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# A spatially explicit approach to assess the suitability for rice cultivation in an inland valley in central Benin

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ABSTRACT

The selection of optimal areas for specific cultivation systems is an important step in achieving increased, sustainable rice production in Benin. This study aims to determine suitable areas for rice production in the inland valley of Tossahou using a GIS-based approach that evaluates and combines biophysical factors such as climate, hydrology, soil and landscape, following the FAO parameter method and guidelines for land evaluation. Soil and landscape suitability was assessed for three different rice cultivation systems: rainfed bunded (RB), cultivation under natural flooding (NF), and irrigated cultivation (RI). The results show that in the inland valley (mostly including the hydromorphic zones and the valley bottom) 52% of the area is suitable for irrigated cultivation, 18% for cultivation under natural flood and 1.2% for rainfed bunded rice. Precipitation and temperature were limiting factors for all cultivation systems. Flooding was the most limiting factor for NF while RI and RB were mostly limited by steep slopes and soil texture respectively. As a first attempt in Benin, this study can play an important role in achieving optimised rice production in inland valleys, and additional studies including socio-economic aspects, carried out in the same area, or in areas under similar conditions, are relevant to close the yield gap and improve the selection approach.

## 1. Introduction

An inland valley is defined as a landscape that comprises a complete toposequence from the interfluves to the valley bottom with its seasonally waterlogged depression (Windmeijer and Andriesse, 1993). Often known under various regional names, such as *bas-fonds*, *fadamas* or inland swamps in West Africa, *mbuga* in East Africa and *vleis*, *dambos*, *mapani*, *matoro*, *inuta* or *amaxhaphozi* in Southern Africa (Acres et al., 1985), in practice, the term refers only to the waterlogged area and its hydromorphic fringes (Giertz et al., 2012; IVC, 2005; Thenkabail and Nolte, 1996). In West Africa, inland valleys have important potential for rice-based production systems due to their being largely unexploited, higher water availability, lower soil fragility and higher fertility (Giertz et al., 2012; Rodenburg et al., 2014; Schmitter et al., 2015). However, in Benin, the productivity of rice systems in such wetlands is low due to biophysical and socio-economic constraints (Djagba et al., 2013), including sub-optimal functioning markets for acquiring fertilisers and for the commercialisation of rice products; a lack of financial services to make the necessary investments for intensification; poor management and maintenance of irrigation infrastructures; and inadequate national policies (Saito et al., 2015; Schmitter et al., 2015). In Benin, agriculture contributes to 31.6% of the country's gross domestic product (FAO Stat, 2011). Rice is usually grown to be sold and is not used in subsistence farming due to its high value (Igué, 2000). As the country aims to be self-sufficient in rice in the near future, the government has been actively promoting agricultural development of rice since 2008 (NRDS, 2011). Indeed, local rice production has increased (from 73,853 t in 2008 to 167,000 t in 2011) because of improved input facilities (e.g. seed, fertiliser) made available to farmers through a range of programmes and projects that were set up after the food crisis of 2008. These include the Emergency Program to Support Food Security (PUASA), the NERICA Project, the Development Project of Small Irrigated Perimeters (PAPPI) and the Agricultural Services Restructuring Project (PASR) (Totin et al., 2013). Currently, 90% of the rice

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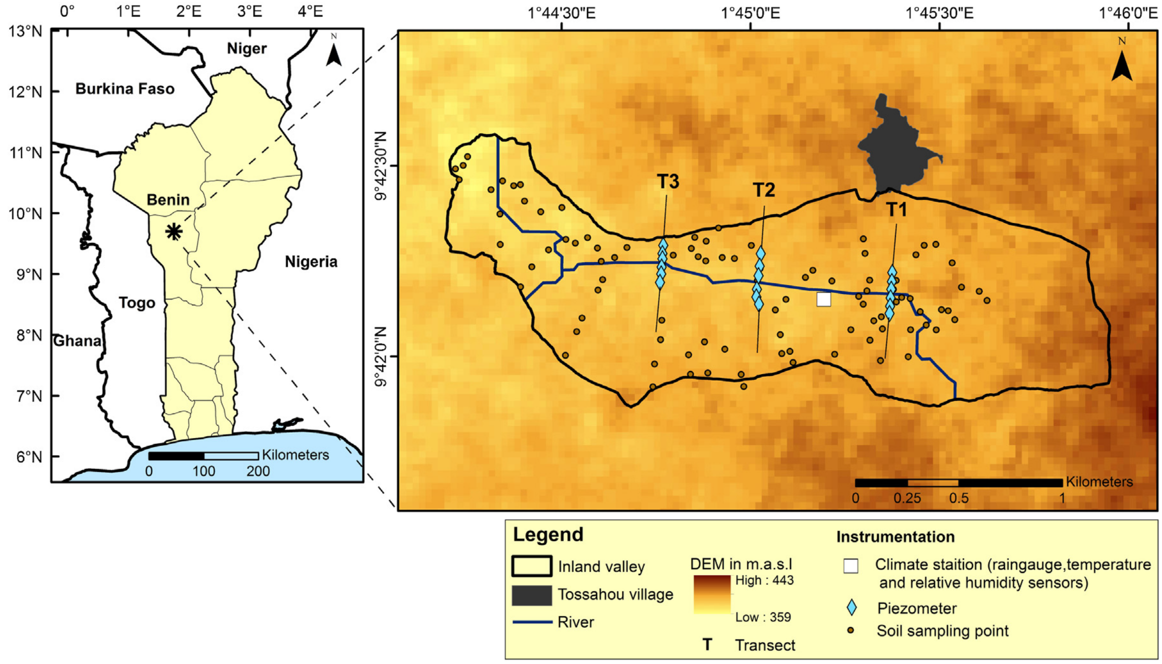

**Fig. 1.** Location of research area and instrumentation.

outputs are produced by small-scale farmers using only 7–10% of the total arable land available (United States Department of Agriculture, 2013), with the average rice farm size for the users and non-users of credit being approximately 0.82 and 0.63 ha, respectively (Kinkingninhoun-Medagbe et al., 2015). Despite this recent increase in rice production, following the implementation of technologies and techniques developed and offered by the government and agricultural development projects, traditional smallholder production is still dependent on the physical conditions of the land. This is due to the insufficient coverage of the input facilities, and also to the lack of capital to compensate for natural constraints in terms of rainfall variability, low chemical fertility and unfavourable physical characteristics of soils (Janssens et al., 2010). Moreover, due to the increasing population pressure, farmers move to more marginal areas and expose themselves to environmental risks. Consequently, they often produce low yields as they are not willing to make more investments. Thus, our method should be of interest to development agencies and NGOs that are interested in assessing suitable areas for development and investment.

Knowing that not all inland valleys are necessarily suitable for crop production (Kotze, 2011; Sakané et al., 2011), several biophysical and socio-economic factors should be investigated during the land evaluation process. Recent studies have developed different quantitative and qualitative methods and approaches to planning land suitability, either for agriculture in general (Krishna and Regil, 2014; Liu et al., 2006; Mokaram and Aminzadeh, 2010) or for specific crop production, such as paddy rice, wheat, maize, mustard, mango and sugarcane (Halder, 2013; Martin and Saha, 2009; Singh, 2012), within a given watershed. Generally, these methods integrate remote sensing or a multi-criteria evaluation, coupled with GIS, and combine, depending on the research, layers of factors such as climate, drainage density, geology, hydrology, landform, land use, soil, topography and vegetation, via a weighted overlay approach (Krishna and Regil, 2014) or a pairwise comparison matrix (Kihoro et al., 2013). Some studies rate the factors based on the proposed method of Sys et al. (1993) and define the suitability ranked classes using the qualitative approach described by the FAO (FAO, 1976; Halder, 2013; Martin and Saha, 2009; Mustafa et al., 2011), and others rely on expert opinion, local agronomists and researchers' knowledge (Kihoro et al., 2013). Among other older studies in West Africa, a GIS-based model developed by Fujii et al. in 2010 was recently applied to select suitable rice cultivation areas in inland valleys in the Mankran and Jolo-Kwaha watersheds from different agro-ecological zones in Ghana that have high potential for rice production (Fujii et al., 2010). However, very few studies address land use planning for rice-based systems in inland valleys.

This study was undertaken in Benin with the goal of assessing the suitability of inland valleys, as a function of the biophysical environment, for three rice cultivation systems: rainfed bunded (RB), cultivation under natural flood (NF) and irrigated cultivation (RI). To evaluate suitability spatially, we used the proposed method of Sys et al. (1991, 1993) and the FAO Guidelines for Land Evaluation (FAO, 1976). The parameters analysed were soil, climate, hydrology and topography. Maps of these parameters were required for the generation of the final suitability maps. Rating maps were overlaid for each cultivation system using Liebig's law of the minimum, which states that plant growth is controlled by the scarcest (limiting) resource and that an increase in this resource increases yields the most (Casanova et al., 2002; Gorban et al., 2010; Spektrum, 1999). For the validation of the suitability maps, in association with the identification of limiting factors for rice production, we proceeded to the identification and classification of the predominant types of agricultural land use, to the assessment of the spatial distribution of rice yields, and to stakeholder interviews in the inland valley. This approach was chosen because of data availability and in accordance with the requirements for the different rice cultivation systems. It was essentially led by the following research questions: (i) How can areas suitable for rice production be identified to aid farmers in selecting favourable fields for a potential rice growth achievement? (ii) How can a resulting suitability map be validated? (iii) What are the physical factors limiting the inland valley suitability for rice production? This study contributes to improving development strategies and land use planning to promote a sustainable management of rice-growing wetland ecosystems in Benin.

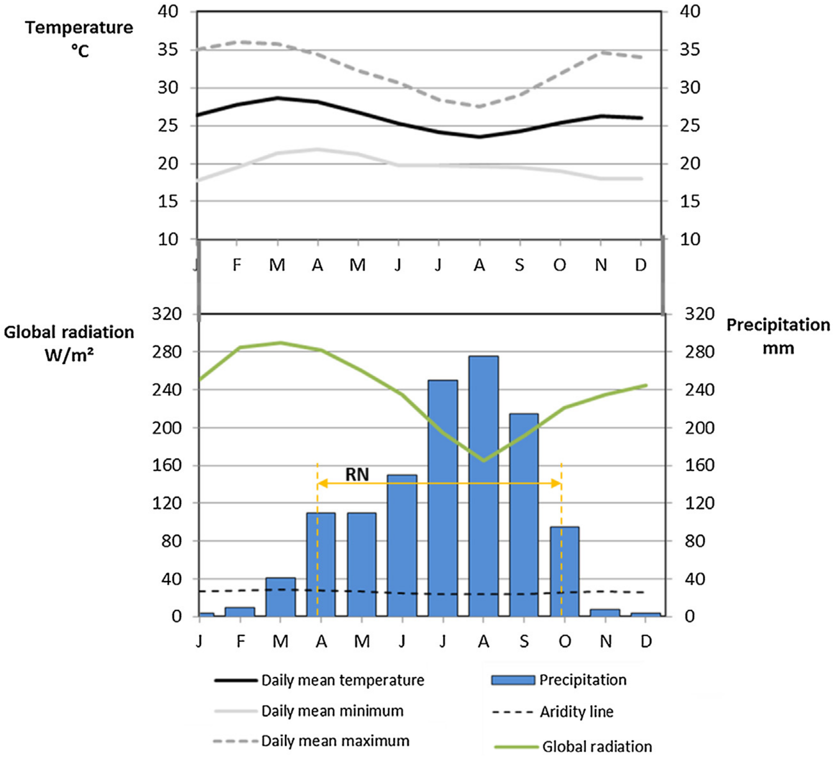

**Fig. 2.** Climatic conditions of Djougou 1991–2000 (IMPETUS 2007). RN, rainy season.

## 2. Methodology

### 2.1. Research area

The inland valley of Tossahou is located in central Benin between 9°42.583′N and 1°44.288′E and 9°41.936′N and 1°45.951′E, approximately 9 km east of the city of Djougou (see Fig. 1). Its contributing catchment belongs to the Upper Ouémé catchment. The area is situated in the South-Sudan agro-climatic zone. Precipitation follows a unimodal pattern that peaks in August (Fink et al., 2010). Both the onset and the total rainfall can vary in this zone, and the growing period of the seasonally cultivated crops is between 90 and 160 days long (Andriesse et al., 1994; Giertz, 2004; Gruber et al., 2009). The average rainfall and potential evapotranspiration are approximately 1200 mm and 1500 mm annually (Lohou et al., 2014). The climate is arid from November to March and the subsequent period from April to October is humid. The average temperature is 25.4 °C, and the mean global radiation is 234 W/m$^2$ (Fig. 2), sustaining very high variations due to cloud cover in the rainy season and during the dry season to dust particles transported by the northeasterly dry and dusty harmattan winds which surge from the Sahara towards the equator to reach the Guinea coast (Knippertz and Fink, 2006; IMPETUS, 2007).

The morphology of the Tossahou inland valley is slightly concave with a flat valley bottom. The topography is diverse and features steep and gentle slopes and a pronounced floodplain in the central part and near the outlet of the valley, which experiences regular flooding. The upland areas are primarily cultivated with yam (*Dioscorea* sp.), maize (*Zea mays* L.), groundnut (*Arachis hypogea*), cassava (*Manihot esculenta* Crantz), sorghum (*Sorghum bicolor*) and cotton (*Gossypium* sp.). The valley bottom is mainly cultivated with rice (*Oryza sativa* L.) and the fringes with a second variety of yam, locally called 'Noudos', with preferentially cassava, sorghum and maize planted in association on the mounds of the yam fields. A land use survey conducted in 2013 revealed that approximately 19.1% of the inland valley was cultivated during the rainy season. The most dominant crop was peanut (4.6%), followed by maize at 3.4%. Cassava, yam, rice, sorghum and cotton were cultivated on 2.7%, 2.3%, 2%, 1.6% and 0.7%, respectively, of the valley. The remaining 1.8% was cultivated with different types of vegetables such as okra, bean, pepper, soyabean and sesame. The land use map is shown in Fig. 3 which also depicts the investigated area which mostly included the valley bottom and the hydromorphic zones.

### 2.2. Suitability analysis

In this study we first applied the FAO guidelines approach for land evaluation (FAO, 1976) which defines and describes the suitability classes based on the rice growth requirements. Thereafter we assessed the environmental physical conditions (including climate, landscape and soil) required for the different cultivation systems which were developed by Sys et al. (1991, 1993). Using the FAO guidelines and crop requirements, the added-value of the research is the GIS-based implementation approach to produce suitability rating maps for each of the parameters involved, and to combine them to generate the final suitability maps based on the limiting factor analysis. Fig. 4 is a flowchart describing the GIS-based approach used in this study.

