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Benefits and limits of inland valley development to enhance agricultural growth: a farmers' perception approach in southern Mali

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Abstract
In the last 40 years in sub-Saharan Africa, huge investments have been made in inland valley (IV) development for agricultural production. Understanding the agricultural and socioeconomic impacts of IV development may help develop strategies for modernization and optimization of irrigation systems. A farmers' perception approach was used to analyze the impacts of IV development on agricultural and hydraulic performances and on farmers' socioeconomic conditions in the circle of Sikasso, Mali. Data were collected through focus group discussions, field visits and participatory observations in 37 inland valleys of which 17 were developed. The two main water control systems observed in developed inland valleys were (1) controlled submersion with bunded plots dedicated to rice and (2) spate irrigation regulated by weirs and cofferdams. Compared to undeveloped inland valleys, controlled submersion and spate irrigation expanded the cultivated area in the rainy season. In the dry season, crop extension was observed only in spate irrigation schemes. Higher crop productivity was observed in inland valleys located close to an urban market and in valleys cultivated during the off-season. Spate irrigation is widespread in bigger inland valleys with more water resources and is often associated with the cultivation of higher value off-season crops. Consequently, we observed farmers had individual and collective investment capacity in spate irrigation schemes than in controlled submersion and undeveloped inland valleys. The study highlighted the importance of re-thinking the design of water control facilities to enable crop diversification to improve the livelihoods of inland valley-dependent communities.

Keywords Inland valleys · Crop diversification · Crop intensification · Land development · Market access · West Africa

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1 Introduction

Since the droughts of the 1970s and 1980s, agricultural harnessing of inland valleys has been considered a key decentralized option to mitigate climate risks and contribute to food security. Inland valleys comprising valley bottoms and their hydromorphic fringes can be considered as sinks into which surface water and groundwater flow from a surrounding catchment (Raunet 1985). Within the landscape, inland valleys are natural harvesters of rainwater and, by definition, sites where water occurs at or close to the surface of the ground (Windmeijer and Andriesse 1993; McCartney et al. 2010). This water availability favors many ecosystem services: plant biodiversity (Junk et al. 2006), fisheries in ponds, forage production (Adams 1993) and flooded or irrigated agriculture (Verhoeven and Setter 2010). The cropping season can be considerably expanded with early crops such as maize in dry areas, rice in flooded areas during the rainy season and off-season crops where a shallow water table enables irrigation (Ahmadi 1998; Erenstein et al. 2006a, b; Sakurai 2006; Singbo and Oude Lansink 2010; Giertz et al. 2012).

Excluding large alluvial plains, inland valleys are estimated to account for 3.6% of sub-Saharan Africa, corresponding to approximately 85 million ha (Andriesse et al. 1994). In southern Mali, inland valley ecosystems are estimated to account for about 300,000 ha or 5% of the total cultivable area (Bariau 1993). With soils that are more fertile than in the uplands and water and/or soil moisture available throughout the year, inland valleys provide smallholder farmers with opportunities to produce crops all year round, particularly in drought years, thereby mitigating food shortages in upland fields and improving farmers' incomes (Dossou-Yovo et al. 2017). However, despite their high agricultural potential, only 10–25% of the total inland valley area in sub-Saharan Africa is used for agricultural production (Rodenburg et al. 2014) because of human and natural constraints such as the lack of available labor (Paresys et al. 2018), poor water control (Totin et al. 2014) and limited access to appropriate technologies (Giertz et al. 2012). To tap the potential of inland valleys for agricultural production, many water control facilities have been developed thanks to public investments, cooperation and development projects. In Mali alone, hundreds of inland valleys covering a total area of 14,300 ha benefited from development projects up to the end of the 2000s (DNGR 2012). The objective of inland valley development projects was to improve water control in these valleys to extend and intensify crop production (Singbo and Oude Lansink 2010).

Despite the large number of projects, there is very little empirical evidence for impacts of water control facilities, since ex-post evaluations of projects are rare or are rarely available (Metzger and Günther 2015). In the Sudanian zone of West Africa, recent program assessments in Mali, Burkina Faso and Guinea yielded contradictory results. Katic et al. (2013) conducted an ex-post cost-benefit analysis of two inland valley development programs, *Initiatives Intégrées pour la Croissance Economique au Mali* (IICEM) in Mali and *Programme d'Aménagement des Bas-Fonds du Sud-Ouest* (PABSO) in Burkina Faso. The authors focused on calculating the economic returns derived from the change in agricultural production due to the construction of water control facilities. They found positive returns in most of the sites, with an average economic internal rate of return of 58% in Mali and 8% in Burkina Faso. The economic internal rate of return is defined as the rate at which the net present value of all the cash flows (both positive and negative) from a project equal zero (Francis et al. 2005). The factors that most influenced profitability were the increase in rice yields and the extension of high value-added vegetable crops in the dry season. However, these assessments were only made in four sites a few years after the project was completed and were based on expected long-term cash flows with the optimistic assumptions that increased returns would be preserved, and that the infrastructure would be well maintained. These assumptions were rebutted by the assessments of Delarue (2007), who found results had not been sustained and that the benefits of inland valley development programs in eastern Guinea had disappeared over time. Further studies are thus needed to evaluate the long-term impacts of inland valley development on agricultural production.

