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Research Paper

Variability and determinants of yields in rice production systems of West Africa

Abibou Niang[a,b,*,1], Mathias Becker[b], Frank Ewert[b,2], Ibnou Dieng[a], Thomas Gaiser[b], Atsuko Tanaka[a,c], Kalimuthu Senthilkumar[d], Jonne Rodenburg[d,3], Jean-Martial Johnson[a], Cyriaque Akakpo[e], Zacharie Segda[f], Henri Gbakatchetche[g], Famara Jaiteh[h], Ralph K. Bam[i], Wilson Dogbe[j], Sékou Keita[k], Nianankoro Kamissoko[l], Illiassou Maïga Mossi[m], Oladele S. Bakare[n], Madiama Cissé[o], Idriss Baggie[p], Komlan A. Ablede[q], Kazuki Saito[a]

[a] *Africa Rice Center (AfricaRice), 01 B.P. 2031, Cotonou, Benin*
[b] *Institute of Crop Science and Resource Conservation (INRES), University of Bonn, 53115 Bonn, Germany*
[c] *Japan International Cooperation Agency (JICA), Benin Office, 01 B.P. 7097, Cotonou, Benin*
[d] *Africa Rice Center (AfricaRice), Regional Station for East and Southern Africa, P.O. Box 33581, Dar es Salaam, Tanzania*
[e] *Programme Recherche Rizicole, Institut National des Recherches Agricoles du Bénin (INRAB), B.P. 143, Bohicon, Benin*
[f] *Programme Riz, Institut de l'Environnement et de Recherches Agricoles (INERA), 04 B.P. 8645 Ouagadougou, Burkina Faso*
[g] *Programme Riz, Centre National de Recherche Agronomique (CNRA), B.P. 440, Man, Côte d'Ivoire*
[h] *Cereals Programme, National Agricultural Research Institute (NARI), P.M.B. 144, Brikama, Gambia*
[i] *Rice Programme, CSIR-Crops Research Institute (CRI), P.O. Box 3785, Fumesua-Kumasi, Ghana*
[j] *Rice Research for Development Programme, CSIR-Savanna Agricultural Research Institute (SARI), P.O. Box 52, Tamale, Ghana*
[k] *Programme Riz, Institut de Recherche Agronomique de Guinée (IRAG), Kankan, B.P. 1523, Conakry, Guinea*
[l] *Programme Riz irrigué, Institut d'Économie Rurale (IER), Niono, B.P. 258, Bamako, Mali*
[m] *Cultures irriguées, Institut National de la Recherche Agronomique du Niger (INRAN), B.P. 429, Niamey, Niger*
[n] *Information & Documentation, National Cereals Research Institute (NCRI), P.M.B. 8 Badeggi, Niger State, Nigeria*
[o] *Institut Sénégalais de Recherches Agricoles (ISRA), B.P. 240, Saint-Louis, Senegal*
[p] *Soil and Crop Resource Management, Rokupr Agricultural Research Centre (RARC), P.M.B. 736 Freetown, Sierra Leone*
[q] *Programme Riz, Institut Togolais de Recherche Agronomique (ITRA), B.P. 1163, Lomé, Togo*

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ABSTRACT

Rice (*Oryza* spp.) is the major staple food for most countries in West Africa, but local production does not meet demand. Rice is grown mainly by smallholder farmers, and yields are generally low with high temporal and spatial variability. Low yields have been attributed to unfavorable climate conditions, poor soil quality, and sub-optimum agricultural practices. The objectives of this study were to assess variation in yields of three major rice production systems (irrigated lowland, rainfed lowland, and upland) across three climatic zones (semi-arid, sub-humid, and humid), and identify factors affecting that variation. We analyzed data on yield, climate, soil, and agricultural practices for 1305 farmers' fields at 22 sites in 11 West African countries between 2012 and 2014. A boundary function approach was used to determine attainable yields. Random forest algorithm was used to identify factors responsible for yield variation. Average rice yield was 4.1, 2.0, and 1.5 t ha^{-1} in irrigated lowland, rainfed lowland, and rainfed upland systems, respectively, with maximum attainable yields of 8.3, 6.5, and 4.0 t ha^{-1}. Yield difference between attainable and average yield tended to be higher in irrigated and rainfed lowland systems. In those two systems, yields were highest in the semi-arid zone, while no difference in yields among climatic zones was apparent for upland rice. High rice yields were associated with high solar radiation, high

* Corresponding author at: Africa Rice Center (AfricaRice), 01 B.P. 2031, Cotonou, Benin.
E-mail address: abib.niang@gmail.com (A. Niang).

[1] Currently at: Olam International Ltd. In Gabon, Galerie Tsika, BP 1024, Libreville, Gabon.
[2] Currently at: Leibniz Centre for Agricultural Landscape Research (ZALF), 15374 Muncheberg, Germany.
[3] Currently at: Africa Rice Center (AfricaRice), 01 B.P. 4029, Abidjan 01, Côte d'Ivoire.

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maximum temperature, intermediate air humidity, multiple split nitrogen (N) fertilizer applications, high frequency of weeding operations, the use of certified seeds, and well-leveled fields in the irrigated lowland system. Minimum temperature, solar radiation, rainfall, construction of field bunds, varietal choice, and the frequency of weeding operations were determinants of rice yield variation in the rainfed lowland system. Varietal choice, bird control, and frequency of weeding operations affected rice yields in the upland system. Improving access to inputs, improving input use efficiencies, and site-specific management strategies are recommended as priority interventions to boost rice yields at regional scale independent of production system and climatic zone.

1. Introduction

With six million hectares or 60% of the continent's rice-growing area, West Africa is the most important rice production region in Africa (Diagne et al., 2013); however, it requires enhanced rice production to meet current and future demand (van Ittersum et al., 2016; van Oort et al., 2016). Production systems comprise irrigated lowlands, rainfed lowlands, and uplands, with deep-water and mangrove rice being of only minor importance (Balasubramanian et al., 2007). Rice is grown across agro-ecological zones that are differentiated by the length of the growing period (LGP). The agro-ecological zones consist of the Sahel with an LGP of 65–90 days, corresponding to arid and semi-arid zones; the dry savanna with an LGP of 90–180 days and the moist savanna with an LGP of 180–270 days, corresponding to the sub-humid zone; and the forest with an LGP >270 days, corresponding to humid zone (Peel et al., 2007). In this paper, we use the term 'climatic zone' which comprises arid, semi-arid, sub-humid, and humid zones as shown in Fig. 1.

Climatic attributes such as rainfall, solar radiation, and temperature change markedly across climatic zones, with substantially higher solar radiation but also much greater temperature and humidity amplitudes in the arid than the humid zone (Windmeijer and Andriesse, 1993). Although high solar radiation is generally associated with high yield, extreme temperatures can cause heat- or cold-induced spikelet sterility, resulting in low yield (van Oort et al., 2014). These climatic conditions differentially affect soil weathering with associated changes in nutrient stocks, cation exchange capacity (CEC), and pH (Bouma and Finke, 1993). Thus, rice soils in the humid forest zone tend to be highly weathered and acidic with macronutrient deficiencies (Haefele and Wopereis, 2005) and microelement toxicities (Becker and Asch, 2005). On the other hand, soils in the arid and semi-arid zones are mostly little weathered with generally higher CEC and soil pH, but salinity and alkalinity problems are commonly observed (Asch et al., 1995; Ceuppens et al., 1997; Saito et al., 2013).

Irrespective of climatic zones, irrigated rice is generally produced in bunded paddy fields with irrigation, which allows for the cultivation of more than one crop per year. In all but the arid zone, rainfed lowland rice is grown on level to slightly sloping, unbunded or bunded fields in lower parts of the toposequence in inland valleys (Touré et al., 2009). Upland rice is produced on level or sloping unbunded fields in hilly regions within the undulating inland valley landscape with low groundwater tables. Such diverse growing conditions result in large variation in yields across production systems (Becker and Johnson, 2001a,b; Becker et al., 2003) and farmers' fields within a given system (Saito et al., 2013).

Apart from these climatic and edaphic properties, and the production systems themselves, farmers' rice yields are also affected by agricultural practices, which are largely determined by the resource endowment of the farmers that affects the production orientation, cropping intensity, and input use (Angulo et al., 2012; Tanaka et al., 2013). Large between-farm variability has been observed for crop establishment date and methods (Tanaka et al., 2013, 2015), varietal choice (Dingkuhn and Asch, 1999), tillage method (Becker et al., 2003), water management (Becker and Johnson, 2001a), the amount and timing of fertilizer applications (Haefele et al., 2003), and the frequency and type of weed and pest control (Wopereis et al., 1999; Kent et al., 2001). All these factors have been reported to affect yields and possibly explain their variability.

Most previous studies assessing on-farm rice yields, yield variation, and agricultural practices in West Africa were conducted in the mid- to late 1990s (Wopereis et al., 1999; Becker and Johnson, 2001a,b; Becker et al., 2003), with only two recent studies of irrigated lowland rice (Tanaka et al., 2013, 2015), and most have focused on Côte d'Ivoire and Senegal. Recently, Tanaka et al. (2017) showed yield variation in three major rice production systems in 19 sub-Saharan African countries, but they did not consider any agricultural practices. With rice being grown in all 17 countries of the region and with changing rice demand, increasing globalization effects, and recent technological innovations (new varieties, mechanization, access to information and communications technology, etc.), rice production systems and agricultural practices have evolved differentially in the past decade with likely implications on yields and yield variability. Furthermore, few studies in West Africa have considered climatic attributes when assessing on-farm yield variation. Thus, it appears timely to re-assess the performance attributes of the major rice production systems. The objectives of this study were to determine variations in yield of major rice production systems (irrigated lowland, rainfed lowland, and upland rice) across climatic zones (semi-arid, sub-humid, and humid) in West Africa, and to identify the role of climatic and edaphic attributes and of agricultural practices affecting rice yields and their variation in West Africa.

2. Material and methods

2.1. Study sites and sampling frame

The cross-sectional study of rice performance attributes and their determinants was conducted at 22 sites in 11 countries (Fig. 1). These study sites were selected by national agricultural research institutes and are considered priority intervention sites for national rice research and development. Each study site comprised up to eight rice-producing villages, except for Bo and Kenema in Sierra Leone with 20 villages (where number of farmers per village was relatively small), with an average of 12 farmers being randomly selected in each village (34–93 farmers per study site). The field surveys were performed during the rainy seasons in 2012, 2013, and 2014. In total, the sample comprised 1368 farmers' fields before data cleaning. The distribution of the sites by country and climatic zone, the sample size of farmers, and the period of data collection are summarized in Table 1. Climate data were collected from automated weather stations established in most of the study sites: solar radiation, rainfall, and minimum and maximum temperatures.

When ground station data time series were incomplete, weather data were obtained from the online Global Summary of the Day