#### 2.2.1. FAO land evaluation approach

The framework of the FAO land evaluation approach is a collection of concepts, principles and procedures with which an evaluation system can be developed. The concepts are scale-independent and can be employed at different levels of intensity and for all types of land use if the requirements can be defined (FAO, 1976; Verheye et al., 2009). The evaluation approach is plant specific and first requires the identification of crop growth requirements, which are subsequently matched with the attributes of the land of interest in terms of slope, flooding and drainage conditions, as well as soil properties. The methodology then follows

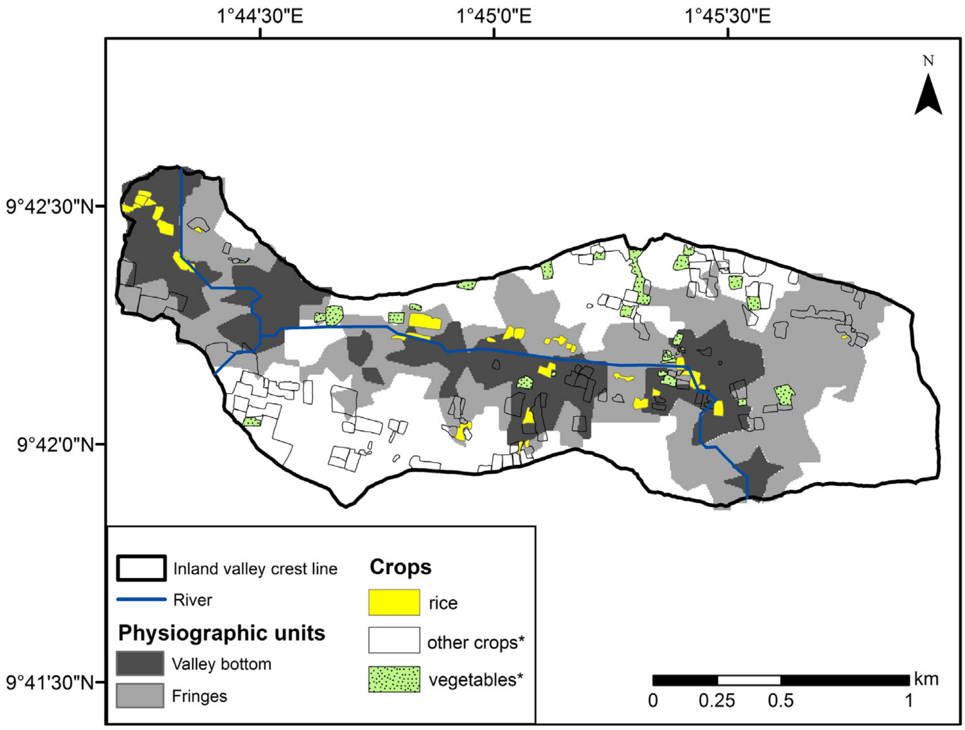

**Fig. 3.** Physiographic units and spatial representation of agricultural land use in the wet season 2013.

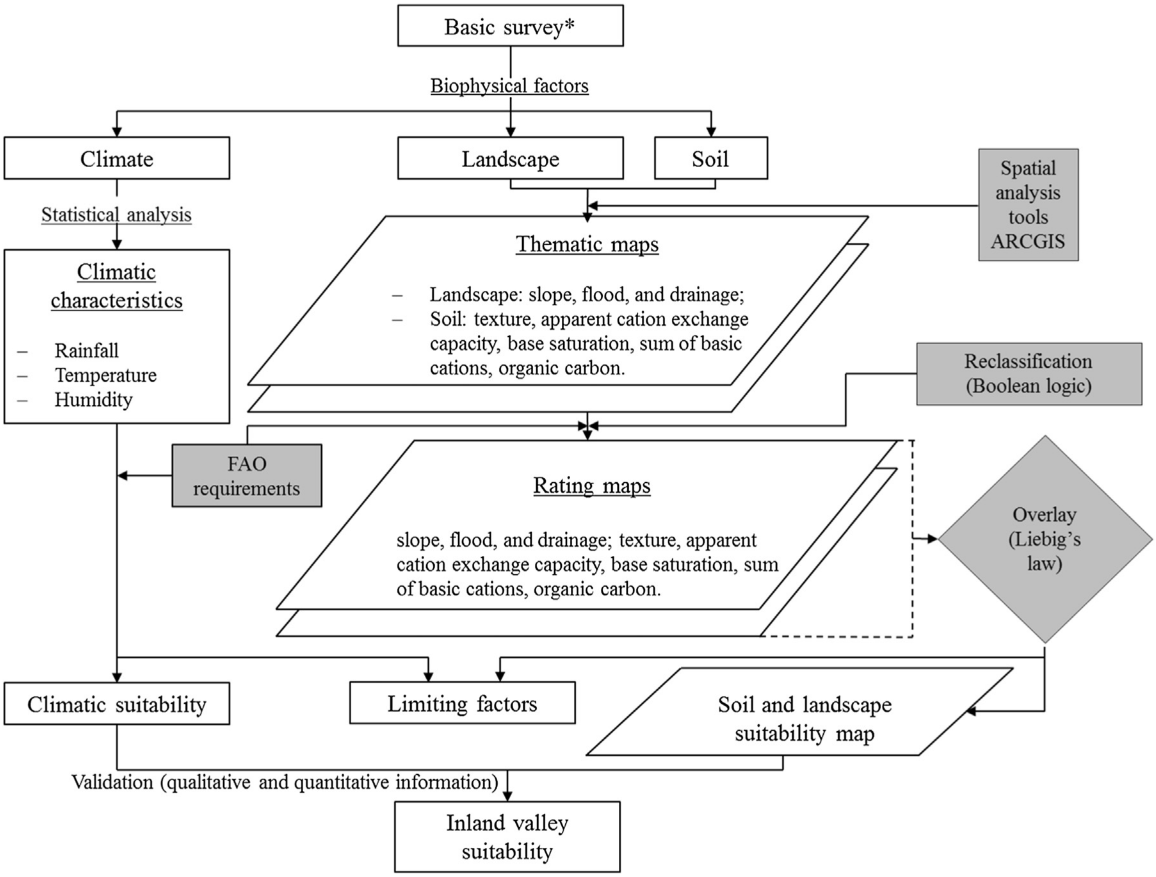

**Fig. 4.** Methodological approach for the inland valley suitability evaluation.
*Basic survey includes climatic and hydrological data measurement, soil sampling for soil map, and land use survey for using GPS for landscape.

either a two-stage or a parallel approach. The parallel approach was employed in this study and the emphasis was on quantitative land classification.

Two land suitability orders and five land suitability classes are distinguished. The land suitability orders are suitable (S) and not suitable (N). The suitable order describes land that is expected to yield benefits under sustained use, which justifies the inputs without the risk of damage to land resources. The not suitable order is used to describe land where sustained use of the land under consideration is not possible due to deficits in land quality. The order suitable is composed of the highly suitable (S1), moderately suitable (S2) and marginally suitable (S3) classes, while the order not suitable is composed of the currently not suitable (N1) and not suitable (N2) classes. The currently not suitable class consists of land that is assumed to exhibit limitations which may be overcome in time but cannot be used currently due to technical limitations or unacceptable costs.

### 2.2.2. *Outline of data requirements*

The FAO crop requirements approach by Sys et al. (1991, 1993) can be divided into two parts, the climatic requirements and the landscape and soil requirements, which are dependent on the intensification level in the study area. As we saw no evidence of an irrigation scheme or agricultural machinery being used and the rice fields were manually prepared using the hoe, a low level of management was chosen to best describe the inland valley. The climatic requirements for rice cultivation, according to Sys et al. (1993), assume a growing cycle between 90 and 120 days and are divided into four groups: precipitation, temperature, humidity and radiation characteristics. An overview of all climatic requirements used for the three cultivation systems is given in Table A1.

Likewise, the soil and landscape requirements are also divided into four groups: topography, wetness, physical soil characteristics and soil fertility characteristics. The topography group includes the relief of the research area. The wetness group is defined by flooding and drainage. The duration and depth of floods are considered to define the flood classes presented in Table A2. Drainage is appraised as good, moderate, imperfect, poor or very poor and requires a differentiation of the suitability of fine loamy and clayey and coarse loamy and sandy families. The only factor evaluated in the physical soil characteristics group was the soil texture due to insufficient data on other characteristics. In the soil fertility characteristics group, the suitability of the apparent cation exchange capacity (in cmol(+)/kg clay), base saturation (%), sum of basic cations (in cmol(+)/kg soil), quantity of organic carbon (%) and pH value (measured in water) are evaluated (Table A3).

### 2.2.3. *Spatial implementation in GIS environment*

To evaluate the soil and landscape criteria, thematic maps were developed for each of the following factors: texture, apparent cation exchange capacity, base saturation, sum of basic cations, organic carbon, pH, slope, flooding and drainage. To create the suitability maps for the three analysed rice cultivation systems, the created raster maps of the landscape and soil requirements were reclassified along with the suitability using Boolean logic. According to Boolean logic, boundaries that determine whether an element is included in a set are clearly defined, meaning that the element is either included or excluded in a set. However, the approach does not allow partial memberships of an element in a set as values are restricted to two points, 0 if excluded and 1 if included (Banai, 1993; Collins et al., 2001; Nisar Ahamed et al., 2000; Sicat et al., 2005). In total, 22 distinct rating maps were created for the different factors and cultivation systems. To generate the composite suitability maps, the rating maps were overlaid in accordance with the cultivation system. For the overlay process based on Liebig's law of the minimum, the rating of the worst factor in a region overrides the rating of all other factors, effectively determining land suitability by the limiting factor (Kiefer, 1965).

### 2.2.4. *Validation of the suitability maps*

The accuracy of the suitability maps was validated in two ways. First, the locations of the mapped rice fields (areas from 0.04 to 0.51 ha) and yields were correlated to the predicted suitability classes for the respective cultivation system. From the 27 fields that were mapped, only 15 could be harvested by sickle in accordance with the farmers' decision. Depending on the field size, two to six sub-plots of 1 $m^2$ were marked at locations chosen to represent the variability within each field (Roel et al., 2007). For fields where rice was grown in association with other crops such as yams or maize, $2 \times 2\,m^2$ sub-plot size was adopted to account for heterogeneity as much as possible. Grain yield and total above-ground biomass were determined in each sub-plot. Grain moisture upon harvest was measured, and the yields were converted to 14% moisture content, as recommended (Schmitter et al., 2015). All of the harvested rice fields were cultivated under natural flood with a grain yield ranged from 0.3 to 3 t/ha.

Second, the results were compared to the farmers' opinions of the areas that are best suited for the cultivation of rice based on their own knowledge and experience. Over the total number of 18 farmers who cultivated rice in the inland valley, 12 were randomly chosen and individually interviewed following a questionnaire form in a face-to-face interchange. For rainfed bunded and irrigated cultivation, no validation could be made because no fields of the respective cultivation systems were observed with the exception of a single bunded field. Thus, the suitability results obtained for such cultivation systems may reveal more uncertainties from the fringes toward the highest areas.

## 2.3. *Meteorological and hydrological data collection*

To assess the climatic suitability of the target region for rice production, precipitation was automatically measured every 5 min using a tipping-bucket rain gauge with a resolution of 0.2 mm, and temperature and relative humidity were recorded hourly by a Gemini Tiny Tag sensor. Radiation and wind speed data were measured every 5 min at a climate station (of the SMART-IV project) located 30 km from Pélébina village. As depicted in Fig. 1, the inland valley was divided into three transverse transects located at the upstream, midstream and downstream parts, respectively (Windmeijer and Andriesse, 1993). Along each transect, six 2-m-long piezometers were installed, from which we measured the shallow groundwater depth every three days on the slope, fringe and in the valley bottom. All measurements were undertaken over the 2013 wet season from April to October.

## 2.4. *Soil analysis and mapping*

To determine the soil site suitability for each cultivation system, as no soil map was available, 100 topsoil samples of the A horizon, organically enriched notably by detritus resulting from plant senescence, were collected from different positions in the inland valley at a depth of 15–20 cm using a 1.5 m auger drill. Subsequently, the soil texture, soil organic carbon (SOC) to total nitrogen (TN) ratio, cation exchange capacity (CEC), pH and phosphorus (P) were determined in the soil scientific laboratory of the University Bonn. To estimate soil properties at unsampled locations, the choice of the optimal interpolation technique is an important issue in site-specific analysis. In this study, this was performed by applying the inverse distance weighted method of interpolation using Arc GIS 10.2.

**Table 1**
Descriptive statistics of topsoil properties in the fringes ($n = 65$) and the valley bottom ($n = 35$) from 100 soil samples.

| | Minimum | | Maximum | | Mean | | SD | |
|---|---|---|---|---|---|---|---|---|
| | Valley bottom | Fringes | Valley bottom | Fringes | Valley bottom | Fringes | Valley bottom | Fringes |
| Sand (%) | 5.3 | 4.7 | 88.6 | 90.6 | 46.5 | 69.0 | 0.9 | 0.7 |
| Silt (%) | 9.4 | 7.6 | 64.9 | 47 | 32.4 | 20.6 | 13.9 | 9.5 |
| Clay (%) | 1.9 | 1.7 | 50.7 | 50.5 | 21.1 | 10.4 | 14.1 | 9.4 |
| pH ($H_2O$) | 5.1 | 5.1 | 6.3 | 6.5 | 5.7 | 5.7 | 0.3 | 0.2 |
| SOC (%) | 0.5 | 0.3 | 4.3 | 3.4 | 1.5 | 0.9 | 0.9 | 0.7 |
| $CEC_{app}$ (cmol cM kg) | 13.1 | 22.8 | 519.1 | 831.2 | 101.2 | 183.2 | 113.5 | 181.2 |
| BS (%) | 1.2 | 2.4 | 100 | 100 | 62.8 | 34.4 | 35.6 | 33.7 |
| SBC (cmol cM kg) | 0.3 | 0.3 | 25.1 | 29.5 | 8.8 | 3.9 | 7.5 | 5.3 |

SD, standard deviation; SOC, soil organic carbon; $CEC_{app}$, apparent cation exchange capacity; BS, base saturation; SBC, sum of basic cations.

### 2.5. *Landscape data*

The landscape suitability was mainly analysed based on characteristics such as slope, flood and drainage. Slope is an important factor in determining the suitability for rice cultivation (Dengiz, 2013; Gumma et al., 2009; Kuria et al., 2011). A common procedure is to derive slope maps from a digital elevation model (Gumma et al., 2009; Masoud et al., 2013). The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) was used for the research area. However, the performance of the derived slope model was inadequate due to the coarseness of the DEM, and no significant correlation could be determined between the derived values and the field measurements with a clinometer (field data includes slope information of the three transects and data from visited rice fields). Therefore, an alternative slope map was generated by first comparing evaluation values from the DEM to the observed slope values, as it was observed that the slopes became gentler with descending altitude, which is typical for inland valleys (Windmeijer and Andriesse, 1993). Based on this information, the DEM was reclassified according to altitude and local clinometric observations. The reclassified slope values were then correlated with the observed values from 38 observations in total, and a correlation of $r = 0.660$ ($p \leq 0.01$) was observed.

Flooding is undeniably one of the most important factors in assessing land suitability for rice cultivation. To map the extent and depth of flooding, several datasets were used to delineate flooded areas: the DEM, the numbers of days the piezometers were flooded and a GIS shapefile of flooded areas created during the IMPETUS inventory campaign in 2006 by Giertz et al. (2012). Qualitative information from stakeholder interviews on the location of areas likely to be flooded and the respective length of flood periods and frequency was also included in the evaluation process. This information is of vital importance in augmenting sparsely available hydrological information (Lightfoot et al., 2009; Sicat et al., 2005). The drainage characteristics of the inundated areas were derived from the previously created flood map and the classification was done according to the flood duration as defined in the FAO soil drainage classes by Sys et al. (1991).

### 2.6. *Spatial assessment*

At this study scale, no land use map was available for the extraction of the location of the different rice cultivation systems implemented in the inland valley. Thus, cultivated fields and cultures were identified, recorded, and mapped using GPS to record present agricultural land use. This step was mostly important to check the fitness of the different rice fields to the predicted suitable areas and to evaluate the actual extent to which the agro-potentiality of the inland valley is used as a whole. Related outputs from the overlay of layers were also used to link the observed yields to the management practices involved at the fields while determining the limiting factors. The mapping of the cultivated fields was conducted from July to November during the rainy season. Post processing and calculation of surface areas were conducted using Arc GIS 10.2.

### 2.7. *Survey of farmers*

Relevant information from the qualitative interviews with farmers was used to validate the generated suitability maps. The 12 rice farmer interviewees were questioned about possible suitable and not suitable areas for rice production and the factors likely to restrict cultivation from their experience in the inland valley. They were additionally asked to give quantitative and qualitative information on management practices, such as land preparation, sowing date, frequency of weeding and fertiliser application, and on soil and landscape properties, such as soil quality, soil moisture and flood depth. The cultivation under natural flood rice cultivation system was the current system most commonly adopted by the farmers in the inland valley.

## 3. Results

### 3.1. *Landscape characteristics*

The resulting map of the reclassified slope shows the highest values to be between 8 and 16% in the far eastern part of the inland valley, while slopes of values from 6 up to 8% were found in the east, northeast and southeast. In the central part, they were moderate (2–6%) and gentle in the valley bottoms (1–2%). The topography is decidedly flatter in the western part, with inclinations between 1 and 2%, and flattening to 0–1% near the outlet of the valley in the northwest.

Based on the delineation of the flooded areas and reclassification of the flood map, 9% of the inland valley area is flooded for less than two months and up to 20 cm deep during an average rainy season and is accordingly classified as moderately to imperfectly drained; 14.7% is flooded for 3–4 months up to 20 cm deep and is poorly drained; and 2.3% of the area is inundated for 3–4 months to 20–80 cm deep and is very poorly drained.

### 3.2. *Soil properties*

The soil sample analysis shows a high variability of soil texture throughout the inland valley. The predominant soil texture in the study area and especially on the fringes is sandy loam according to the USDA classification (United States Department of Agriculture, 2014). In the valley bottom, this texture is featured along with the silty clay loam texture (Table 1). The soils in the inland valley were moderately acid with pH values between 5.11 and 6.5. Values between 0.31 and 4.25 g/kg were found for SOC, and the apparent CEC values ranged from 13.31 cmol c/kg clay up to 831.16 cmol c/kg clay.

**Table 2**
Correlation values of soil properties with the inland valley morphological characteristics using laboratory results of the analysis of the same 100 soil samples used in Table 1.

| | Soil properties | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Mor[a] | Clay | Silt | Sand | pH | SOC | $CEC_{app}$ | BS | SBC |
| *p* | <0.0001 | <0.0001 | <0.0001 | n.s. | <0.0001 | 0.02 | <0.0001 | <0.0001 |
| *r* | −0.42 | −0.45 | 0.47 | 0.003 | −0.36 | 0.24 | −0.37 | −0.35 |

SOC, soil organic carbon; CECapp, apparent cation exchange capacity; BS, base saturation; SBC, sum of basic cations.

[a] Mor, variable accounting for morphology taking values of 1 for the valley bottom and 2 for the fringes.

The Pearson bivariate correlation shows that most of the soil properties are significantly correlated with the morphology of the inland valley (Table 2). For instance, significant differences in the soil properties, such as clay, silt sand, SOC and apparent CEC are seen between the fringes and the valley bottom. A significant decrease of 51% for clay ($p < 0.001$), 36% for silt ($p < 0.001$) and 40% for SOC ($p = 0.001$) are revealed from the valley bottom to the fringes. The sand content ($p < 0.001$) and the apparent CEC ($p = 0.007$) increases significantly towards the fringes at 48% and 81%, respectively.

### 3.3. *Suitability mapping*

The climatic suitability of the inland valley for the different rice cultivation systems ranges from high to moderate with respect to precipitation, temperature and relative humidity. For all cultivation systems, the limiting factors were the precipitation in the fourth month and the average temperature in the second month during the monitoring period. As the rainy season 2013 was considerably drier than the long-term average, the suitability would have been likewise lower. It was therefore decided to use averaged daily precipitation data from nearby Djougou for the years 1996–2005. The precipitation in the first month was not suitable for the cultivation of rainfed bunded and the cultivation under natural flood. Based on the ten-year average, this changed to highly suitable. Likewise, the precipitation in the fourth month was marginally suitable for rainfed bunded and cultivation under natural flood. When using the rainfall average, the suitability turned out to be moderate (Table A4).

Regarding landscape and soil, the suitability values were 52.1% for irrigated cultivation, 17.8% for cultivation under natural flood and only 1.2% for rainfed bunded (Fig. 5). More precisely, most of the inland valley is moderately suitable for irrigated cultivation at 9.7%, with 42.2% being marginally suitable. The highly suitable class is not represented for irrigated cultivation. As far as cultivation under natural flood is concerned, 13.0% is highly, 6.5% moderately and 10.8% marginally suitable. For rainfed bunded, only 0.6% is moderately and 0.7% is marginally suitable. The most-limiting factor determined for cultivation under natural flood was flooding, with 17.4% and 80% of the area being not suitable. The suitability map for irrigated cultivation shows that the western and southern parts of the valley are not or currently not suitable, mainly due to steep slopes. Concerning the cultivation of rainfed bunded rice, soil texture is the most-limiting factor, with 94% of the area being not suitable as the sandy loam texture predominant in the inland valley is classified not suitable (Sys et al., 1991, 1993). However, this parameter was not the most limiting for the other rice cultivation systems. For the suitability analysis, a set of parameters from the FAO recommendation was selected to be used for every cultivation system. Prior to the assessment, the extent to which these parameters might be limiting could not be appraised effectively.

### 3.4. *Validation*

Out of the 27 rice fields mapped within the inland valley, 26 were cultivated under natural floods, and only one under bunded conditions. All 26 fields lie within the area identified as being suitable for rice cultivation under natural floods. However, the field cultivated for rainfed bunded was located in an area determined by the classification approach to be unsuitable due to the sandy texture of the soil. Thus, the creation of bunds was a means for the farmers to harvest water and make the soils suitable.

The average yield observed under natural floods was 1.4 ± 1 t/ha. In areas highly suitable for cultivation under natural floods the average yield was 2.4 ± 0.9 t/ha. The yield observed in areas classified as moderately, marginally and currently not suitable was respectively 2.1 ± 0.3 t/ha, 1.0 ± 0.6 t/ha, 1.1 ± 1.1 t/ha. No field was mapped in the areas classified as not suitable.

Most interviewees indicated either areas close to the valley outlet or in the midstream valley bottom, which are flooded during the rainy season, to be suitable for rice cultivation. The descriptions coincided with the suitability map for cultivation under natural flood, in which these areas were considered to be either moderately or highly suitable. Some other farmers stated that the lower slopes of the valley, which stay moist during the rainy season, are best suited for rice cultivation. No farmer mentioned the cultivation of bunded rice, and this might indicate some unknown factor restricting adoption of the system.

## 4. Discussion

### 4.1. *Suitability of the inland valley and limiting biophysical factors for rice cultivation*

No significant correlation could be determined between rice yield and suitability class. The spatial extent of the areas suitable for rice cultivation under natural flood was expected. According to their own experience, the farmers refer to the valley bottom as a landscape unit endowed with limited risks of water scarcity and high level of fertility on which they could produce rice before flooding occurs. Therefore, other parts of the inland valley predicted to be suitable for rice cultivation were preferentially used to grow yams, a major staple crop and more profitable for many households, in association with other crops such as sorghum or maize.

The low percentage of suitable areas for the production of rainfed bunded rice can be explained by the constraints of the soil texture, as sandy soils dominate in the inland valley. Coarse-textured soils are generally less productive, with low inherent fertility and low water-holding capacity in relation to high percolation rates (Haefele et al., 2014), by which nutrients are easily leached beyond the root zone. This reflects the importance of increasing rainwater utilisation efficiency by percolation limitation on well-drained soils, which was indicated by Garrity et al. (1992) to improve rice yield in the lowland.

Though steep slopes restrict the suitability for irrigated cultivation to half of the total inland valley area, this percentage was higher than expected as infrastructural constraints prohibit irrigation at the moment. No irrigation scheme was implemented in the research area, the exception being small household vegetable gardens that were irrigated with well water using either watering pots or calabashes. Additionally, there is no municipal water supply, and the local population relies on open wells and a few foot-pumps

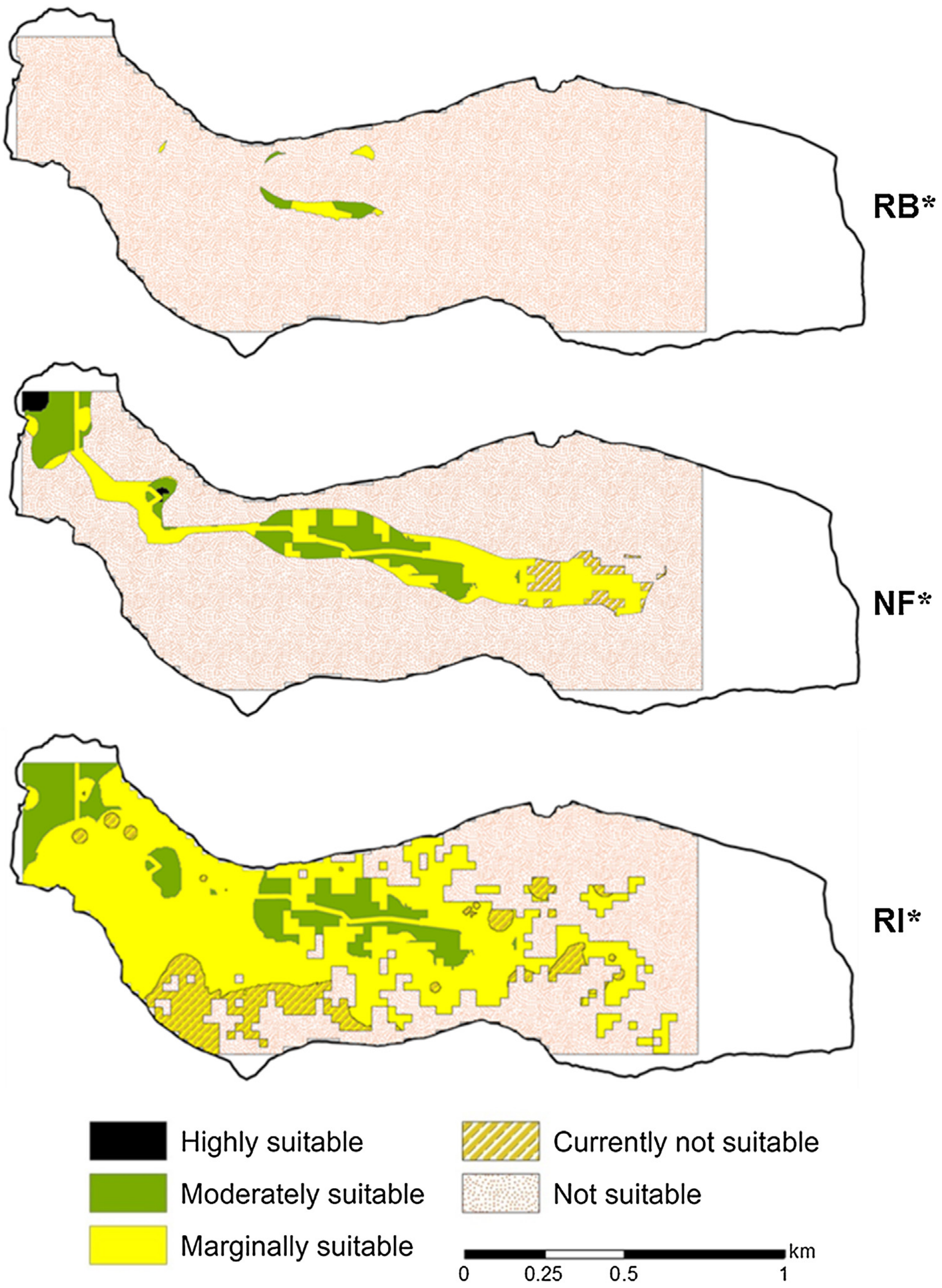

**Fig. 5.** Results of soil and landscape suitability evaluation. * RB, rainfed bunded; NF, rice cultivated under natural flood; RI, irrigated rice.

to access drinking water. However, similar studies conducted in the Tana delta area in Kenya (Kuria et al., 2011) and in the Central Anatolian region of Turkey (Dengiz, 2013) found that adverse soil physical and chemical properties were limiting the suitability for irrigated rice cropping to 67% and 55.5% of highly to moderately suitable land (Kihoro et al., 2013). Specifically, these studies revealed within their related sites of investigation, important and unused potential areas for growing rice to achieving optimum utilisation of available land resources. Basically, the suitability analysis was conducted following the FAO guidelines by matching both land characteristics and rice requirements to produce a final suitability map for each study area. In the Tana delta area, the GIS-based approach used by Kuria et al. (2011) involved the combination of selected theme layers of landforms, agricultural lands, soil properties (texture, sodicity and salinity), which revealed that 9% of the study area was currently unsuitable due to limitation factors such as partly sandy clay texture, saline, low water retention and high hydraulic conductivity (Kihoro et al., 2013; Kuria et al., 2011). In the Central Anatolian region, the overlay of topography (landform and slope) and soil (nutrients availability, drainage, texture, hydraulic conductivity, salinity, pH) theme layers showed that 34% of the study area was unsuitable due to both soil and topographic conditions (Dengiz, 2013). As in other previous studies, the selected approach to assess the suitability for rice cultivation in this investigation demonstrates the capability of GIS to integrate spatial and attribute data to extract additional and reliable meaning with high accuracy (Halder, 2013; Kihoro et al., 2013; Krishna and Regil, 2014; Kuria et al., 2011; Liu et al., 2006). Although adequate results were achieved, this study was limited in its ability to produce valuable information on the relative importance of soil and landscape factors, only taking into account the local conditions of a single inland valley. Additionally, a limitation of the use of the Boolean logic in the overlay process was revealed in the occurrence of overlapping areas that featured a good suitability attribute on every cultivation system map. This requires a thorough analysis for discretising the areas by defining the parameter boundary thresholds, in order to assign the best suited cultivation system to the different parts. Although this analysis was beyond the scope of this study, it could be tested by using fuzzy logic which permits partial memberships.

However, the methodology and the ensuing findings are useful and could be adopted for diverse studies under similar agro-climatological conditions, which should additionally account for currently omitted factors in the suitability evaluation, such as the percentage of coarse fragments and the soil depth. For the purpose of regionalisation, the similarity among inland valleys in the region with respect to landscape and soil and their nearness in the geographical space should be assessed first. And further, in the resulting clusters derivation process, the similarity measurement of values of the selected agro-ecological attributes should be performed carefully in consideration of the existent irrigation facilities and socio-economic factors.

### *4.2. Constraints and assets to optimising rice production within the inland valley*

As the harvested rice fields were almost exclusively cultivated under natural flood conditions and lie within areas classified to be suitable for such a cultivation system, one would expect high values of actual rice yield, assuming that soil and landscape are not limiting conditions. However, the average grain yield measured within the inland valley was very low (1.4 ± 1 t/ha) in comparison with the potential yield obtained by Worou et al. (2013) who reported values from 3.81 to 4.36 t/ha on average over four wet seasons in the same region. In the study conducted by Worou et al. (2013), yields were investigated in rainfed lowland rice in a researcher-managed on-farm trial in order to evaluate the efficiency of bunding and fertiliser application for improving rice productivity in the upslope and downslope positions in inland valley (Worou et al., 2013). However, the yield gap in the areas of favourable physical conditions in the inland valley of Tossahou, in the present study, could mainly indicate an important influence of the social and economic environment as source of constraints that might affect farmers' decisions and result in the high restriction of the yield noted. Actually, land pressure is very low and not constraining in the village due to the low population, and the access to land is usually gained through lease, gift or inheritance following the agreement of the owners. Nonetheless, various difficulties were mentioned by the farmers during the interviews and could qualitatively be discussed for characterising the actual socio-economic constraints on rice production within the inland valley. In general, the farmers have no assured access to credit to buy seeds and fertilisers and no subsidies are currently acquired from the government. Moreover, the access to market is almost non-existent as only a small portion of the harvest could be sold during the local market day and the remaining part was used for subsistence or barter due to the lack of transportation means to reach more distant and larger market places. This state of affairs causes the farmers to become heavily indebted from one season to another. Gradually, they become discouraged from producing more rice and even refrain from adopting recommended and costly activities on their fields which are therefore cultivated to a lower extent. It has been reported that even for the few having some resources from another job, the labour costs were not affordable specifically for weeding as the weed pressure is very high in the valley bottom. The valley bottom was remarkably infested with weeds in many areas during the monitoring period, and the farmers have pointed out the strong competition of these weeds with the rice plants and the high labour-intensiveness of removing them, as only hand weeding was performed due to economic reasons, which, however, is rather good for protecting the environment from herbicide pollution.

Other existent constraints were mentioned during the post-processing of the paddy such as the lack of adequate threshing areas and materials for husking. In addition, the need has been highlighted for training in effective rice cultivation and acquisition of knowledge of high-yielding and stress-tolerant rice varieties. No selected varieties of rice are specifically used in the inland valley, and rice is directly seeded, which could also lead to a higher risk of yield losses due to weed competition (Chauhan, 2013; Ogban and Babalola, 2003). Chauhan (2013) have shown that weeds could cause yield losses of up to 50% in direct-seeded fields even after one hand weeding (Chauhan, 2013).

In the light of all above, the yield gap could be closed if a favourable socio-economic environment is made accessible to the farmers.

## 5. Conclusion

This paper attempts to assess the climate, landscape and soil suitability in the inland valley of Tossahou in Benin, based on the FAO land evaluation guidelines and parameter method develop by Sys et al. (1991, 1993) to map potential areas of favourable conditions for expanding and optimising rice production, using GIS techniques. Three rice cultivation systems were considered, namely irrigated, bunded and cultivation under natural floods. The results reveal that more than half of the inland valley is of good suitability for the irrigated system, whereas the cultivation under natural floods is best suited only for the central valley bottom. The low potential for rainfed bunded rice cultivation is mostly due to the sandy soil texture occurring throughout the inland valley. In general, the most-limiting physical factors are the precipitation, temperature, flooding, steep slopes and soil texture. However, we were limited by the absence of cultivated fields to validate the suitability maps for the irrigated and bunded cultivation systems.

The low grain yield recorded on fields of favourable physical land conditions sheds light on the need to understand the constraining impact of the socio-economic environment on rice cultivation within the inland valley. Prior to the study, no methodological approach was applied in Benin to evaluate the land suitability for rice production. Thus, this approach can be adopted by researchers to conduct diverse studies in inland valleys under similar agro-climatological conditions, with a need to be improved for a detailed discretisation in the overlapping areas which proved to be suitable for all cultivation systems. Moreover, the findings should make an important contribution at local level for complementary and necessary socio-economic analyses which lie beyond the scope of this study, and are relevant for the yield improvement in the potential areas identified.

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## Appendix A

See Tables A1–A4.

**Table A1**
Climatic requirements for different rice cropping systems as applied.

| | Suitability class[a] | | | |
|---|---|---|---|---|
| | S1 | S2 | S3 | N2 |
| P 1 month (mm) | | | | |
| RB/NF | $175 < P < 500$ | $125 < P < 175$ or $500 < P < 650$ | $100 < P < 125$ or $650 < P < 750$ | $P < 100$ or $P > 750$ |
| P 2 and 3 month (mm) | | | | |
| RB/NF | $175 < P < 500$ | $125 < P < 175$ or $500 < P < 650$ | $100 < P < 125$ or $650P < 750$ | $P < 100$ or $P > 750$ |
| P 4 month (mm) | | | | |
| RB/NF | $50 < P < 300$ | $30 < P < 50$ or $300 < P < 500$ | $P < 30$ or $500 < P < 600$ | $P < 600$ |
| $T_{mean}$ growth cycle (°C) | | | | |
| RB/NF | $24 < T < 36$ | $18 < T < 24$ or $T > 36$ | $10 < T < 18$ | $T < 10$(RU),$T < 18$(RB/RF) |
| $T_{max}$ mean (°C) | | | | |
| RB/NF/RI | $30 < T < 40$ | $26 < T < 30$ or $40 < T < 45$ | $21 < T < 26$ o r$45 < T < 50$ | $T < 21$ or $T > 50$ |
| $T_{mean}$ 2 month (°C) | | | | |
| RB/NF/RI | $24 < T < 36$ | $18 < T < 24$ or $36 < T < 42$ | $10 < T < 18$ or $42 < T < 45$ | $T < 10$ or $T > 45$ |
| $T_{min}$ 4 month (°C) | | | | |
| RB/NF/RI | $14 < T < 15$ | $10 < T < 14$ or $25 < T < 28$ | $7 < T < 10$ or $28 < T < 30$ | $T < 7$ or $T > 30$ |
| RH 1 and 2 month (%) | | | | |
| RB/NF/RI | $50 < RH < 90$ | $40 < RH < 50$ or $90 < RH < 100$ | $30 < RH < 40$ | $RH < 30$ |
| $RH_{harvest}$ (%) | | | | |
| RB/NF/RI | $33 < RH < 80$ | $30 < RH < 33$ or $rH > 80$ | $RH < 30$ | – |

Adapted from Sys et al. (1991, 1993).

P, total precipitation (mm); T, temperature; $T_{mean,}$ growth cycle, mean temperature during growing cycle; Tmax mean, mean maximal temperature of warmest month; Tmin, mean minimal temperature ripening stage (4th month); $RH_{harvest}$, relative humidity at harvest stage (4th month).

RB, rainfed bunded; NF, rice cultivated under natural flood; RI, irrigated rice.

[a] S1, Highly suitable; S2, Moderately suitable; S3, Marginally suitable; N2, Not suitable.

**Table A2**
FAO flood classes.

| Flood depth subclasses | Duration of floods subclasses | | | |
|---|---|---|---|---|
| | 1 ($Du < 2$ months) | 2 ($2 < Du < 3$ months) | 3 ($3 < Du < 4$ months) | 4 ($Du > 4$ months) |
| 1($0 < De < 10$ cm) | 11 | 21[a] | 31 | 41 |
| 2($10 < De < 20$ cm) | 12 | 22 | 32 | 42 |
| 3($20 < De < 40$ cm) | 13 | 23 | 33 | 43 |
| 4($40 < De < 80$ cm) | 14 | 24 | 34 | 44 |
| 5 ($De > 80$ cm) | 15 | 25 | 35 | 45 |

Adapted from Sys et al. (1991, 1993).

Du, duration of flood; De, depth classes.

[a] 21, flood class with duration of flood between 2 and 3 month (duration of floods subclass 2) and flood depth between 10 and 20 cm (flood depth subclass 1).

**Table A3**
Soil and landscape requirements for different rice cropping systems as applied.

| Suitability class | S1[b] | S2[b] | S3[b] | N1[b] | N2[b] |
|---|---|---|---|---|---|
| Slope (%) | | | | | |
| RB[c] | $0 < S < 4$ | $4 < S < 8$ | $8 < S < 25$ | – | $S > 25$ |
| NF[c] | $S = 0$ | $0 < S < 2$ | $2 < S < 4$ | $4 < S < 6$ | $S > 6$ |
| RI[c] | $0 < S < 1$ | $1 < S < 2$ | $2 < S < 4$ | – | $S > 4$ |
| Flood (classes) | | | | | |
| RB | 0.11,12,21,22 | 13,23,41,42 | 14,23,24,34,43 | 15,25,44 | 35,45 |
| NF | 32,32 | 33,41 and 43 | 21 and 24,34,44 | – | 11–15,25,35,45 |
| RI | 0.11,12,21,31,32 | 13,23,33,41 and 43 | 14,24,34,44 | – | 15,25,35,45 |
| Drainage[a] | | | | | |
| RB | imp | poor,mod | good | – | very poor |
| NF | poor | poor,impt | mod | – | good |
| RI | imp-mod | poor,good | poor | – | – |
| Texture | | | | | |
| RB | SiC-SiCL | CL | SiL | – | L-LS |
| NF/RI | SiC-CL | SiL-SCL | SL-LS | – | – |
| $CEC_{app}$ (cmol cM $kg^{-1}$)[a] | | | | | |
| RB/NF/RI | $CEC > 24$ and $<16$ | $CEC < 16$ (−)[c] | $CEC < 16$ (+)[c] | – | – |
| BS (%)[a] | | | | | |
| NF | $BS > 50$ and $<35$ | $35 < BS < 20$ | $BS < 20$ | – | – |
| RB/RI | $BS > 80$ and $<50$ | $50 < BS < 35$ | $35 < BS < 20$ | $BS < 20$ | – |
| SBC (cmol cM $kg^{-1}$)[a] | | | | | |

Table A3 (*Continued*)

| Suitability class | S1[b] | S2[b] | S3[b] | N1[b] | N2[b] |
|---|---|---|---|---|---|
| NF | SBC > 4 and <2.8 | 2.8 < SBC < 1.6 | SBC < 1.6 | – | – |
| RB/RI | SBC > 6.5 and <4 | 2.8 < SBC < 4 | 2.8 > SBC > 1.6 | SBC < 20 | – |
| pH | | | | Only RU | RB/NF/RI |
| RB/NF/RI | 6.5 > pH > 5.5 | 5.5 ≥ pH > 5.0 | 5.0 > pH > 4.5 | pH < 4.5 | pH < 4.5 |
| SOC (%)[a] | | | | | |
| RB/NF/RI | SOC > 2 and <1.5 | 1.5 < SOC < 0.8 | SOC < 0.8 | – | – |

Adapted from Sys et al. (1991, 1993).

CECapp, apparent cation exchange capacity; BS, base saturation; SBC, sum of basic cations; SOC, soil organic carbon; S, slope; 0, no flooding; 11–45, flood classes values from Table A2.

[a] Drainage: v. poor – very poor, mod – moderate, imp – imperfect.

[b] S1, Highly suitable; S2, Moderately suitable; S3, Marginally suitable; N1, Currently not suitable; N2, Not suitable.

[c] RB, rainfed bunded; NF, rice cultivated under natural flood; RI, irrigated rice; (−), slightly; (+), considerably.

**Table A4**
Climatic suitability.

| Climatic characteristics | 2013 (1996–2005) | RB | NF | RI |
|---|---|---|---|---|
| Prec. 1st month (mm) | 91 (288) | N 2 (S 1) | N 2 (S 1) | – |
| Prec. 2nd month (mm) | 236 | S 1 | S 1 | – |
| Prec. 3rd month (mm) | 203 | S 1 | S 1 | – |
| Prec. 4th month (mm) | 9 (30) | S 3 (S 2) | S 3 (S 2) | – |
| $T_{mean}$ growth cycle (°C) | 24.9 | S 1 | S 1 | S 1 |
| $T_{max}$ mean (°C) | 34.7 | S 1 | S 1 | S 1 |
| $T_{mean}$ 2nd month (°C) | 23.6 | S 2 | S 2 | S 2 |
| $T_{min}$ 4th month (°C) | 19.1 | S 1 | S 1 | S 1 |
| RH 1st and 2nd month (%) | 88.7 | S 1 | S 1 | S 1 |
| $RH_{harvest}$ (%) | 75.9 | S 1 | S 1 | S 1 |

$T_{mean}$ growth cycle, mean temperature during growing cycle; $RH_{harvest}$, relative humidity at harvest stage (4th month); S1, Highly suitable; S2, Moderately suitable; S3, Marginally suitable; N2, Not suitable.

RB, rainfed bunded; NF, rice cultivated under natural flood; RI, irrigated rice.

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