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Spatiotemporal Survey of Multiple Rice Diseases in Irrigated Areas Compared to Rainfed Lowlands in the Western Burkina Faso

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Abstract

Multiple constraints affect rice yields in West Africa. Among these constraints are viral, bacterial, and fungal pathogens. We aimed to describe the spatiotemporal patterns of occurrence and incidence of multiple rice diseases in farmers' fields in contrasting rice growing systems in the western Burkina Faso. For this purpose, we selected a set of three pairs of sites, each comprising an irrigated area and a neighboring rainfed lowland, and studied them over four consecutive years. We first performed interviews with the rice farmers to better characterize the management practices at the different sites. This study revealed that the transplanting of rice and the possibility of growing rice twice a year are restricted to irrigated areas, while other practices, such as the use of registered rice cultivars, fertilization, and pesticides, are not specific but differ between the two rice growing systems. Then, we performed symptom observations at these study sites to monitor the following four diseases: yellow mottle disease, Bacterial Leaf Streak (BLS), rice leaf blast, and brown spot. The infection rates were found to be higher in irrigated areas than in rainfed lowlands, both when analyzing all observed symptoms together (any of the four diseases) and when specifically considering each of the two diseases: BLS and rice leaf blast. Brown spot was particularly prevalent in all six study sites, while yellow mottle disease was particularly structured geographically. Various diseases were frequently found together in the same field (co-occurrence) or even on the same plant (coinfection), especially in irrigated areas.

Keywords: *Bipolaris* spp, Burkina Faso, Epidemiology, *Magnaporthe oryzae*, Rice, RYMV, *Xanthomonas oryzae*

Yield losses that occur because of pathogens and insect pests in major crops are estimated at 17 to 30% worldwide, with the highest losses evidenced in food-deficit regions with fast-growing populations (Savary et al. 2019). Such drastic yield losses emphasize the need to develop efficient control strategies to achieve food security. Understanding the spatiotemporal dynamics of crop diseases and identifying the risk factors are of primary importance for guiding the deployment of control strategies (Carvajal-Yepes et al. 2019), as illustrated by the management of potato mildew, cereal rust, apple scab, and cassava mosaic (Jones 1998). The availability of recent field data is critical for this purpose and will likely become the major issue as a large range of analytical tools becomes available (Savary et al. 2011a).

Spatiotemporal field surveys allow the accumulation of data for this purpose and may either focus on a particular disease or target multiple diseases at once. The latter case appears to be more challenging, as it requires specific protocols and field workers with extended skills, potentially explaining why this type of survey remains rare in the literature (but see Savary et al. 2011b, 2016). However, spatiotemporal surveys of multiple crop diseases can generate a wealth of information in a cost-effective way and generate pertinent information on the co-occurrence (i.e., simultaneous presence in the same site) of multiple diseases over a geographic area. Indeed, co-occurrence is a prerequisite for coinfection, i.e., the simultaneous infection of the same plant by various pathogens. Coinfecting pathogens frequently interact within plants in positive (synergism) or negative (antagonism) ways (Abdullah et al. 2017), with striking consequences on pathogen multiplication and symptom expression (Barrett et al. 2009; Syller 2012), and further impact on evolutionary and epidemiological outcomes (Tollenaere et al. 2016). In this study, we described the spatial occurrence and incidence of four major rice diseases in six study sites in the western Burkina Faso.

Rice is a major staple crop in West Africa. It accounts for 25% of the overall cereal consumption, second only to maize (Mendez del Villar and Bauer 2013). Over recent decades, West Africa specifically has experienced a large surge in rice consumption (8% increase each year from 2009 to 2019; Soullier et al. 2020) as a consequence of demographic growth and habit changes caused by urbanization (preference for fast-prepared foods such as rice). To face such a growing demand and, particularly, following the 2008 price crisis, West African states are developing ambitious projects to increase local rice production and decrease their dependency on the worldwide rice market (Demont 2013; Soullier et al. 2020). For example, in Burkina Faso, rice-growing areas increased more than threefold between 2006 and 2016 (FAO), and the average annual growth of production was 6% between 2009 and 2019 (Soullier et al. 2020). Such a production increase is, however, lower than the average annual national consumption growth (12%) so that the dependence of the country on importations is maintained, and the importance of sustained efforts to increase local rice production is highlighted.

Rice cultivation in West Africa is performed within four major production systems: rainfed upland, rainfed lowland, irrigated, and mangrove swamps (AfricaRice 2011; Katic et al. 2013). Among these four rice production systems, irrigated rice and rainfed upland rice are particularly important in Burkina Faso. First, irrigated rice, introduced in the 1960s with labor-intensive and costly infrastructures, remains restricted to particular sites (<30% of harvest areas; CountrySTAT

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2021). However, irrigated rice constitutes more than half of the total paddy rice produced as a consequence of the relatively high productivity of this system, up to 4 to 7 t/ha per year (MAHRH 2011). On the other hand, rainfed lowland rice is grown in valleys in regions where rainfall is sufficient and represents the largest rice growing surface in the country (67% between 1984 and 2009; MAHRH 2011). Rainfed rice systems are characterized by a lack of water control, and their yields remain low; for example, a yield of only 2 t/ha per year was estimated at the Dano site (Serpantié et al. 2019), and rice grown under this system is mostly dedicated to self-consumption.

A study consulting rice farmers in the Malanville area in Benin (Nonvide et al. 2018) showed significant differences in the socioeconomic and demographic characteristics between rice farmers from irrigated areas versus those from rainfed lowlands, with differences in rice cultivation practices. Notably, irrigated areas presented higher fertilizer application rates and the more frequent use of improved high-quality seeds compared with those in rainfed farming systems (Nonvide et al. 2018). Irrigated areas and rainfed lowlands in West Africa thus represent two rice production systems that are characterized by their contrasting water availability/control but also differ in many other aspects that cannot be distinguished.

Various constraints hamper the development of rice production in West Africa (Balasubramanian et al. 2007). Diseases are one of these constraints and were considered the major cause of crop losses observed in fields in a farmer survey in the Cascades region in Burkina Faso (Kam et al. 2013). The major rice diseases in Africa include yellow mottle disease, Bacterial Leaf Blight (BLB), Bacterial Leaf Streak (BLS), rice blast, and brown spot (Séré et al. 2013).

Rice yellow mottle disease, caused by the rice yellow mottle virus (RYMV), is endemic in Africa and is estimated to cause approximately 4.3% of rice production losses in Sub-Saharan Africa (Savary et al. 2019). This disease occurs in different rice systems, but epidemics are less frequent in rainfed rice than in irrigated rice (Traore et al. 2009). Agricultural intensification is considered to favor RYMV epidemics as a consequence of the generalization of susceptible cultivars and the transplanting step, which favors mechanical transmission (Traore et al. 2009).

The bacteria *Xanthomonas oryzae* presents two pathovars (pv.): pv. *oryzae*, causing BLB, and pv. *oryzicola*, causing BLS; these two diseases constrain rice production in much of Asia and parts of Africa (Nino-Liu et al. 2006). In particular, BLS is considered as an emerging disease in West Africa (Wonni et al. 2011). The disease is seedborne and seed-transmitted; its development is favored by rain, high humidity (>80%), and high temperatures (28–30°C) (Cartwright et al. 2018).

Rice blast disease, caused by *Magnaporthe oryzae*—syn. *Pyricularia oryzae*—can be particularly destructive, causing an estimated 4.2% of rice production losses in Sub-Saharan Africa (Savary et al. 2019). Major factors known to affect this type of epidemic development are rice cultivar, climatic factors (temperature, humidity, and the presence of dew; Ou 1985), water management, and nitrogen fertilization (Long et al. 2000). Losses caused by blast are greatest in upland rice and in intensive, high-input rice cultivation regions (Cartwright et al. 2018).

Brown spot, caused by *Bipolaris oryzae,* is estimated to cause 3.8% of rice production losses worldwide (Savary et al. 2019), second only to rice blast in terms of its economic importance (Cartwright et al. 2018). This disease was classically known to be associated with scarce water resources (as it is prevalent in rainfed lowlands and uplands, and higher incidence of the disease is observed in lower rainfall years) combined with nutritional imbalances, particularly the lack of nitrogen. Consequently, the disease is often associated with resource-poor farmers' fields (Barnwal et al. 2013; Mew and Gonzales 2002; Pannu et al. 2005). However, its recent reemergence on a large array of conditions (Barnwal et al. 2013) challenges this statement and may be linked to climate change (Bregaglio et al. 2013; Savary et al. 2011a).

Rice and its diseases constitute an ideal model in crop epidemiology (Savary et al. 2011b), because of the central role of rice in global food security (Zeigler and Barclay 2008), the importance of rice diseases as yield-reducing factors (Savary et al. 2019), the existence of large-scale field survey data, and the specificity of various rice disease symptoms enabling symptom-based epidemiological approaches. In Africa, research on rice diseases is active in terms of pathogen collection and characterization and the evaluation of control methods. However, studies describing the epidemiological patterns of rice diseases in farmers' fields remain rare, especially studies simultaneously considering multiple diseases, with very few exceptions including the descriptions of rice diseases in mangrove swamp rice in Sierra Leone (Fomba 1984), and a study on the fungal seed-borne diseases of rice conducted in Burkina Faso (Ouedraogo et al. 2016).

This work presents an observational study of rice disease symptoms in smallholder rice fields in western Burkina Faso. We first described the six study sites in terms of agricultural practices (sociological information, rice cultivars, fertilization practices, and off-season crops) to improve the characterization of the practices used in each rice production system: irrigated areas and rainfed lowlands. Then, we documented the spatiotemporal dynamics of four major rice diseases: yellow mottle, bacterial leaf streak, leaf blast, and brown spot. More specifically, our aim was to compare disease levels between two contrasting rice production systems (irrigated areas compared with rainfed lowlands) and to estimate the levels of disease co-occurrence and coinfection among the four considered rice diseases.

Materials and Methods

Overall rationale of the study and choice of studied fields. The study area is in the western Burkina Faso, in a 100 × 100-km location within the two regions Hauts-Bassins (Houet and Kenedougou provinces) and Cascades (Comoe and Lereba provinces) in the Sudanian bioclimatic area (Fig. 1).

The study sites are located within three geographical zones (Bama, Banzon, and Karfiguela), and we studied an irrigated area and a neighboring rainfed lowland area in each of these three zones (Table 1 and Fig. 1). The irrigated areas and rainfed lowlands were chosen as "neighboring" (maximal distance between the irrigated and lowland fields within a geographical zone was 7 km) to assume similar climatic conditions. In this context, we assume that for each zone, only the rice-growing practices differed between the irrigated areas and rainfed lowlands. We returned to these six sites annually from 2016 to 2019. Prior to this study period, an initial survey (Tollenaere et al. 2017) was performed in 2015 that included two of the study areas (both irrigated), Banzon and Karfiguela, and these data were included in some subsequent analyses.

Within each of these six sites, we used aerial pictures and selected the studied fields so that they would be accessible and evenly distributed spatially within site. Such field selection was performed before getting to the field so that symptom observations could not bias field selection. Each studied field was approximately a square of 25 meters on each side (ca. 625 square meters). The total number of fields studied per year and per site ranged between 5 and 11; the details are shown in Table 1. Over the 5-year (2015–2019) period, 203 observations were performed (179 observations over the 2016–2019 period). In every case, we obtained permission from the farmers to work in their fields, and the management of the entire project followed the guidelines of the Nagoya protocol regarding access and benefit-sharing.

Farmers' interviews. We aimed to characterize each site and each production system (irrigated areas and rainfed lowlands) in terms of sociological information, rice cultivars, cultivation practices, and off-season crops. For this purpose, interviews with farmers were performed for 81% of the surveyed fields, with a total of 165 interviews performed over the 2015 to 2019 period (see Table 1 for detailed information regarding each site and year). The interviews were mostly performed face-to-face but also sometimes (37/165 = 22%) by phone.

The survey questionnaire included a set of questions concerning four topics: (i) the farmer (age, gender, whether rice is cultivated to sell or for self-consumption), (ii) the rice cultivars grown, (iii) the cultivation practices used in the field (planting, fertilization, pesticides), and (iv) the preceding crops (in the dry season and previous wet season). The original list of questions was slightly amended across the study years. All collected data were recorded in the Afrivey (AfricaSys) application on a smartphone.

Protocol for symptom observations. The observations were performed at the maximum tillering or heading initiation stages of the field from September to December each year.

Each studied field was visually inspected carefully for the presence of major rice diseases. We particularly focused on the following four diseases, for which the detection was confirmed by serological, molecular, or biological analyses (see below): yellow mottle disease, BLS, rice leaf blast, and brown spot.

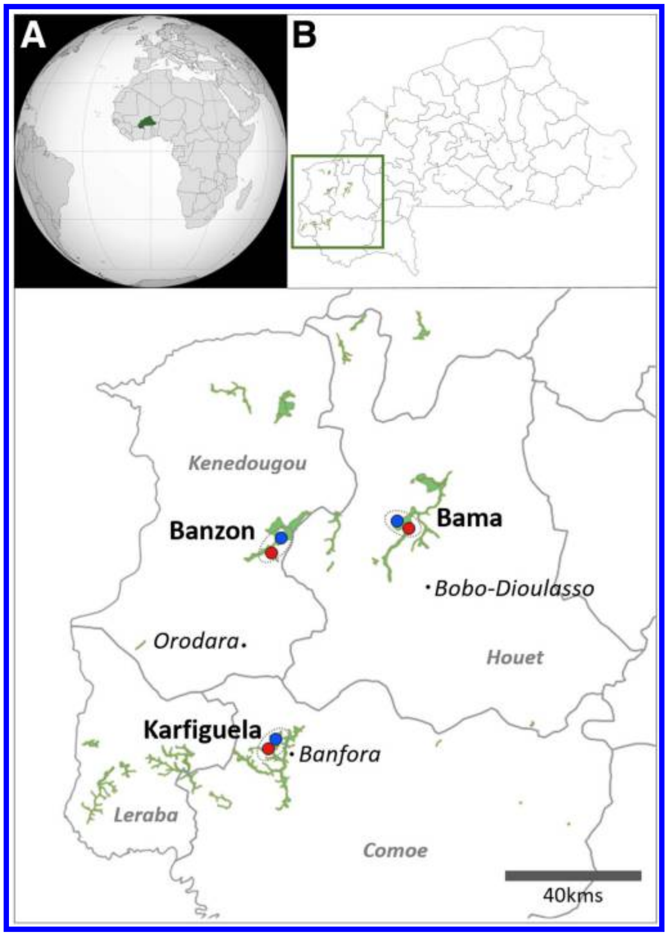

Fig. 1. Locations of the study sites: **A,** location of Burkina Faso in Africa; **B,** location of the area studied in Burkina Faso; and **C,** precise locations of the six rice growing study sites with irrigated sites in blue and rainfed lowland sites in red within the three geographical zones (Bama, Banzon, and Karfiguela). The locations of all rice fields and irrigated areas according to the Burkina Faso land occupation database (https://www.ignfi.fr/fr/portfolio-item/occupation-des-terres-burkina-fao) are indicated in maps **B and C**. Three major cities (Bobo-Dioulasso, Banfora, and Orodara) and four provinces (Comoe, Houet, Kenedougou, and Leraba) are mentioned.

The presence or absence of each of these four diseases was reported in the Afrivey application for each studied field. In addition, each field was subdivided in a 4 × 4 grid (materialized using wooden stakes), and the incidence (0 to 100% infected plants based on observations of specific symptoms by carefully pacing around each cell) was estimated in four cells of a diagonal transect in the grid. Moreover, we annotated the presence or absence (with no severity estimates) of the observed symptoms on the leaves of each of the 16 plants located at the intersections of the 4 × 4 grid. Three leaves of each of these 16 studied plants per field were dried and stored in paper envelopes in plastic bags containing silica gel for further laboratory analyses performed to confirm the symptom-based diagnosis.

We recorded all the data (from the fields, diagonal cells, and plant hierarchical levels) directly in the Afrivey application, as with the data obtained from the farmer interviews.

Pathogen detection to assess symptom recognition. To determine the accuracy of disease identification based on symptoms in the field, a subset of collected samples was submitted to laboratory detection methods. In particular, 85 leaves presenting yellow mottle-specific symptoms and collected in 2015 were submitted to RYMV-specific serological detection, by ELISA (Traoré et al. 2008) in INERA Kamboinse, PathoBios platform (Burkina Faso). A few leaves presenting BLS symptoms were kept fresh following the sampling and frozen (–20°C) when back in the laboratory. *Xanthomonas oryzae*-specific molecular amplification (Lang et al. 2010) was performed in the Bobo-Dioulasso molecular biology PathoBios platform (Burkina Faso) on a set of samples collected in 2016 (n = 5) and then on a set collected in 2017 (n = 12). The leaves presenting rice blast or brown spot symptoms were kept dried in an envelope containing silica gel. Back at the mycology laboratory at INERA Farako-Bâ (Burkina Faso), we arranged the leaf samples on humid blotting paper in a growth chamber with a 12-h/12-h light/darkness cycle. After one week of incubation, mycelial growth was observed with a binocular microscope, and spores were observed using a light microscope. The fungi were identified following the classical methodology (Mathur and Kongsdal 2003). In addition, for the brown spot identification, 21 strains were isolated from the symptomatic samples collected in 2018, and molecular characterization (sequencing of ITS, GPD and EF1 genes) was performed in Cirad (Montpellier, France).

Data analysis. The data analysis was performed using R software (R Core Team 2018) using various packages for the analyses (see above) and 'ggplot2' (Wickham 2016) for visualization.

The data on rice cultivation practices obtained from farmers' interviews (165 interviews, Table 1) were analyzed using multiple correspondence analysis (MCA) on a subset of nine variables describing the cultivars divided into four categories (the rice cultivars FKR62N on the one hand, the rice cultivar FKR64 on the other hand, other registered, and finally unregistered cultivars), and the management practices, direct seedling or transplanting, the presence/absence of mineral fertilization, the presence/absence of organic fertilization, the number of NPK applications, the number of urea applications, herbicide application (or not), insecticide application (or not), and crop type planted in the off-season (rice, legumes or nothing). First, we

Table 1. List of the six sites studied from 2015 to 2019 in western Burkina Faso

	Number of fields studied[b]				
Studied site (name of the village)[a]	**2015**	**2016**	**2017**	**2018**	**2019**
Bama-RL (Badala)	0	6 (6)	8 (5)	7 (5)	6 (6)
Bama-IR (Bama)	0	10 (10)	8 (4)	9 (7)	7 (6)
Banzon-RL (Senzon)	0	5 (5)	7 (4)	7 (6)	7 (5)
Banzon-IR (Banzon)	12 (11)	8 (8)	8 (7)	11 (9)	6 (5)
Karfiguela-RL (Tengrela)	0	5 (5)	7 (7)	7 (6)	6 (6)
Karfiguela-IR (Karfiguela)	12 (11)	9 (7)	8 (3)	9 (7)	8 (4)
Total (all sites)	24 (22)	43 (41)	46 (30)	50 (40)	40 (32)

[a] RL: rainfed lowlands; IR: irrigated areas.
[b] The number of rice fields where symptom observations were performed are indicated for each year, with the number of fields where farmers' interviews could be performed in parentheses.

used the package 'missDMA' to impute missing data in the dataset. Then, the packages 'FactoMineR' and 'factoextra' were used to perform the MCA analysis and to visualize the results, respectively. The sample sizes at each site and year were small for the rice cultivation practices (Table 1), so we performed a visual representation to characterize the rice cultivation practices at each site but did not statistically analyze the data.

Second, in order to compare the disease pressures in irrigated areas compared with those in rainfed lowlands, we analyzed the symptom data at various scales (field and plant) using generalized linear mixed models (GLMMs) using the package 'lme4' in R. Type III ANOVA was performed with the package 'car', and a contrast analysis was performed using the package 'lsmeans'.

The presence or absence of different types of symptoms at the plant level was modeled using binomial regression over the 2016 to 2019 dataset, i.e., 16 plants × 179 fields = 2,864 observations. First, we considered the presence or absence of symptoms of any of the four main rice diseases, yellow mottle disease, BLS, rice leaf blast, and brown spot, as a multipathogen response variable. Then, we modeled the presence or absence of symptoms of each of the four main studied diseases (yellow mottle disease, BLS, blast, and brown spot) independently. The same kind of modeling was performed for each of these five variables, with the year and field included as random effects and the rice production system, the geographical zone, and their interaction included as fixed effects (only the significant factors were included in the final version of each model).

At the field level, the presence or absence of each of the four diseases in each field and year was modeled using binomial regression over the 2016 to 2019 dataset (179 observations). Four GLMMs were run with the rice production system, the geographical zone and their interaction (if significant) included as fixed effects and the year included as a random effect.

We then added the presence or absence of the three other diseases to the four GLMMs to assess the potential statistical associations among the four main studied diseases. The levels of cooccurrence were also estimated for each disease pair (six in total) in each site and year.

Finally, the levels of coinfection were estimated at each site and year considering simultaneous presence of symptoms of at least two diseases of the four diseases studied (yellow mottle disease, BLS, rice blast, and brown spot) on the same rice plant.

Results

Obtained data. The obtained data are available on the IRD data storage platform (https://dataverse.ird.fr) with doi 10.23708/8FDWIE. Five datasets are included: (i) a dataset of the sampling dates of the studied fields, (ii) a dataset containing the results of the interviews with farmers, (iii) a dataset containing the symptom observations at the field level (presence/absence of each disease in the field), (iv) a dataset with the symptom observations listed at the cell level (incidence estimate of each disease in the four diagonal cells of each grid), and finally (v) a dataset containing symptom observations in each of the particular plants. Only the precise location of each rice field (GPS coordinate) remains as a private file to preserve the anonymity of the farmers.

The total number of field visits for symptom observations and sampling over the 2015 to 2019 period was 203, while the number of interviews performed with farmers was 165 (Table 1). The observation dates differed between the irrigated areas and rainfed lowlands, as the rice season is slightly later and more variable in irrigated areas (data not shown).

The set of samples collected in 2015 and analyzed by RYMV-specific ELISA resulted in 80/84 (95.2%) RYMV-positive samples. *Xanthomonas oryzae*-specific molecular detection revealed the presence of *Xanthomonas oryzae* in almost all cases (16/17, 94.1%). A total of 22 rice blast symptomatic samples collected in 2017 and 2018 resulted in fungal development typical of *M. oryzae*, and 95 of the brown spot symptomatic leaf samples resulted in fungal strains morphologically corresponding to *Bipolaris* spp. (H. K. Kaboré, A. I., Kassankogno, and D. Tharreau, *personal communication*). Finally, molecular analysis confirmed 19 of 21 (90.4%) of analyzed fungal strains isolated from the symptomatic samples collected in 2018 as the genus *Bipolaris* (H. K. Kaboré and D. Tharreau, *personal communication*), while the remaining two strains (2/21 = 9.5%) were *Exserohilum rostratum* (syn. *Setosphaeria rostrata*), also known to cause brown spot symptoms in rice (Kusai et al. 2016). Symptom recognition was consequently considered as accurate for yellow mottle disease, BLS, rice leaf blast, and brown spot.

Characterization of agricultural practices used in each rice production system. The rice farmers interviewed were mostly men (139/165, 84% of all interviews performed), but this factor varied among sites, with particularly few women (<10%) interviewed in the Bama and Banzon zones (both in the irrigated and lowland areas), while women represented almost 80% of surveyed farmers in the Karfiguela lowland areas (Tengrela site). In addition, the age structure varied among sites, with the proportion of young farmers surveyed (<35 years) being 34.5% on average but varying from <20% in the Banzon and Karfiguela irrigated areas to >45% in the Bama zone and Karfiguela lowlands.

The interviewed farmers owned the studied rice fields in many cases (35/72, 48%) and even in all cases in the Karfiguela irrigated areas, while farmers who owned the fields composed <30% of the realized interviews in the Banzon and Karfiguela lowlands. Most farmers cultivated rice to sell it (54/69 of cases, 78%), except in the Karfiguela zone, where self-consumption was the main purpose of rice growing (78% of the cases in the irrigated areas of Karfiguela, while in Tengrela, self-consumption was always the case; none of the interviewed farmers sold their rice).

The agricultural practices (including information on rice cultivars, planting, fertilization, pesticides, and preceding crops) differed between the studied sites in irrigated areas and rainfed lowlands (Fig. 2).

In particular, a second rice season was possible only in irrigated areas (32 of 69 cases, 46%; see Fig. 2 and Supplementary Fig. 1B). Legume production in rotation with rice was more common in rainfed lowlands (14/47, 30%) than in irrigated areas (6/69, 9%). Crop rotations were particularly common in Badala (13/21, 62%), where green beans (and to a lesser extent eggplant, cabbage, or tomato) were frequently cultivated in rotation with rice.

Rice planting was also highly discriminant; all farmers from the studied irrigated fields transplanted seedlings from nurseries, while this was only the case in 12% of the interviews (8/66) conducted in rainfed lowlands (never in the Banzon lowlands). Direct sowing (with no transplanting step) remained the most common management practice in the studied rainfed lowlands.

The most common rice cultivar (54 of 161, 34%) was the Chinese cultivar TS2, registered in Burkina Faso as FKR64. The NERICA ('New Rice for Africa')-registered rice cultivar FKR62N was also very common, representing 34 of 161 cases (21%). Registered cultivars (including FKR64, FKR62N, and others) represented >92% (90/98) of the rice cultivars observed during the surveys in irrigated areas and less than half of those determined during the surveys in rainfed lowlands (29/63, 46%), with striking differences observed among sites. Indeed, unregistered cultivars represented 40% of the cases (8/20) in the Bama lowlands and all (23/23, 100%) of the cases in the Karfiguela lowlands (see Fig. 2 and Supplementary Fig. 1A).

Mineral fertilization more generally consisted of one NPK and one urea application or one NPK and two urea applications. Mineral fertilization was always applied in irrigated areas (94/94 cases) but was less frequent in rainfed lowlands, with 46 cases of 66 (70%) reporting mineral fertilization. It was particularly uncommon in Tengrela (only 8/24, 33%), where organic fertilization (namely, manure from household waste) was more widely used than in other sites (11/24, 46%). Indeed, organic fertilization was only used in 16% (25/158) of the observed cases over the whole dataset. It was particularly uncommon in irrigated areas (7/92, 8%), with a relative exception in Bama (5/24, 21%).

Herbicide use was very frequent in the dataset (119/127 cases, 94%). All farmers from irrigated areas said they used herbicides in their fields, while this was the case for 86.4% (51/59) of the interviews performed in rainfed lowlands. Insecticide use was also common (76/96, 80%), especially in irrigated areas (50/56, 90%)

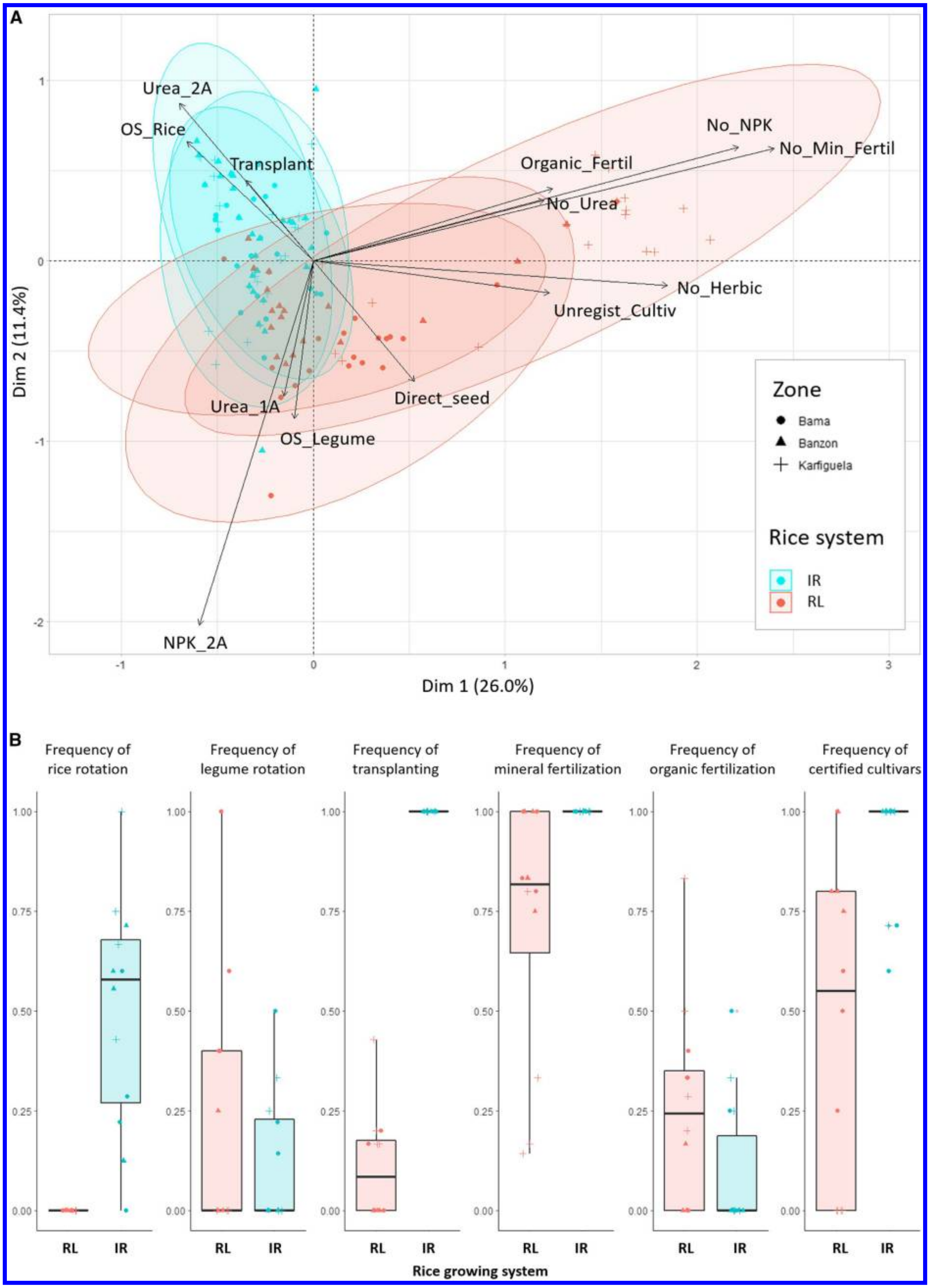

Fig. 2. Characterization of rice cultivation practices within the studied sites based on farmers' interviews. The colors correspond to the rice growing system (red for rainfed lowlands and blue for irrigated areas), while the shape of the points refers to the geographic zone. **A,** Representation of the multiple component analysis (MCA) results. Each point corresponds to one field in a particular year; the figure comprises 165 points (all interviews conducted between 2015 and 2019). The arrows represent the variables contributing to axis 1 or axis 2 more than the average expected under the null hypothesis: no mineral fertilization ("No_Min_Fertil"), the presence of organic fertilization ("Organic_Fertil"), the number of urea or NPK applications ("No_Urea", "Urea_1A", "Urea_2A", "No_NPK", "NPK_2A"), the type of transplanting ("Direct_seed" or "Transplant"), the absence of herbicide ("No_Herbic"), the use of unregistered cultivars ("Unregist_Cultiv"), and the culture performed during the off-season ("OS_Rice", "OS_Legume") are denoted. **B,** Repartition of several rice cultivation practices in irrigated areas compared with rainfed lowlands in the different years (2016–2019 dataset). Each point corresponds to one site in a particular year, and the legend is the same as that in **A**.

compared with that in lowlands (26/40, 65%). The herbicides used belonged to different World Health Organization (WHO) toxicity categories (II-III-U, slightly to moderately hazardous), while the identified insecticides all belonged to type II (moderately hazardous). All pesticides identified, except one (an herbicide containing paraquat, cited nine times), were probated by the Sahelian Pesticide Committee. The most commonly used herbicides included an herbicide containing bensulfuron-methyl (43/94, 46%), one based on 2,4-D dimethylamine salt (18/94, 19%), and one containing glyphosate (17/94, 18%). An insecticide based on deltamethrine was most commonly used (31/47, 66%).

Overall, strong differentiation in terms of agricultural practices was found between the two rice systems, with more variability observed among the rainfed lowland sites; the rainfed rice site in the Karfiguela zone was the most different compared with the Bama and Banzon lowland sites (Fig. 2).

Comparison of disease occurrence and incidence in the two rice production systems. The analysis of all observed symptoms at the plant level revealed no effect of the geographical zone or of the interaction between the zone and rice system on disease occurrences. Only the rice production system was a significant factor in the analysis, revealing the higher incidence of any of the four main rice diseases in irrigated areas compared with in rainfed lowlands ('rice growing system' fixed effect, df = 1, Chi = 5.28, $P = 0.022$) (Fig. 3). The contrast analysis showed that the differences observed between the irrigated and lowland areas were significant within the Bama zone (z-ratio = –2.97, $P = 0.003$) but not within the Banzon or Karfiguela geographical zones.

The comparison between the irrigated areas and rainfed lowlands, in terms of disease occurrence at the field scale and the incidence estimates considering each observed disease independently (yellow mottle disease, BLS, rice leaf blast, and brown spot), appears in Figure 4. The results of the statistical tests are reported in Table 2. The average occurrence over the whole dataset (179 fields) for each of the four diseases is presented in the diagonal of Figure 5. The occurrences ranged from 30.2% of the studied fields for rice yellow mottle disease to 79.9% for brown spot. The average incidences over the whole dataset (2,864 observed plants) were 6.5% for RYMV, 6.7% for BLS, 9.9% for rice leaf blast, and 32.2% for brown spot.

We found significant interactions between the zone and rice growing system for both yellow mottle disease and brown spot, with congruences between the field and plant scales (Table 2). The effect of the rice system on these two diseases depended on the geographical zone. This result is especially striking for yellow mottle disease, for which higher frequencies of infected fields and plants were found in the irrigated area in Banzon, while the opposite was observed in the Bama zone (Table 2 and Supplementary Fig. 2). For brown spot, the frequencies of infected fields (143/179 = 80%) and plants (922/2,864 = 32%) were much higher than those observed for other diseases (Fig. 4). Only the Bama lowlands had a lower disease incidence than the corresponding neighboring irrigated area (Table 2 and Supplementary Fig. 2).

For both BLS and rice leaf blast, the interaction between the zone and rice growing system was not a significant variable in the models. In these two cases, we found a significant effect of the rice system: observations of BLS- and rice blast-specific symptoms were more common in irrigated areas than in rainfed lowlands both at the field and plant scales (Fig. 4 and Table 2). At the plant level, this effect was congruently significant over the three zones for BLS, while this effect was the case in Banzon only at the field level (Table 2 and Supplementary Fig. 3A).

Co-occurrence and coinfection. When running additional GLMMs including the presence/absence of the three other diseases as fixed effects, we obtained various significant effects (only brown spot was not involved in any significant association). The presence of yellow mottle disease was positively associated with the presence

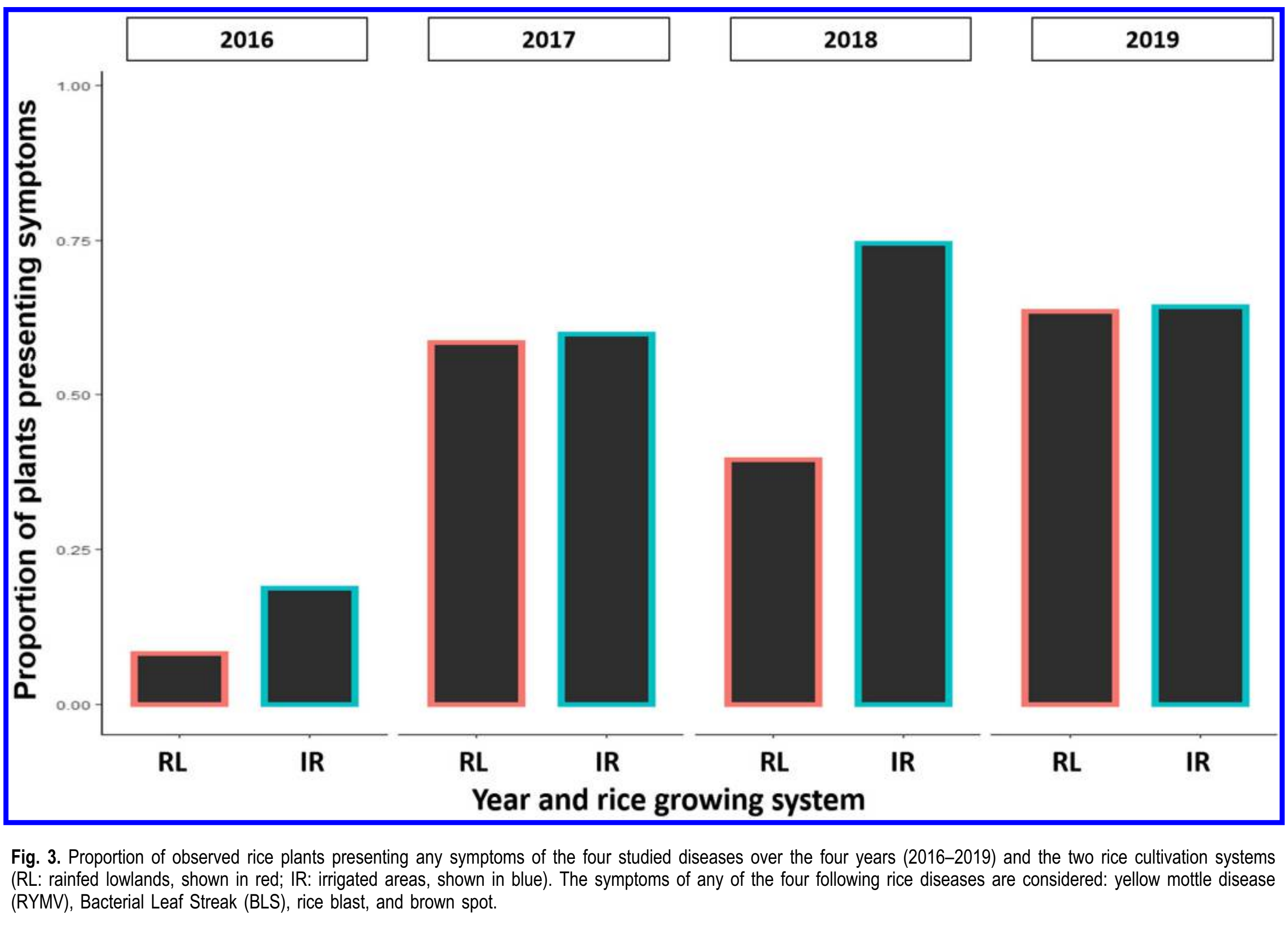

Fig. 3. Proportion of observed rice plants presenting any symptoms of the four studied diseases over the four years (2016–2019) and the two rice cultivation systems (RL: rainfed lowlands, shown in red; IR: irrigated areas, shown in blue). The symptoms of any of the four following rice diseases are considered: yellow mottle disease (RYMV), Bacterial Leaf Streak (BLS), rice blast, and brown spot.

of BLS (Chi = 8.52, $P = 0.003$) and negatively associated with rice blast (Chi = 7.11, $P = 0.007$). The presence of BLS was positively associated with the presence of both yellow mottle disease (Chi = 10.36, $P = 0.001$) and rice blast (Chi = 7.70, $P = 0.005$). Finally, the presence of rice blast was negatively associated with the presence of yellow mottle disease (Chi = 5.45, $P = 0.019$).

The co-occurrence levels within the whole dataset varied among the disease pairs, from 10% (17/179) for RYMV and rice blast to 41% (73/179) for brown spot and rice blast. In many cases, we observed higher co-occurrence levels in irrigated areas than in rainfed lowland sites (Fig. 5).

The overall level of coinfection, considering the four studied diseases, was 5% (152/2,864). These coinfection levels reached 7% (116/1,616) when focusing on the samples collected in irrigated areas (Supplementary Fig. 3B). The highest coinfection level was found in the Banzon irrigated area in 2019 (Supplementary Fig. 3B), where 20% (19/96) of sampled plants presented the symptoms of at least two of the main studied diseases (rice yellow mottle, BLS, rice blast, and brown spot).

Discussion

Despite the importance of rice in the field of food safety, especially in the present context of global change and the challenge of food security in areas with fast-growing populations, epidemiological surveys of rice diseases in smallholder fields with spatiotemporal analysis of disease incidences remain limited worldwide, especially in Africa. In addition, with the noteworthy exception of a multiple-rice-disease dataset comprising four countries from tropical and subtropical Asia (Savary et al. 2011b; Savary et al. 2000), very few studies have documented the epidemiology of various rice diseases simultaneously to allow the generation of a wealth of data on various specific diseases and to document co-occurrence and coinfection. Here, we presented the first multilocal and pluriannual analysis of multiple rice diseases in two contrasting rice production systems in the western Burkina Faso.

We performed an analysis of rice cultivation management practices based on interviews with farmers conducted at the six studied sites in the western Burkina Faso.

Most interviewed farmers were men, except in the rainfed lowland area of Tengrela in the Karfiguela zone. The Cascades region, where the Karfiguela zone is located, is known as an area in which women constitute the majority of rice farmers (Kam et al. 2013; Sié et al. 1998). In our study, as in a study conducted in Benin (Nonvide et al. 2018), it seems that the areas prone to higher production are restricted to production conducted by men. Younger farmers were found at some sites, particularly but not exclusively in rainfed lowlands, while Nonvide et al. (2018) reported that farmers were younger in rainfed lowlands than in irrigated areas in Benin. The purpose of rice cultivation differed depending on the zone: most farmers cultivated rice to sell it in the Bama and Banzon geographical zones, while self-consumption was dominant in the Karfiguela zone, as previously reported for the Cascades region (Kam et al. 2013).

The agricultural practice regarding rice cultivation differed globally between irrigated areas and rainfed lowlands, and site-specific features were also evidenced in our results. The specific management practices reported in irrigated areas included the transplanting step and the possibility of growing rice twice a year. On the other hand, the absence of mineral fertilization, or not using herbicide, was only reported in rainfed lowlands. Other practices were not system-specific but had strong differences in frequency, such as the use of registered cultivars that are much more frequent in irrigated areas than in rainfed lowlands.

In Benin, Nonvide et al. (2018) also reported that improved seeds were more frequent in irrigated areas than in rainfed rice areas. More globally, the adoption of improved rice varieties (including NERICA) in West Africa increased after the 2008 food crisis, with an impact on poverty reduction and food security (Arouna et al. 2017), but training programs are also required to reach rice farmers in lowland areas (Kijima et al. 2012). In addition, registered cultivars are not necessarily resistant to rice diseases. Here, among the two registered cultivars most frequently grown in the studied sites (FKR64 = TS2 and FKR62N), only FKR62N was shown to be moderately resistant to rice blast (Kassankogno et al. 2015), while both cultivars are susceptible to RYMV and BLS (Sereme et al. 2016a, Sereme et al. 2016b; Wonni et al. 2011; I. Wonni, *personal communication*). Information on the spatial variation in rice diseases, as was documented in this study, is important for driving the local deployment of resistant cultivars.

Finally, in terms of fertilization, Nonvide et al. (2018) reported no difference in the frequency of fertilizer use in Benin but a significant difference in the fertilizer application rate (in kg/ha). Our study documented the presence/absence of mineral fertilization and the number of applications, but not the fertilizer application rate. A more detailed

Table 2. Results of the generalized linear mixed models (GLMMs) regarding the presence/absence of specific symptoms at the field and plant levels for each of the four diseases: yellow mottle disease (RYMV), bacterial leaf streak (BLS), rice blast, and brown spot[a]

	Yellow mottle disease		BLS		Rice blast		Brown spot	
	Field-level data (2016–2019, 179 observations)							
Variables	**Chi**	***P* value[b]**	**Chi**	***P* value[b]**	**Chi**	***P* value[b]**	**Chi**	***P* value[b]**
Rice system (df = 1)	10.72	0.001063**	8.98	0.002723**	10.30	0.00133**	8.20	0.004182**
Geographical zone (df = 2)	4.75	0.093223	7.13	0.028364*		NS	13.39	0.001238**
Rice system*Zone (df = 2)	28.60	6.162*e*-07***		NS		NS	8.13	0.017151*
CONTRASTS (RL-IR)	**z-ratio**	***P* value**	**z-ratio**	***P* value**	**z-ratio**	***P* value**	**z-ratio**	***P* value**
Zone = Bama	3.27	0.001	–1.048	0.295	–2.107	0.035	–2.86	0.004
Zone = Banzon	–3.79	0.000	–2.567	0.010	–2.241	0.025	0.55	0.583
Zone = Karfiguela	1.87	0.062	–1.577	0.115	–1.321	0.187	0.96	0.338
	Plant-level data (2016–2019, 179 × 16 = 2,864 observations)							
Variables	**Chi**	***P* value**	**Chi**	***P* value**	**Chi**	***P* value**	**Chi**	***P* value**
Rice system (df = 1)	7.84	0.005121**	14.41	0.0001473***	6.11	0.013453*	9.48	0.0020764**
Geographical zone (df = 2)	2.65	0.266	7.87	0.0195825*	13.65	0.001087**	13.64	0.0010936**
Rice system*Zone (df = 2)	25.14	3.480*e*-06***		NS		NS	11.00	0.0040823**
CONTRASTS (RL-IR)	**z-ratio**	***P* value**	**z-ratio**	***P* value**	**z-ratio**	***P* value**	**z-ratio**	***P* value**
Zone = Bama	2.80	0.005	–2.097	0.036	–1.72	0.086	–3.08	0.002
Zone = Banzon	–3.61	0.000	–2.417	0.016	–1.44	0.151	1.08	0.279
Zone = Karfiguela	2.19	0.028	–2.135	0.033	–1.17	0.244	0.89	0.374

[a] The eight models include the ‘rice growing system’, ‘zone’, and their interaction, if significant, as fixed effects. The models applied at the field level include the ‘year’ as a random effect, while those realized at the plant level include both the ‘year’ and ‘field_ID’ as random effects. Type 3 ANOVA was performed for the models including interaction terms, and contrast analyses tested whether the rice system significantly affected the studied variables within each of the three zones.

[b] * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; NS = not significant.

(quantitative) survey of farmers at selected sites could reveal more subtle differences among and within the study sites in terms of fertilization as well as other management practices, such as manual weeding, irrigation, or soil management.

Overall, the six study sites exhibit a high diversity of agricultural practices for rice cultivation. We demonstrate strong differences between irrigated areas and rainfed lowlands. Management practices are less intensive in rainfed lowlands than in irrigated areas, probably because the incurred risks are high in rainfed lowlands (Serpantié et al. 2019). It is also important to note that a high variability is found among the rainfed lowland sites: the management practices are particularly different from irrigated areas in the lowlands of Karfiguela (Tengrela lakeside) but are much less different in the lowlands of Banzon (village of Senzon).

The frequency of yellow mottle disease was not structured by the rice growing system but, instead, was particularly prevalent in the irrigated areas of Banzon and, to a lesser extent, in the rainfed lowlands of the Bama zone (Badala village). The emergence and epidemic dynamics observed over the last 50 years are thought to be linked to the intensification of rice agriculture, with particular practices such as transplanting (seedbed nurseries) contributing to the build-up of RYMV inoculum (Traore et al. 2009). This is consistent with the high incidence of RYMV found in the irrigated perimeter of Banzon but not in the observations from the Bama zone, where the rainfed lowlands (Badala) had more symptomatic plants than the neighboring irrigated area. Although this rice virus is one of the major models used for plant virus molecular epidemiology research (Pagán et al. 2016; Trovão et al. 2015), its patterns have mostly been described at large geographical scales. Further investigations at the local scale could provide new insights into RYMV epidemiology, especially considering the complexity of its transmission (various insects and mechanical transmission).

BLS was predominant in irrigated areas compared with rainfed lowlands. This could be related to the more constant presence of water, which is a major transmission mode of *Xanthomonas oryzae oryzicola*, and the high level of humidity favoring bacterial infection (Nino-Liu et al. 2006; Cartwright et al. 2018). As for *Xanthomonas oryzae*, irrigation water is considered a reservoir for many plant-pathogenic bacteria (Lamichhane and Bartoli 2015). In addition, the higher level of BLS in the irrigated areas could be caused by the higher frequency of mineral fertilization recorded in this rice production system. Indeed, excess nitrogen levels favor BLB epidemics

Fig. 4. Effect of the rice production system (irrigated areas, shown in blue, versus rainfed lowlands, shown in red) on specific symptoms observed for the four major diseases, yellow mottle disease (RYMV), bacterial leaf streak (BLS), rice blast, and brown spot, over the four studied years (2016–2019). **A,** Proportion of fields presenting specific symptoms for each of the four diseases for each rice growing system and year; **B,** average incidence level estimated in the four diagonal cells of each field for each of the four diseases and for each rice growing system and year; and **C,** proportion of sampled plants that presented specific symptoms for each of the four diseases and for each rice growing system and year.

(Reddy et al. 1979), although, to our knowledge, this effect has not been documented for BLS. Finally, we note that BLS seems to be well established (as it was found here in all six study sites), although it was reported in Burkina Faso only recently (Wonni et al. 2011). The seed transmission of BLS could also be an important driver of the epidemic success of BLS in the studied country. Although it is often considered a less important disease than BLB, the high incidence of BLS reported here requires the rapid development of control measures.

We found rice leaf blast to be particularly prevalent in irrigated areas compared with rainfed lowlands. Considering the literature on the factors favoring rice blast epidemics (Long et al. 2000; Ou 1985), we speculate that the microclimate (higher humidity) and the higher mineral fertilization in irrigated areas than in lowlands could be the driving factors underlying the observed differences between irrigated areas and rainfed lowlands.

Brown spot is the disease presenting the highest within-field incidence compared with the other diseases studied. This confirms an earlier study on rice seeds in which, on average, 84% of analyzed rice seed batches (from 3 to 76% of seeds infected within batches) were found to be infected in a 2013 to 2014 survey in 28 locations across rice-growing regions in Burkina Faso (Ouedraogo et al. 2016). Our results do not fit with the classical view of a rice disease associated with particularly poor conditions because (i) brown spot is found almost everywhere, with 79.9% of the studied fields presenting symptoms, and (ii) the rainfed lowland production system, in which mineral fertilization is much less frequent than it is in irrigated areas, does not present higher brown spot incidences. Brown spot is emerging in various rice growing countries, as reported, for example, in Bangladesh (Hossain et al. 2014) and the Ivory Coast (Bouet et al. 2015). However, as with other chronic crop diseases, it has received a lower level of attention than acute diseases such as rice blast (Savary et al. 2011a). More work, preferably studies also including brown spot severity estimates in addition to the occurrence frequencies of fields and plants, is encouraged to drive the understanding of the environmental factors that favor epidemics and to better understand the drivers of this emergence.

Overall, we found that symptomatic plants are more frequent in irrigated areas than in rainfed lowlands. Irrigation is arguably one of the most important cultural practices in the management of plant disease (Café-Filho et al. 2018), and the other differences observed between irrigated areas and rainfed lowlands (in particular, the differences observed in terms of transplanting, crop rotation, fertilization, and cultivars) are also classically known to affect plant disease dynamics. Our study performed in farmer fields globally compares the two contrasting rice production systems and cannot separate the confounding factors. Additional data are required to identify the effects of specific practices on multiple diseases in rice in Burkina Faso.

The development of irrigated areas carries strong hope to develop rice production in Burkina Faso and in Sub-Saharan Africa in general (Xie et al. 2018). However, although rice yields are much higher in irrigated areas than in rainfed lowlands, they are not as high as expected (Ragasa and Chapoto 2017), and the poverty of farmers in irrigated areas, where the input burdens are higher, remains worrying, as exemplified by the case study of Bagré in the East Center of Burkina Faso (Daré et al. 2019; Tapsoba et al. 2018). The major constraints identified by farmers in the irrigated area of Malanville in Benin include water management problems (water unavailability and flooding) and poor access to production inputs, agricultural information, and markets (Nonvide et al. 2018). Irrigated systems require large amounts of water and inputs, causing them to be considered less sustainable, particularly in the context of climate change. Their higher yields are, however, essential for facing the challenge of rice self-sufficiency.

We speculate that the losses that occur because of diseases contribute to the prevention of expected yields being realized in irrigated areas; however, more work, including estimating rice yield losses that occur caused by different diseases, is required to better understand the factors affecting rice yields in each rice production system in Burkina Faso.

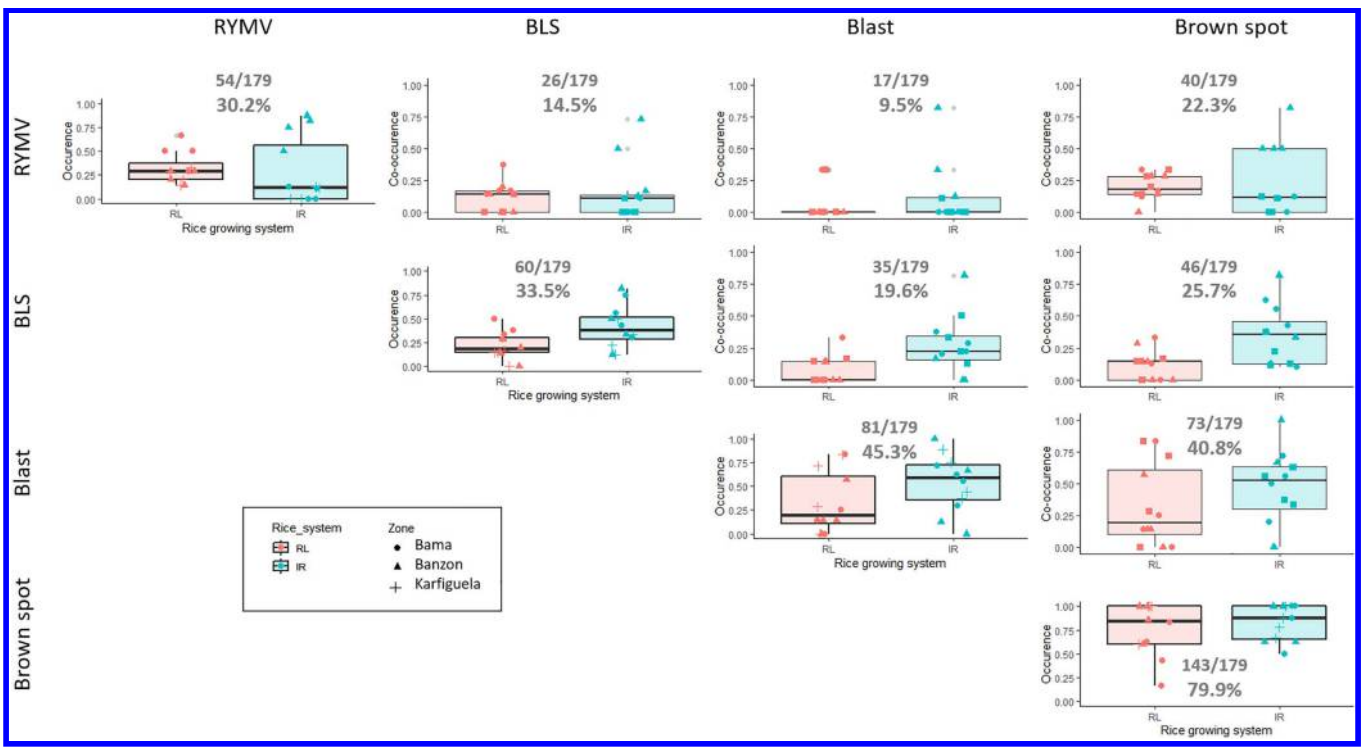

Fig. 5. Analysis of the presence/absence (each disease, on the diagonal) and co-occurrence (disease pairs) data from the 2016–2019 field-scale observations of the four major rice diseases: yellow mottle disease (RYMV), bacterial leaf streak (BLS), rice blast and brown spot. On the diagonal: the frequency of the presence of one disease (one point corresponds to one site in a particular year) in rainfed lowlands versus irrigated areas. The numbers in gray refer to the whole dataset (179 observations) showing the numbers of fields in which specific symptoms were observed and the corresponding frequencies. Right upper part: frequency of the co-occurrence of a disease pair (one point corresponds to one site in a particular year) in rainfed lowlands versus irrigated areas. The numbers in gray refer to the whole dataset (179 observations), showing the numbers of fields in which specific symptoms of two diseases were simultaneously observed and the corresponding frequencies.

The originality of our approach involves the consideration of multiple diseases simultaneously. In addition to the gains of time and money associated with such an approach, this method allows us to address new epidemiological questions, such as the quantitative importance of multiple infections in the studied agroecosystem (Tollenaere et al. 2016). Analyses of the co-occurrence of various species are frequently performed to detect interactions among species (i.e., the influence of the presence of one species on the occurrence of another species). Here, at the field level, we report positive associations between the presence of yellow mottle disease and BLS, as well as between BLS and rice blast, and a negative association between yellow mottle disease and rice blast. These statistical associations must, however, be taken with caution, as a recent critical analysis highlights that the co-occurrence of various diseases in the same field is not evidence of ecological interactions (Blanchet et al. 2020). However, the positive association observed between the presence of yellow mottle disease and BLS is particularly interesting considering that reciprocal interactions between the virus RYMV and the bacteria *Xanthomonas oryzae* have been reported experimentally (Tollenaere et al. 2017). Experimental work on other pathogen pairs has not been investigated to our knowledge, with one exception: antagonistic interactions were reported between *M. oryzae* and *B. oryzae* (Bahous et al. 2003), but the interactions did not correspond to a significant statistical association between disease occurrences (rice blast and brown spot) in our dataset.

Our study documents high levels of co-occurrence among various rice diseases in the studied small fields (25 × 25 meters), from 10% (yellow mottle disease and rice blast) to 41% (brown spot and rice blast). These co-occurrence levels were higher in irrigated areas than in rainfed lowlands. This is important because only situations in which pathogens circulate within the same sites and fields lead to the opportunity for pathogen–pathogen interactions, with important impacts on the outcomes of pathogen multiplication and infection (Abdullah et al. 2017; Syller 2012; Tollenaere et al. 2016).

At the plant level, in accordance with our previous data on RYMV-*Xanthomonas oryzae* coinfection (Tollenaere et al. 2017) and coinfection by multiple rice pathogenic bacteria (Bangratz et al. 2020), here, we document relatively high levels of coinfection, especially in one of the studied irrigated areas (Banzon zone). However, because this study consists only of symptom observations and because symptoms can be blurred in coinfection situations (Tollenaere et al. 2016), further research using molecular detection tools is required to complement the study of multiple infections by various rice pathogens in West Africa.

Our study area corresponds to the major rice growing area in Burkina Faso, where farmers perform a variety of rice-growing practices. Although it only represented a small geographical area (ca. 100 × 100 km), a study encompassing four Asian countries showed that production systems (PS) and disease syndromes (S) were not site-specific, with the same PS and S found at very geographically distant locations, while very different PS and S occurred in close proximity (Savary et al. 2011b; Savary et al. 2000). Therefore, our results are likely to provide important insight for rice production in West Africa in general and, consequently, to contribute to filling a data gap regarding rice diseases in this area. The results herein emphasize the critical need to pursue the development of efficient disease control strategies that are especially applicable by small farmers in irrigated areas.

We encourage more spatiotemporal surveys of rice diseases in Africa, including surveys of the rainfed upland rice growing system. Upland rice is uncommon in Burkina Faso and, consequently, was not considered in this study, but it is more important in coastal countries (particularly Guinea and Côte d'Ivoire) and represented 40% of rice-growing areas in Sub-Saharan Africa in 2008 (AfricaRice 2011). Studies investigating disease occurrences within a cropping season (whereas observations were performed in our study once a year) could generate more detailed epidemiological data. Surveying multiple rice diseases at once is demanding in terms of expertise but reveals efficiency in terms of time and money and generates new data on the relative distributions of multiple pathogens within an agrosystem and their possibilities of interacting within plants. Finally, the design of efficient disease control strategies, such as resistant cultivars or management practices, should be efficient not only against one biotic constraint but should also take into account the multiple pests faced by the crops in each rice cultivation system.

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