The factors that affect agricultural development in inland valleys have been investigated by several authors. Using geo-referenced lowland data around four urban centers along an ecological gradient in Côte d'Ivoire and Mali, a study by Erenstein (2006) found that intensification of lowland agriculture was associated with proximity to urban markets, an agro-ecological gradient, land development and non-native users of the lowlands. Sakané et al. (2014) reported that the variable nature of household dependence on inland valley resources in Kenya and Tanzania was reflected in diverse production orientations with different levels of land use intensity and subsequent land-use intensification of lowlands. Using spatial and multivariate techniques, Dossou-Yovo et al. (2017) reported that the diversity of biophysical characteristics of inland valleys and the socioeconomic attributes of their surrounding environments played a determinant role in farmers' decision making concerning the type, duration and intensity of inland valley uses. However, little is known about the relationship between the biophysical characteristics, water control facilities and agricultural intensification in inland valleys. Additionally, the impacts of water control facilities on farmers' socioeconomic conditions have not been documented to date. The objectives of the present study were thus to: (1) understand the relationship between the biophysical characteristics of inland valleys and the type of water control facilities, and (2) evaluate the impacts of the water control facilities on crop intensification, crop extension, water constraints and farmers' socioeconomic conditions, all based on farmers' perceptions.

2 Materials and methods

2.1 Study area

The study was conducted in the circle of Sikasso in the region of Sikasso between latitude 12°30′N and longitude 8°45′W (Fig. 1). The study area is located in the Sudanian agro-ecological zone with a unimodal rainfall regime according to the White classification (1983). Mean annual rainfall ranges from 800 to 1200 mm (data from 1980 to 2010). The rainy season lasts from May to October and is followed by a dry season from November to April when daily average air temperature and daily potential evapotranspiration rise and reach a maximum of 31 °C and 8 mm, respectively, in April (Fig. 2). Climate change scenarios foresee a decrease in the annual rainfall of between 7.5 and 15% by 2100 compared to the average rainfall for the period 1961–1990 (Traoré et al. 2004), which will certainly lead to changes in inland valley hydrology insofar as the volume of annual runoff represents 23–37% of the cumulated annual rainfall (Lamagat 1980), suggesting that other factors like land cover, evaporation and groundwater recharge contribute to inland valley hydrology. Research for the present study was conducted at 37 sites in inland valleys, split between 17 inland valleys developed thank to projects and 20 inland valleys that are cultivated in the absence of any water control structures. Each site represents a section of an inland valley, generally belonging to one village. Sampling at each site was based on the hydrographic network, the spatial distribution throughout the region and accessibility.

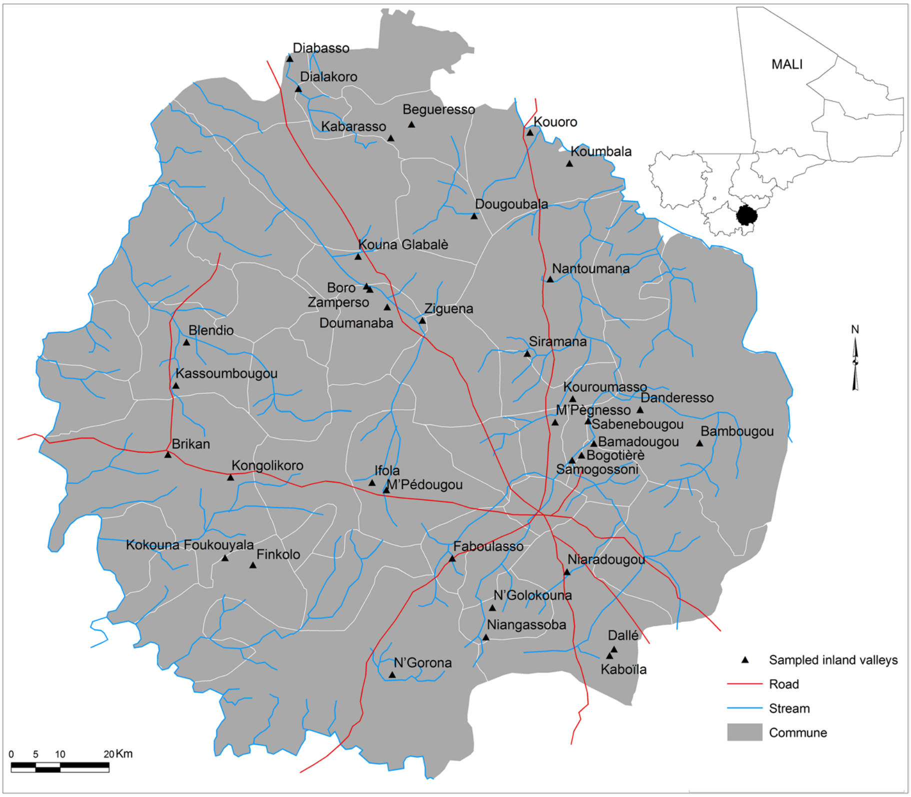
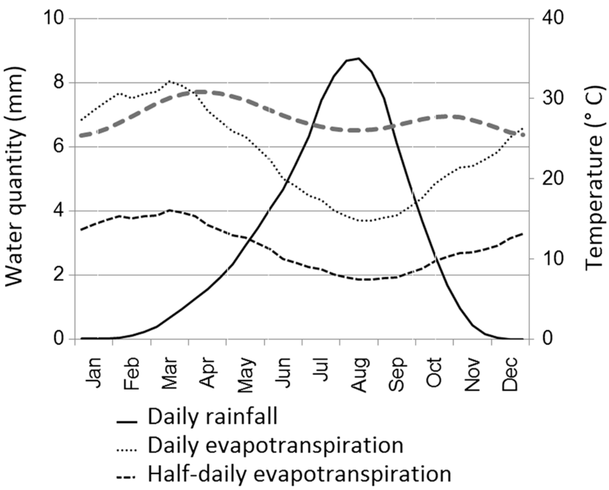


Fig. 1 Location of the inland valleys investigated in Mali

Fig. 2 Seasonal fluctuations in daily rainfall, evapotranspiration, half-evapotranspiration and average air temperature from 1980 to 2010



2.2 Data collection

Data were collected in two steps: first, inland valley sites and their mapping (limits of the area subject to flooding and coordinates of the center) were identified with a Global Positioning System receiver and second, information was collected in focus group discussions with the users of inland valleys. Focus group discussions were conducted during the rainy season (May to October) and the dry season (November to April) in 2010. Data were collected on the economic environment, land development, agricultural productivity, water constraints and farmers' socioeconomic conditions. Field visits were made to collect additional data on the physical and hydrological characteristics of the inland valleys. The data were collected from small focus groups comprising 5–20 farmers separated into gender groups in each inland valley. The questions asked during the focus group discussions were in the local language to insure the respondents fully understood the questions. In total, the dataset comprised 32 variables divided into six categories: physical environment, land development, agricultural features and outcomes, economic environment, socioeconomic impact and water constraints (Table 1). The physical environment provides information on the surface area of the inland valley, the height of flooding, the depth of the water table in the dry season, the shape, soil texture and risk of drying up of the inland valley when there is a dry spell during the rainy season. Land development describes the type of water control facility, management, year of construction and current condition. Agricultural productivity provides information on the total cultivated area in the rainy and dry seasons, cropping intensity and crop productivity in the rainy and dry seasons. The economic environment provides information on the distance between the inland valley and a market, the presence of equipment for dehusking and storage in the village in the inland valley concerned. The socioeconomic impact describes the impact of water control facilities on access to land according to gender and origin and on individual and collective farmers' investment capacity. Water constraints describe the major constraints related to water control. To facilitate discussion of the results, exchange of information, cooperation and collaboration among stakeholders, the data collected were summarized in a report that provides an overview of the main characteristics of the 37 inland valleys sites surveyed (Lidon et al. 2012).

Table 1 Description of themes and variables

Theme	Variables
Physical environment	Extent of inland valley, height of flooding, depth of water table, shape, soil texture, risk of drying out in the inland valley bottom
Land development	Type of water control facility, management, year of construction, condition of the structure
Agricultural productivity	Cultivated area in the rainy season and in the dry season, cropping intensity and crop productivity in the rainy and dry seasons
Economic environment	Distance to market, equipment for dehusking and storage
Socioeconomic impact	Access to land according to gender, origin, contribution to individual and collective investment capacity
Water constraints	No major problem, violent high-water surge, poor water control resulting in excess water in some parts and lack of water in other parts of inland valleys, early ending of rainy season and stream flows leading to lack of water at the end of the cropping cycle, others

2.3 Data analysis

Principal component analysis was performed to understand the relationship between the biophysical characteristics of the inland valleys and the type of water control facilities. The following variables were considered: surface area of the inland valley, the shape, soil texture, risk of drying up in the bottom of the inland valley, the height of flooding, the depth of the water table and the type of water control facilities. The impact of inland valley development on crop extension was evaluated by comparing the percentage of the inland valley used for agricultural production in the rainy season and in the dry season in undeveloped and developed inland valleys. The data collected on the developed inland valleys were further disaggregated among the types of water control facilities to evaluate the effect, if any, of the type of water control facilities on crop extension in inland valleys. The impact of inland valley development on crop intensification and hydraulic performance was evaluated by comparing the cropping intensity, agricultural productivity in the rainy and dry seasons and water constraints in undeveloped and developed inland valleys. Here again, the data were disaggregated among the types of water control facilities and further by considering the condition and management of water control facilities. Cropping intensity was calculated by dividing the sum of the cultivated area in the rainy and dry season by the maximum surface area cultivated in the rainy and dry seasons. Agricultural productivity in inland valleys was evaluated in economic terms because in general, at least two crops were produced in the dry season in inland valleys. In the rainy season, the main crop was rice, while in dry season, the main crops included sweet potatoes, potatoes and tomatoes. Agricultural productivity of an inland valley over one season was calculated by dividing the total gross income from inland valley cropping during that season by the total cultivated area. The total income from farming in an inland valley over one season was calculated by summing the revenue (production multiplied by price) of the different crops grown by the farmers of the inland valley. The socioeconomic impact of inland valley development was evaluated by comparing the accessibility of the land according to gender, origin and the collective and individual investment capacities of farmers in undeveloped inland valleys and with the different types of water control facilities. Farmers' collective investment capacity included farmers' capacity to invest in the social and economic development of the village through participation in local governance processes, entrepreneurship, health and welfare infrastructures. Farmers' individual investment capacity included their capacity to purchase equipment for personal use (motorbike, other vehicle, etc.) and for agricultural use (tractor, pump, etc.). In the focus group discussions, farmers were asked whether and how the use of inland valley and its development have affected their investment capacity.

All the statistical analyses were performed with R software (R Development Core Team 2011). An analysis of variance was performed to evaluate the effects of water control facility, crop diversification and market proximity on crop extension and intensification. Bivariate analyses using t tests were carried out to evaluate the difference in water constraints in relation to inland valley development, the condition of the water control facilities and management by farmers. Modalities of the variable 'water constraints' included no major problem, violent high-water surge, the early ending of rainy season and streamflow and poor water control. Modalities of the variable 'inland valley development' comprised controlled submersion, spate irrigation and undeveloped inland valley. Modalities of the variable 'status of water control facilities' were in good condition or degraded. Modalities of the variable 'management by farmers' included the presence of an active management committee present or the absence of an active management committee. All variables included in the bivariate analyses were transformed into dummy variables prior to analysis.

Following Erenstein et al. (2006a), an inland valley was categorized as being close to a market when the distance between the inland valley and the market was less than 30 km. Accordingly, an inland valley located more than 30 km from market was categorized as being far from a market. The regional market of Sikasso was used as reference to categorize inland valleys as close to or far from a market since Sikasso market enables the purchase of farm inputs (fertilizers, improved seeds and agrochemicals) and is an outlet for farm outputs (potatoes, vegetables, fruit and rice grown for the market) for farmers in many regions of Mali (Vitale and Sanders 2005).

3 Results

3.1 Relationship between the type of water control facilities and biophysical characteristics of inland valleys

Of the 37 inland valleys investigated, 46% were developed and 54% were not. The main water control facilities found in the developed inland valleys were spate irrigation which was implemented in 53% of the developed inland valleys and controlled submersion implemented in 47% of the developed inland valleys. Considering the study area as a whole, 1570 ha of inland valleys were developed using controlled submersion, 1570 ha using spate irrigation, and 2726 ha of inland valleys were not developed in the circle of Sikasso. Spate irrigation is defined by Haile (2007) as a resource system whereby flood water is released through ephemeral streams or seasonal rivers and diverted to irrigable fields. According to Lawrence and Van Steenbergen (2005), spate irrigation is a scheme redirecting flash floods from the river bed using conveyance structures (canals) to bunded fields situated at a certain distance from the water source. The word ‘spate’ (meaning ‘flood’ or ‘inundation’) refers to water originating from the upper part of river catchments that is diverted in the lower part of rivers and spread over agricultural land (Komakech et al. 2011). In the circle of Sikasso, the spate irrigation scheme comprised one dam, usually a cofferdam, a diversion weir, and the main intake structure. The dam was used to limit the flow of water in the minor bed of the stream thereby increasing the depth of the water upstream of the scheme, and of conveying water in inland valleys through the diversion weir and the main intake structure.

A controlled submersion scheme can be classified as a partial water control irrigation system. In Mali, controlled submersion schemes were developed in the 1960s to improve the traditional rice free flooding system with dikes and gates to control the entry of water into flood plains and inland valleys (Barbier et al. 2011). In the circle of Sikasso, the controlled submersion scheme comprised bunded rice fields on contour lines sometimes complemented by a weir and secondary and tertiary irrigation canals to supply rice cropping areas.

In the principal component analysis of the type of water control facility and the biophysical characteristics of inland valleys, the first two axes explained 70% of the total inertia (Fig. 3). The principal component 1 (PC_1) was associated with type of water control facility, the risk of drying up in the bottom of inland valley in the rainy season, the depth of the water table in the dry season and flooding height, with loading values

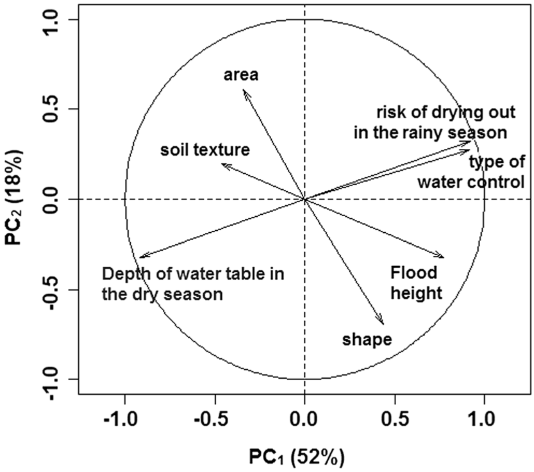


Fig. 3 Projection on the first two axes of the principal component analysis of the biophysical characteristics of inland valleys and types of water control

up to 52%. Principal component 2 (PC_2) was associated with the surface area and shape of the inland valley with loading values up to 18%. Spate irrigation schemes were found in inland valleys that did not dry up in the rainy season and where flooding height was more than 1 m and water table was less than 2 m deep in the dry season. Conversely, controlled submersion schemes were found in inland valleys that dried up when there was a long drought spell in the rainy season and where flooding height in the rainy season was less than 1 m and the water table was deeper than 2 m in the dry season. Overall, the analysis revealed good consistency between the types of water control facilities and the main biophysical descriptors of the hydrological functioning of inland valleys (Lidon et al. 1998), suggesting that spate irrigation and controlled submersion as water control facilities have different suitable domains for scaling.

3.2 Effects of inland valley development on crop extension

The average surface area of the inland valleys investigated was 363 ha (Table 2). The average area cultivated in the rainy season (225 ha) represented 62% of the surface area

Table 2 Inland valley (IV) area, percentage of IV area cultivated in the rainy season (RS), in the dry season (DS), cultivated area (ha) in the dry season (DS) and the presence of off-season crops in different types of water control facilities

Type of water control	IV area (ha)	Percentage of IV cultivated in the RS (%)	Percentage of IV cultivated in the DS (%)	Cultivated area in the DS (ha)	Presence of off-season crops (%)
Spate irrigation	440 a	81 a	34 a	151 a	100
Controlled submersion	513 a	42 b	17 a	67 b	37
Not developed	136 b	75 a	21 a	34 b	60
SED	215	12	19	94	–
P value	0.01	0.003	0.53	0.037	0.01

SED standard error of the difference

of the inland valleys, while the average area cultivated in the dry season (87 ha) represented 24% of the surface area of the inland valleys. In the rainy season, the percentage of inland valley area cultivated was significantly higher in valleys with spate irrigation (81%) and in undeveloped inland valleys (75%) than in valleys with controlled submersion (42%). In the dry season, the percentage of inland valleys cultivated was also higher under spate irrigation (34%) and in undeveloped inland valleys (21%) than under controlled submersion (17%) although the differences were not statistically significant since only a small portion of inland valley area was cultivated in the dry season. However, the area cultivated in the dry season differed between the types of water control facilities and was significantly higher under spate irrigation (151 ha) than under controlled submersion (67 ha) and undeveloped inland valleys (34 ha) (Table 2). There was a significant difference in the presence of off-season crops between the types of water control facilities. Off-season crops were cultivated in all the inland valleys developed using spate irrigation and in only 60% of undeveloped inland valleys. The lowest percentage (37.5%) of off-season crops was found in inland valleys with controlled submersion (Table 2). Compared with undeveloped inland valleys and those with controlled submersion, spate irrigation increased the percentage of the surface area of inland valleys cultivated in the rainy season, the area cultivated in the dry season and crop diversification in inland valleys (i.e., the presence of off-season crops).

3.3 Impacts of inland valley development on crop productivity and cropping intensity

The average productivity of the main crops grown in the dry season (potato, sweet potato and tomato) was KUS$ 2.2 ± 0.95/ha, i.e., more than four times higher than the average productivity of rice (the main rainy season crop) (Table 3). This showed that rice produced a lower income for farmers in inland valleys than off-season crops. Rice productivity was higher in undeveloped inland valleys (KUS$ 0.46/ha) than under controlled submersion (KUS$ 0.36/ha) which theoretically allows better water control. Conversely, the highest rice productivity was observed under spate irrigation where plot development was nonexistent (KUS$ 0.55/ha). Cropping intensity was higher under spate irrigation than in undeveloped inland valleys and under controlled submersion, although the differences were not statistically significant (Table 3).

Table 3 Rice productivity in the rainy season, off-season crops (potatoes and other vegetables) productivity in the dry season and cropping intensity under the different types of water control

Type of IV water control	Rice productivity in the rainy season (KUS$/ha)	Productivity of off-season crops (potatoes and other vegetables) in the dry season (KUS$/ha)	Cropping intensity
Spate irrigation	0.55 a	3.28 a	1.4 a
Controlled submersion	0.36 a	1.82 a	1.2 a
Not developed	0.46 a	1.50 a	1.3 a
SED	ns	ns	ns
P value	0.30	0.06	0.33

SED standard error of the difference

3.4 Impacts of inland valley development on the occurrence of water constraints

Three types of water constraints were faced by farmers: violent high-water surges; poor water control resulting in excess water in some parts of inland valleys and lack of water in other parts; and early ending of the rainy season and of stream flows resulting in lack of water at the end of the cropping cycle. Statistical analyses showed that the frequencies of occurrence of water constraints were independent of the type of water control facilities (Table 4). However, the frequencies of major water constraints and early ending of rainy season and stream flows were significantly lower when water control facilities were in good condition compared with when they were degraded (Table 4), indicating that the water constraints varied with the condition of the water control facility independently of its type. Furthermore, water control facilities were more degraded in inland valleys developed using controlled submersion than those developed using spate irrigation (Table 5).

The water control facilities were more degraded in the absence of an active management committee (Table 6). However, the existence of an active management committee did not guarantee the good condition of the water control facility since 50% of the water control facilities in inland valleys managed by an active management committee were degraded. The deterioration of water control facilities with age (Fig. 4) could explain why maintenance actions by management committees were not able to mitigate the effect of aging and that proper rehabilitation of the water control facilities was needed.

Table 4 Frequency of water management constraints according to the type of water control and the condition of the facilities

Variables	No major problem (%)	Violent high-water surge (%)	Early ending of rainy season and stream flows (%)	Poor water control (%)
Type of water control (T)				
Spate irrigation	33	43	33	33
Controlled submersion	25	25	63	50
P value (main T effect)	0.35	0.35	0.10	0.24
Condition of water control facility (S)				
Good	67	33	0	33
Degraded	9	27	73	45
P value (main S effect)	0.01	0.40	<0.001	0.31

Table 5 Type of water control and condition of the facilities in the inland valleys investigated

Type of water control	Good condition	Degraded condition	Chi-square score
Spate irrigation (%)	44	56	7.9 (0.005)
Controlled submersion (%)	25	75	

NB. The value in brackets is the *p* value

Table 6 Presence of an active management committee and frequency of good and degraded water control facility

State of water control facility	Active management committee (%)	Management committee inactive or non-existent (%)	*P* value
Good (%)	50	14	0.04
Degraded (%)	50	86	0.04

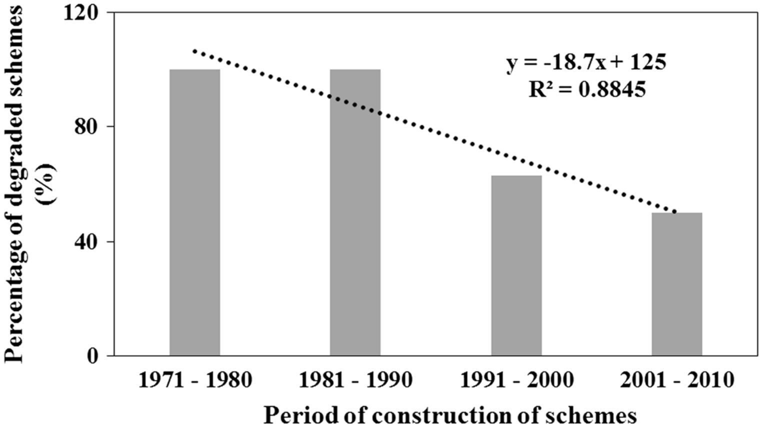


Fig. 4 Percentage of degraded inland valleys according to their ages

3.5 Impacts of inland valley development on access to land and farmers' investment capacities

In inland valleys, access to land by women and migrant populations was affected by water control facilities (Table 7). Spate irrigation and controlled submersion reduced access to land by women and increased access to land by men (Table 7). In undeveloped inland valleys, mixed farmers' groups (i.e., containing both men and women) were the main users (75%) followed by groups of men (15%) and groups of women (10%). The situation differed significantly in inland valleys developed using spate irrigation and

Table 7 Water control facilities, accessibility of land by gender and origin and increase in farmers collective and individual investment capacities

Socioeconomic impact	Non-developed IV	Spate irrigation	Controlled submersion
Land accessible to mixed group (%)	75	44	38
Land accessible to male group (%)	15	56	50
Land accessible to female group (%)	10	0	11
Land accessible to indigenous population (%)	55	44	50
Land accessible to indigenous and migrant population (%)	45	56	50
Increase in collective investment (%)	85	100	88
Increase in individual investment (%)	80	100	75

controlled submersion, where the groups of men were the most dominant with 56 and 50%, respectively, and the groups of women were inferior with 0 and 11%, respectively. Following inland valley development, men's access to land increased while women's access to land decreased. Water control facilities also affected access to land by migrant populations (Table 7). Indigenous farmers were the most dominant in 55% of the undeveloped inland valleys while mixed groups of indigenous and migrant farmers were the most dominant in more than 50% of the inland valleys developed using spate irrigation and controlled submersion, showing that inland valley development did increase access to land by migrant farmers. Spate irrigation increased both the collective (local economic development) and individual investment capacities of farmers (ownership of a motorcycle, bicycle, agricultural equipment) in all inland valleys. Controlled submersion increased the collective investment capacity of farmers in 88% of inland valleys and their individual investment capacities in 75% of inland valleys (Table 7). In general, farmers appeared to be more satisfied with the impacts of spate irrigation on their investment capacities (Table 7).

3.6 Impact of off-season crops and market proximity on crop intensification in inland valleys

Annual crop productivity was significantly higher in inland valleys where off-season crops were cultivated than in inland valleys where no crop was cultivated in the off-season. Annual crop productivity was also higher in the inland valleys located close to a market compared with inland valleys that were located far from a market (Table 8). Surprisingly,

Table 8 Presence of off-season crops, proximity to a market, cropping intensity, productivity in the rainy season, in the dry season and throughout the year

Treatment	Cropping intensity	Productivity in the rainy season (KUS$/ha)	Productivity in the dry season (KUS$/ha)	Annual productivity (KUS$/ha)
Presence of an off-season crop (Off)				
Off-season crop present (Off1)	1.4 a	0.51 a	2.96 a	2.06 a
Off-season crop absent (Off0)	1.0 b	0.34 b	0 b	0.34 b
SED (main Off effect)	0.19	0.13	1.06	1.0.6
Proximity to market (M)				
Close to market (M1)	1.5 a	0.48 a	3.65 a	3.32 a
Far from market (M0)	1.2 a	0.45 a	1.47 b	0.92 b
SED (main M effect)	ns	ns	0.89	1.00
Source of variation	Probability level of F			
ANOVA summary				
Presence of off-season crop (Off)	<0.001	0.03	<0.001	0.01
Proximity to market (M)	0.08	0.78	0.005	<0.001
M × Off	0.67	0.57	0.33	0.15

the presence of off-season crops was associated with higher productivity of inland valleys during the rainy season while market proximity was associated with higher productivity of inland valleys during the dry season, both contributing to agricultural intensification in inland valleys.

4 Discussion

This study revealed that from the farmers' point of view, water control facilities were primarily a way to extend areas with favorable water conditions for the cultivation of rice and off-season crops. Because groundwater dynamics is a major factor influencing water conditions in the inland valleys in the region of Sikasso (Legoupil et al. 1997), most of the developed areas included a weir to dam the bed of minor streams to increase water depth upstream. As shown by previous surveys (Blanchet and Lidon 1996), the presence of a weir has a significant impact on groundwater dynamics. When the elevation of the water table adjacent to the stream bed is lower than the water level in the stream, erecting a dam to the minor bed of streams increased the level of groundwater table upstream. This resulted in early flooding of rice plots at the beginning of the rainy season and delayed the drop in the groundwater table, thereby facilitating watering of off-season crops.

Contrary to the findings of Dossou-Yovo et al. (2018), field investigations revealed that, according to the farmers, water constraints in developed areas were similar to those in undeveloped areas used for agricultural production. The fact that similar water constraints were observed in developed and undeveloped inland valleys can be attributed to the degradation of water control facilities as a consequence of their long lifespan (around 12 years) and to the fact that the farmers were not sufficiently involved in the development of the water control structures, which limited their willingness to insure their proper maintenance, as reported by previous authors (Dembele et al. 2012; Djagba et al. 2013).

By redistributing plots, the development of inland valleys has tended to change the conditions of access to land. Indeed, inland valley development is often hampered by complex or unfavorable land tenure arrangements (Fu et al. 2010). This was evidenced by the fact that in undeveloped inland valleys, groups including both men and women were the main users of inland valleys, while in developed inland valleys, groups of men were the predominant users. This result confirms frequent reports that the construction of a water control facility reduces women's access to lowland use (Sakurai 2002, 2006). One explanation for the fact that inland development reduces access to land by women is that in Mali, plots are allocated to individuals within the farm by a male elder following patrilineal inheritance. The most fertile lands are managed by men. Women are allocated the less fertile or more unreliable plots through their husbands or the male farm managers at the beginning of the growing season. Thus, plots may not be allocated to women until men have sown their preferred plots, and there is weak tenure security from 1 year to the next. Following the development of the inland valley, men perceive a change in the value of the plots and therefore choose to farm the inland valley to the detriment of women. A similar observation was made by Rogé et al. (2017) in the circles of Tominian, Dioïla and Bougouni in Mali. However, the development of inland valleys increased access to land to migrant farmers. This can be attributed to the fact that inland valley development increased the cultivable area and therefore, extends access to land to the whole population of the village. Nevertheless, it is difficult to draw a final conclusion insofar as in West Africa, the percentage of migrant farmers as well as land tenure situations vary considerably from one village to another (Saïdou et al. 2007).

The economic performance of cropping systems overshadows the development of inland valleys, even though the latter increases the cultivated area (Dembele et al. 2012). Furthermore, on a regional basis, the development of inland valleys is expected to be a better proxy of closeness to growing urban cities, cultivation of off-season vegetables and market access to ease procurement of external inputs generating a marketable surplus to pay for their use (Erenstein 2006; Parrot et al. 2008; De Bon et al. 2010; Mawois et al. 2011; Sakané et al. 2011). By increasing the total cultivable area and the number of farmers, inland valley development increases population growth, which in turn triggers the process of turning human settlements into villages, villages into towns and towns into cities, as reported by Bricas and Seck (2004). An undeniable asset of inland valley development in the circle of Sikasso is that the water control facilities increase production by increasing the cultivable area. In contrast, under the current conditions of lowland uses, water control facilities have not increased crop intensification. Cropping intensity and crop productivity did not differ significantly in developed and undeveloped inland valleys. The fact that water control facilities did not enable crop intensification in inland valleys could be attributed to the fact that the development of inland valleys development did not guarantee adequate control of the water particularly due to the aging infrastructure and farmers consequently perceived production risks to be similar in developed and undeveloped inland valleys. This perception of potential risks in developed inland valleys discourages farmers from investing in agricultural inputs (seed, labor, agro-chemical, etc.) and mechanization to increase rice productivity.

According to this logic, the economic return of farmers in inland valleys is a function of the economic performance of their cropping systems independently of the presence of water control facilities in their inland valley. The results of the study showed that these performances, like the benefits obtained from the use of the inland valleys, were closely linked to the presence of off-season crops and proximity to a market. Although this type of study does not enable precise analysis of the marketing constraints facing off-season crops, the fact that crop productivity was higher in inland valleys located close to a market and where off-season crops present suggests that proximity to a market has been a determining factor in the presence of off-season crops and in the productivity of inland valleys, which is consistent with the results of previous studies in West Africa (Balasubramanian et al. 2007; Sakané et al. 2011; Dossou-Yovo et al. 2017). The fact that spate irrigation enables the production of off-season crops which have a higher market value than rainfed rice, helps explain the farmers were more satisfied with spate irrigation (Table 7). This result ties in well with the results of previous studies showing that the output value per input cost of off-season vegetable was more than double of that of rice (Huong et al. 2013) and reached the same conclusion that crop diversification—through the introduction of off-season vegetables—in rice-based farming systems in inland valleys is a promising way to enhance farmers' livelihoods (Rebelo et al. 2010; Kasem and Thapa 2011; Altieri et al. 2015). The fact that farmers were more satisfied with spate irrigation schemes than with controlled submersion schemes could explain why management committees were more active in the operation and maintenance of spate irrigation schemes and the fact that spate irrigation schemes were less degraded than controlled submersion schemes, as previously reported by Djagba et al. (2013) in southern Benin.

The potential relevance of spate irrigation stems from the fact that its water is generated during storm events when water is often in excess and of little value to the upstream users at the time. A spate irrigation system can be viewed as a system that uses water with a low opportunity cost for relatively high-value purposes (Komakech et al. 2011). In arid and semi-arid areas, where rainfall is insufficient, and its distribution varies considerably between seasons, and where no perennial rivers exist, spate irrigation can be a key component in the production of crops required to sustain livelihoods and improve food security. In those areas, which are often poor, existing storage facilities are not a sufficient buffer against climate variability over time, nor do these areas have the financial capacity to construct more water storage facilities. In this context, spate irrigation is a potential alternative way of improving food security in arid and semi-arid lowlands areas that are subject to flash floods in rivers that are mostly ephemeral.

Unexpectedly, the presence of off-season crops increased crop productivity in the rainy season. This may be explained by the fact that off-season crops generally receive higher doses of fertilizers and better weed control thanks to their high market value. The rice crop produced during the subsequent rainy season thus benefits from the residual effects (fertilizers and fewer weeds) of the preceding off-season crops. This increase in crop productivity in the rainy season in rotation with off-season crops in inland valleys has been reported by other authors and is perceived as an undeniable asset for crop intensification (Erenstein 2006; Erenstein et al. 2006a, b; Senthilkumar et al. 2009; Singbo and Oude Lansink 2010). Another benefit of off-season farming is that it increases the farmers' capital at the beginning of the rainy season thereby enabling them to use improved technologies to enhance the productivity of their crops (Pretty et al. 2011). In inland valleys, further increases in rice yield in the rainy season can be expected from the adoption of good agricultural practices such as animal or motorized traction for fine tillage, proper bunding and levelling, the use of improved varieties and certified seeds, sowing or transplanting in lines, application of judicious doses of composite fertilizers and optimally timed weed control (Becker and Johnson 2001; Touré et al. 2009; Senthilkumar et al. 2018). This study used a farmers' perception approach to analyze the impacts of water control structures on agricultural and hydraulic performances and on farmers' socioeconomic conditions in the circle of Sikasso, Mali. This approach has the advantage of paying special attention to farmers' beliefs, perceptions and preferences, which are reported to be crucial in the adoption of technologies (Heong and Escalada 1999), in sustainable intensification (Agyeman and Evans 2004; Loos et al. 2014; Liao and Brown 2018; Thomson et al. 2019), but are rarely taken into consideration in the research planning agenda (Williamson et al. 2003). One limitation of this study is that it did not include a baseline survey to ensure that before project interventions, farmers in developed and undeveloped inland valleys shared similar characteristics. However, the lack of baseline survey probably did not affect the conclusions of this study, since the data were collected during focus group discussions and included farmers' preferred water control structures and the reasons for their preferences.

5 Conclusions

This study investigated the impacts of inland valley development on crop extension, intensification, water constraints and farmers' socioeconomic conditions in the circle of Sikasso, which has the greatest potential for inland valley cultivation in Mali. The results demonstrated that inland valley development was a determining factor in crop extension and increased the farmers' revenues and investment capacities. Crop intensification in inland valleys depended on the presence of off-season crops and market proximity. Most of the water control structures were very old and in bad condition and did not improve surface water control in developed inland valleys. However, spate irrigation appears to have expanded areas that are favorable for growing rice and off-season crops, as illustrated by the farmers' positive perception of their impact. In view of these findings and in the context of climate change, one of the major challenges of inland valley development projects is to re-think the design of water control facilities to better exploit the groundwater resource and improve control of surface water to sustain the existing off-season crop production system, while also providing an enabling environment for rice intensification and crop diversification for the benefit of the community, and specifically strengthening the position of women in land tenure arrangements issues.

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References

Adams, W. M. (1993). Indigenous use of wetlands and sustainable development in West Africa. *The Geographical Journal, 159,* 209–218. https://doi.org/10.2307/3451412.

Agyeman, J., & Evans, B. (2004). "Just sustainability": The emerging discourse of environmental justice in Britain? *The Geographical Journal, 170,* 155–164.

Ahmadi, N. (1998). Diversité des systèmes de production dans les bas-fonds du Mali-Sud: enjeux économiques et sociaux. In: Ahmadi, N., Teme, B. (Eds.), *Aménagement et mise en valeur des bas-fonds au Mali. Bilan et perspectives nationales, intérêt pour la zone de savane ouest-africaine*. Actes du séminaire, 21–25 Octobre 1996, Sikasso, Mali. Colloques, Cirad, Montpellier, France, 498 p.

Altieri, M. A., Nicholls, C. I., Henao, A., & Lana, M. A. (2015). Agroecology and the design of climate change-resilient farming systems. *Agronomy for Sustainable Development, 35,* 869–890.

Andriesse, W., Fresco, L., van Duivenbooden, N., & Windmeijer, P. (1994). Multi-scale characterization of inland valley agro-ecosystems in West Africa. *Netherlands Journal of Agricultural Science, 42,* 159–179.

Balasubramanian, V., Sie, M., Hijmans, R. J., & Otsuka, K. (2007). Increasing rice productivity in Sub-Saharan Africa: Challenges and opportunities. *Advances in Agronomy, 94,* 55–133. https://doi.org/10.1016/S0065-2113(06)94002-4.

Barbier, B., Ouedraogo, H., Dembélé, