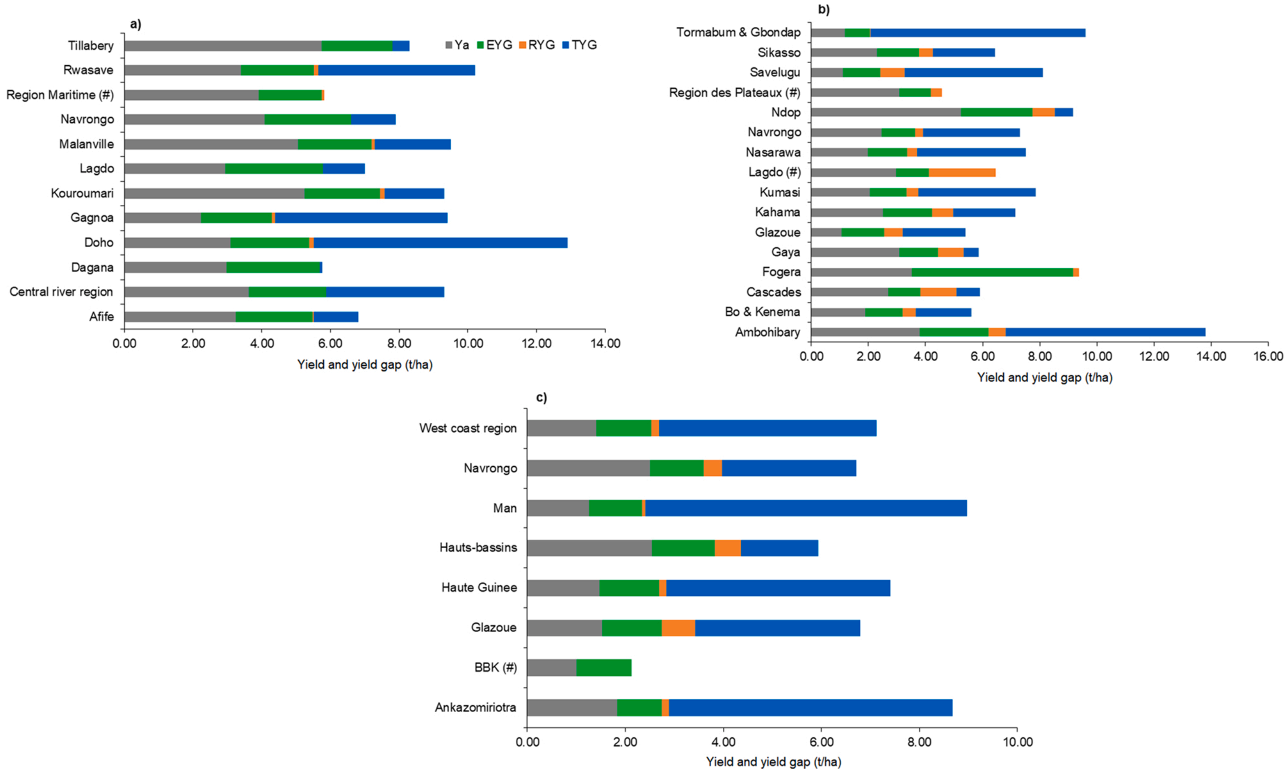

Fig. 4. Yield benchmark decomposed into actual yield (Ya), efficiency yield gap (EYG), resource yield gap (RYG) and technology yield gap (TYG) in a) 12 irrigated lowland sites, b) 16 rainfed lowland sites, and c) 8 rainfed upland sites. The benchmark yield was the potential yield in irrigated lowland and the water-limited potential yield in rainfed lowland and rainfed upland. Hash signs indicate the sites for which the potential yield or the water-limited potential yield was not determined due to a lack of weather data for those sites. BBK: means Bas-Congo, Bandundu, Kinshasa and covers these three neighboring provinces.

yield. Overall, site mean actual yield represented 35–80% of the technical efficient yield (Fig. 6).

Efficiency yield gap varied from 0.88 to 5.65 t/ha overall, with the range between 1.83 and 2.84 t/ha in IL, 0.88 and 5.65 t/ha in RL and 0.90 and 1.28 t/ha in RU (Fig. 4). On average, the efficiency yield gap was 2.27 in IL, 1.71 in RL and 1.13 t/ha in RU (Fig. 4).

Resource yield gaps ranged from 0.01 to 2.33 t/ha overall, with the range between 0.01 and 0.14 t/ha in IL, 0.01 and 2.33 t/ha in RL and 0.06 and 0.68 t/ha in RU (Fig. 4). On average, the resource yield gap was 0.07 in IL, 0.67 in RL and 0.30 t/ha in RU. There were significant differences in the nitrogen fertilizer rates used by the lowest, average and highest yielding farmers in 4 site-production system combinations (Table 3). However, in 32 site-production system combinations, there were no differences in the nitrogen fertilizer rates used by the lowest, average and highest yielding farmers (Table 3).

Technology yield gap ranged from 0 to 7.52 t/ha overall with the range between 0.06 and 7.38 t/ha in IL, 0 and 7.52 t/ha in RL and 1.56 and 6.55 t/ha in RU (Fig. 4). The average technology yield gap was 2.60 in IL, 2.93 in RL and 4.14 t/ha in RU (Fig. 4).

On average, efficiency, resource, and technology yield gaps accounted for 23, 5 and 37 % of the benchmark yield (potential yield in irrigated lowland or water-limited potential yield in rainfed lowland and upland), respectively. The efficiency yield gap was the largest in 39 % of site-production system combinations and technology yield gap was the largest in another 61 % of site-production system combinations (Fig. 4).

Using site mean efficiency and technology yield gaps, cluster analysis classifies 30 site-production systems into four yield gap groups (Fig. 7 and Table 4). Yield gap group (YG) 1 was characterized with large mean

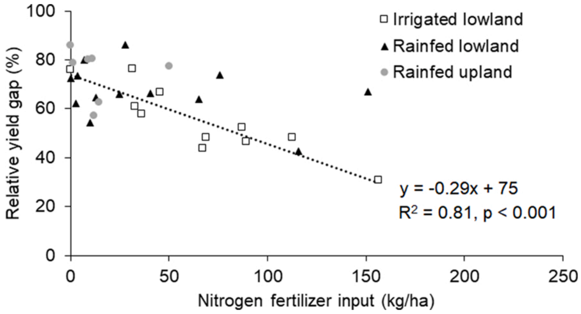

Fig. 5. Relationship between relative yield gap and nitrogen fertilizer inputs. The benchmark was the potential yield in irrigated lowland and water-limited potential yield in rainfed lowland and rainfed upland. Regression lines are presented only for irrigated lowland (dashed line). In rainfed lowland and rainfed upland, the relationships between relative yield gaps and nitrogen fertilizer inputs were not significant, and no regression line was presented. Average nitrogen fertilizer input and relative yield gap in each site were presented.

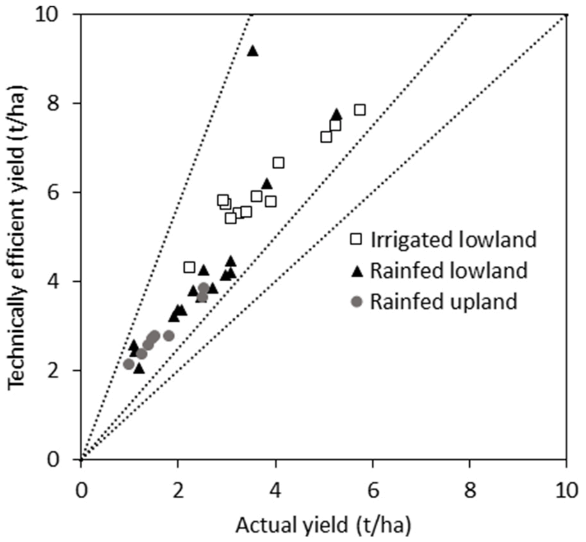

Fig. 6. Relationship between technical efficient yield and actual yield. Lines shown are the 1:1 line, actual yield at 80 % of technical efficient yield, and actual yield at 35 % of technical efficient yield.

efficiency yield gap (> 2 t/ha) and large mean technology yield gap (> 2 t/ha) (Table 4). Yield gap group 2 was characterized with large mean efficiency yield gap and small mean technology yield gap. Yield gap group 3 was characterized with small mean efficiency yield gap (< 2 t/ha) and large mean technology yield gap (> 2 t/ha). Yield gap group 4 was characterized with small mean efficiency yield gap and small mean technology yield gap. For the 4 YG, the mean resource yield gap was small and varied from 0.18 to 0.79 t/ha. Yield gap group 1 had the largest mean total yield gap and the highest potential yield while YG4 had the smallest mean total yield gap and the lowest potential yield. Mean rice yields were higher in YG1 and YG2 than in YG3 and YG4.

The yield gap groups were related to the production systems, soil properties and fertilizer application. All the IL sites belonged to YG1 and YG2 while all RU sites belonged to YG3 and YG4. Comparing YG1 and YG2, IL sites of YG2 had higher N fertilizer application rate and higher percentage of fields with P and K fertilizers application. Among RL sites, YG2 had the highest soil total nitrogen and N fertilizer application rate. Yield gap group 3 comprised RL and RU sites with low soil total nitrogen content and low nitrogen fertilizer application rate. Yield gap group 4 comprised RL and RU sites with relatively lower soil clay content and soil total nitrogen (Table 4).

Table 3
Results of nitrogen (N) fertilizer rates comparison among the lowest, average and highest yielding fields in 36 site-production system combinations in sub-Saharan Africa.

Site name	Country	N (kg/ha)			p-value
		Lowest yielding field	Average yielding field	Highest yielding field	
Irrigated lowland					
Afife	Ghana	89	85	103	0.75
Central river region	The Gambia	28	28	80	0.03
Dagana	Senegal	117	114	100	0.86
Doho	Uganda	0	0	0	–
Gagnoa	Côte d'Ivoire	56	31	13	0.31
Kouroumari	Mali	27	69	97	0.04
Lagdo	Cameroon	32	37	35	0.97
Malanville	Benin	75	88	110	0.44
Navrongo	Ghana	83	72	38	0.15
Region Maritime	Togo	16	12	32	0.12
Rwasave	Rwanda	31	46	58	0.10
Tillabery	Niger	113	159	180	0.20
Rainfed lowland					
Ambohibary	Madagascar	0	0	0	–
Bo and Kenema	Mali	0	29	23	0.35
Cascades	Burkina Faso	6	9	19	0.43
Fogera	Ethiopia	0	3	0	0.61
Gaya	Niger	102	177	30	0.22
Glazoue	Benin	7	6	13	0.51
Kahama	Tanzania	13	15	0	0.38
Kumasi	Ghana	143	59	109	0.50
Ladgo	Cameroon	11	5	0	0.23
Nasarawa	Nigeria	0	5	0	0.75
Navrongo	Ghana	64	19	93	0.10
Ndop	Cameroon	23	118	192	0.03
Region Plateaux	Togo	24	22	0	0.11
Savelugu	Ghana	6	29	42	0.02
Sikasso	Mali	62	70	30	0.32
Torm and Gbondap	Sierra Leone	0	0	0	–
Rainfed upland					
Ankazomiriotra	Madagascar	11	53	69	0.12
BBK*	DRC	0	0	0	–
Glazoue	Benin	11	53	69	0.12
Haute Guinée	Guinée	0	11	5	0.08
Haut-Bassins	Burkina Faso	12	14	0	0.24
Man	Côte d'Ivoire	0	0	0	–
Navrongo	Ghana	61	2	13	0.61
West coast region	The Gambia	9	12	5	0.72

Results are presented only for sites with more than 10 samples of fields. Dash symbol indicates the sites for which the lowest, average and highest yielding farmers did not apply any nitrogen fertilizer.

* BBK: means Bas-Congo, Bandundu, Kinshasa and covers these three neighboring provinces.

4. Discussion

Poor soil fertility such as low soil total nitrogen and low soil clay content has been frequently considered as one of the major constraints for rice production in SSA (Haefele et al., 2014). Our results showed clear evidence for soil total nitrogen content constraining rice yield in rainfed lowland and soil clay content constraining rice yield in rainfed upland (Table 2). However, in irrigated lowland, the results from the stochastic production frontier analysis showed an unexpected negative yield response to soil clay content and soil total nitrogen content (Table 2). The negative response of rice yield to soil clay content in

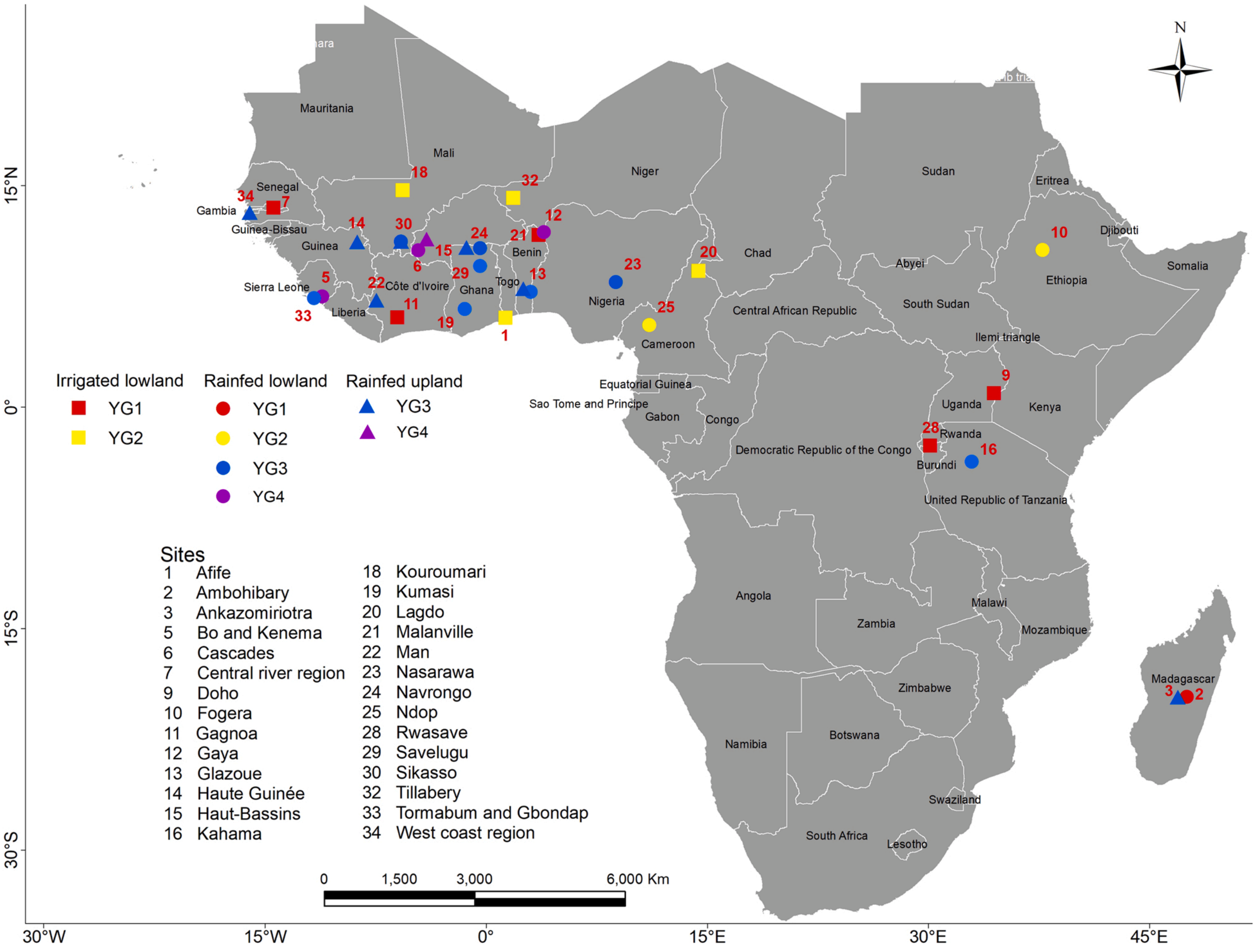

Fig. 7. Location of the yield gap groups identified in the three rice production systems. YG1, YG2, YG3, and YG4 are yield gap groups 1, 2, 3 and 4, respectively. YG1 is characterized by a large efficiency yield gap and a large technology yield gap. YG2 is characterized by a large efficiency yield gap and a small technology yield gap. YG3 is characterized by a small efficiency yield gap and a large technology yield gap. YG4 is characterized by small efficiency yield and a small technology yield gap.

irrigated lowland was also reported by Niang et al. (2017) and could be explained by the fact that some of the sites having a high soil clay content had a low rice yield (Table 1) possibly due to other factors such as poor crop management or micronutrients deficiency or toxicity (Na, Fe) at high soil clay content in anaerobic condition (Dramé et al., 2010). The negative relationship between soil total nitrogen and rice yield could be explained by the fact that in 4 sites (Afife, Doho, Gagnoa, and Rwasave), the soil total nitrogen was relatively high (>0.15 %), but the rice yield was relatively low (<3.3 t/ha) (Table 1). Low rice yield in Afife, Doho and Gagnoa might be related to other factors not included in this study such as poor crop management. In Rwasave located in the Rwanda highlands, cold stress might have limited rice yield (van Oort, 2018). In line with previous studies, our results indicated an increase in rice yield with nitrogen and phosphorus fertilizer application in irrigated lowland (Saito et al., 2019). Compared to the sub-humid zone, the response of rice yield to nitrogen fertilizer application was lower in humid zone possibly due to higher loss of nitrogen through nitrate leaching and surface runoff in the humid zone (Bognonkpe and Becker, 2009). We found a negative interaction between soil pH and nitrogen fertilizer on rice yield. Under high soil pH, this could be attributed to higher loss of nitrogen through ammonia volatilization (Fan and Mackenzie, 1993). Under low soil pH, ammonium might be directly absorbed by rice plants resulting in higher nitrogen uptake (Xiang et al., 2009) or the nitrification of ammonium to nitrate might be inhibited by low soil pH thus reducing the amount of nitrate available through denitrification and consequently a lower loss of nitrogen through N_2O or NO emissions (Simek and Cooper, 2002).

In rainfed lowland, there was a positive interaction between soil total nitrogen and nitrogen fertilizer input, i.e. in soils with high soil total nitrogen, nitrogen fertilizer rate had a greater impact on rice yield (Table 2). Because soil total nitrogen and soil organic carbon are strongly positively correlated in this study ($r = 0.98$), fields with higher soil total nitrogen also had higher soil total organic carbon and may therefore have better soil structure and higher water holding capacity, subsequently leading to a better crop growth at a given nitrogen fertilizer rate (Oldfield et al., 2019). The positive interaction effect between soil total nitrogen and nitrogen fertilizer rate indicated that a combination of building soil organic carbon and applying a target nitrogen fertilizer rate is desirable for increasing rice yield. Agricultural practices such as cover cropping, farm yard and compost manuring that have the potential to build soil organic carbon (Sahrawat, 2010) could represent a strategy to increase nitrogen fertilizer use efficiency in rainfed lowland. There was no relationship between soil total nitrogen and rice yield when nitrogen fertilizer was not applied (Fig. 3). This supports previous findings that indicated that soil total nitrogen was not always related to soil nitrogen mineralization and rice yield without N application (Cassman et al., 1996; Dobermann et al., 2003). Rice yield response to an increase in nitrogen fertilizer input was lower in the semi-arid zone than in the sub-humid zone possibly due to water stress (Wong and Nortcliff, 1995) and in the highland zone than in the sub-humid zone possibly due to cold stress (Njinju et al., 2018). The linear effect of soil clay content on rice yield was not significant, but the quadradic effect of

Table 4

Yield gaps cluster analysis using site mean efficiency yield gap and site mean technology yield gap. The cluster analysis identified four groups: large efficiency yield gap and large technology yield gap, large efficiency yield gap and small technology yield gap, small efficiency yield gap and large technology yield gap, small efficiency yield gap and small technology yield gap. Mean resource yield gap, mean yield gap, mean potential yield, mean yield, soil properties and fertilizer application were calculated for each group. Number of sites in each group is disaggregated by production system.

		Yield gap group (YG)			
		YG_1: Large efficiency yield gap and large technology yield gap	YG2: Large efficiency yield gap and small technology yield gap	YG3: Small efficiency yield gap and large technology yield gap	YG_4: Small efficiency yield gap and small technology yield gap
Yield gaps					
	Mean efficiency yield gap (t/ha)	2.20	2.91	1.24	1.27
	Mean technology yield gap (t/ha)	4.92	0.88	4.11	1.20
	Mean resource yield gap (t/ha)	0.18	0.20	0.38	0.79
	Mean total yield gap (t/ha)	7.30	3.99	5.73	3.26
Potential yield (t/ha)		10.85	8.32	7.50	5.82
Mean yield (t/ha)		3.55	4.33	1.77	2.56
Irrigated lowland					
	Number of sites	5	4	0	0
	pH (H_2O)	5.57	5.90	–	–
	Soil clay content (%)	32	47	–	–
	Soil total nitrogen (%)	0.17	0.10	–	–
	N fertilizer rate (kg/ha)	46	101	–	–
	Field with P fertilizer (%)	61	92	–	–
	Field with K fertilizer (%)	61	73	–	–
Rainfed lowland					
	Number of sites	1	2	8	3
	pH (H_2O)	5.54	5.36	5.38	5.06
	Soil clay content (%)	21	41	23	27
	Soil total nitrogen (%)	0.33	0.38	0.12	0.16
	N fertilizer rate (kg/ha)	1	77	28	44
	Field with P fertilizer (%)	0	32	29	39
	Field with K fertilizer (%)	0	28	27	38
Rainfed upland					
	Number of sites	0	0	6	1
	pH (H_2O)	–	–	5.64	4.02
	Soil clay content (%)	–	–	17	27
	Soil total nitrogen (%)	–	–	0.13	0.06
	N fertilizer rate (kg/ha)	–	–	11	12
	Field with P fertilizer (%)	–	–	28	58
	Field with K fertilizer (%)	–	–	28	58

Dash symbol indicates no data.

soil clay content on rice yield was negative, possibly due to poor soil drainage at high clay content resulting in lower yield (Haefele et al., 2014).

In rainfed upland, rice yield increased with soil clay content in line with previous studies (Haefele et al., 2014). There was a positive interaction between soil clay content and nitrogen fertilizer application rate on rice yield (Table 2), which might be attributed to higher soil moisture and higher nitrogen use efficiency in upland soils with higher clay content (Fageria et al., 2010).

The average total yield gap across sites was 5.0 t/ha in IL, 5.3 t/ha in RL and 5.6 t/ha in RU (Fig. 4). The average relative yield gap across sites was 55 % in IL, 67 % in rainfed lowland and 75 % in rainfed upland (Fig. 5). The total yield gap and the relative yield gap values observed in this study are similar to a recent study using the same method in SSA: 5.5 t/ha and 62 % for IL and 4.3 t/ha and 67 % for RL (van Oort et al., 2017). The site mean relative yield gap decreased with an increase in nitrogen fertilizer input in IL. However, site mean relative yield gaps in RL and RU were independent of the nitrogen fertilizer inputs (Fig. 5), suggesting that other factors such as water stress might have limited rice yield in RL and RU. Across site-production system combinations, the efficiency, resource and technology yield gaps contributed to 33, 8 and 59 % of the total yield gap, respectively. Using the stochastic frontier analysis combined with crop modelling, Silva et al. (2019) found in southern Ethiopia an efficiency, resource and technology yield gap of 30, 12 and 58 % of the total yield gap, respectively in maize farming system and 23, 7 and 70 % of the total yield gap, respectively in wheat farming system. This indicates that rice farming in SSA as well as maize and wheat farming in southern Ethiopia are characterized by large efficiency and large technology yield gaps. The large efficiency yield gap found in our study can be explained by the fact that rice farmers in SSA tended to use inappropriate crop management practices. For example, most farmers remove rice straw from the field or burn it in situ instead of applying rice straw as mulch or incorporating it into the field (Djagba et al., 2018). Also, most farmers do not level properly their fields, which leads to poor water and weed management (Touré et al., 2009). Furthermore, most of the farmers do not apply any organic inputs and do not rotate any crop with rice, which leads to soil mining and poor soil fertility. The large efficiency yield gap found in this study could also be explained by poor weed management particularly inappropriate use of herbicide due to lack of information and know-how on application techniques (Rodenburg et al., 2019). In RL and RU, most farmers do not apply any P and K fertilizer while N fertilizer is often applied only one time and does not coincide with critical growth stages (Saito et al., 2019). The large efficiency yield gap found in this study confirmed that further yield improvements could be derived through better crop management practices like previously reported by Niang et al. (2017, 2018) and Tanaka et al. (2013, 2017). The small resource yield gap found in this study can be attributed to the small variation in input use (e.g., N fertilizer) among the lowest-, average- and highest-yielding farmers. Only in 4 out of 36 site-production system combinations, there were significant differences in the nitrogen fertilizer rate applied by the lowest-, average- and highest-yielding farmers (Table 3). The large technology yield gap found in this study could be attributed to differences in rice varieties if farmers use low-yielding varieties with short duration compared to the simulated one, the use of a small rate of inputs by highest-yielding farmers (e.g. fertilizer application (Table 3)), soil constraints to rice cultivation such as salinity, iron toxicity, phosphorus deficiency which are not considered in crop modelling in this study (Bouman et al., 2001), limited knowledge of improved management practices (Balasubramanian et al., 2007), and the lack of adoption of precision agriculture practices in SSA (Finger et al., 2019). The average rate of nitrogen fertilizer applied by the highest yielding farmers is 44 kg/ha (Table 3) while achieving 7 t/ha requires an average rate of N fertilizer application of 122 kg/ha (Saito et al., 2019). Factors such as financial resource, climate risk, market access, and paddy price variability could be reasons for the use of a low amount of input and sub-optimum nutrient management practices, resulting in a large technology yield gap (Totin et al., 2012, 2015; van Oort et al., 2017). Better understanding of farm(ers) characteristics and regional constraints are required to prioritize short-term needs to narrowing the yield gaps.

The yield gap groups were related to the production systems, soil properties, fertilizer application and rice yield. Yield gap groups 1, 2, 3 and 4 identified in this study are respectively close to the yield groups 2, 1, 4 and 3, reported in Tanaka et al. (2017). In this study, the mean rice yields are 3.6, 4.3, 1.8 and 2.6 t/ha in yield gap groups 1, 2, 3 and 4, respectively (Table 4) while the mean rice yields are 3.5, 5.3, 1.6 and 2.0 t/ha in yield groups 2, 1, 4 and 3, respectively in Tanaka et al. (2017). Narrowing the efficiency yield gap in IL and RL sites of YG1 and YG2 requires the dissemination of available integrated crop management practices such as timely fertilizer application and weed control, and land leveling (Niang et al., 2017; Rodenburg et al., 2019). Narrowing the technology yield gap in YG1 requires the identification of the constraints to inputs use (e.g. fertilizer, labour, herbicide) and the development of technologies for improving input use efficiency. Narrowing the technology yield gap in YG3 requires the development of technologies to improve soil properties, particularly soil total nitrogen. Enhancing rice yield in YG4 remains a challenge due to the low potential for rice cultivation (low water-limited potential yield and poor soil quality) (Table 4). This requires the genetic improvement of rice under water scarce conditions and an improvement of soil properties.

A few limitations might have influenced the results obtained in our study. The first is our assumption on groundwater data for which no high-resolution dataset is available and consequently, simulations were made using the groundwater depth of a typical RL soil and a typical RU soil during the wet season. The second limitation is related to the fact that technical efficient yield was calculated using the entire dataset. But the highest farmer's yield and the potential yield in irrigated lowland or the water-limited potential yield in rainfed systems were determined in each site rather than for each agro-ecological zone. This is because the simulation of potential yield or water-limited potential yield requires variety-specific parameters for crop modeling, and we cannot simulate the potential yield or water-limited potential yield in different sites of the same agro-ecological zone using same variety-specific parameters. Therefore, we recognize that there is a mismatch in the unit of analysis which might induce some biases in the assessment of the resource and technology yield gaps. However, once target sites are identified using results from continental level assessments like in this study, detailed yield gap assessment can be done for each site to overcome the inconsistency in the unit of the analysis. Further study needs to identify appropriate sampling size for decomposing rice yield gaps into efficiency, resource, and technology yield gaps, taking into account year-to-year variability in climatic factors and yield. Also, as mentioned above, the groundwater level should be assessed in each field or representative fields for the simulation of water-limited potential yield. Thirdly, as consequences of the application of the stochastic frontier framework and variability in the data, there might be some biases in the assessment of the technology yield gap which might be partly the resource yield gaps of specific inputs because some of the highest-yielding farmers use a small rate of fertilizer application. This study did not consider other crop management practices except fertilizer management practices. Further assessment of the impact of other crop management practices on the yield gaps is warranted.

5. Conclusion

This is the first study that decomposed the yield gap into efficiency, resource and technology yield gaps in rice farming in SSA and identified priority areas for research and development. Yield gaps ranged from 2.0 to 10.0 t/ha across site-production system combinations. On average, efficiency, resource, and technology yield gaps accounted for 37, 8 and 55 % of the yield gap, respectively. The resource yield gap was relatively small (<1 t/ha), except for two sites in rainfed lowland system. Four yield gaps groups were identified. A group with small efficiency and small technology yield gaps had only 4 sites. A group with a small efficiency yield gap and large technology yield gap had 14 sites. A group with a large efficiency yield gap and small technology yield gap had 5 sites. A group with large efficiency and large technology yield gaps had 7 sites. All irrigated lowland sites had a large efficiency yield gap. Narrowing yield gaps requires the dissemination of integrated crop management practices in yield gaps groups with a large efficiency yield gap. In yield gaps groups with a large technology yield gap, development of technologies to improve soil properties and fertilizer use should be given priority. Increasing rice yield in the yield gap group with small efficiency and small technology yield gaps remains a challenge due to the low potential rice yield. This requires the genetic improvement of rice under water scarce conditions and an improvement of soil properties.

CRediT authorship contribution statement

Elliott Ronald Dossou-Yovo: Methodology, Data curation, Software, Writing - original draft. **Elke Vandamme:** Conceptualization, Methodology, Writing - review & editing. **Ibnou Dieng:** Software,

Writing - review & editing. **Jean-Martial Johnson:** Investigation, Data curation, Writing - review & editing. **Kazuki Saito:** Conceptualization, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fcr.2020.107963.

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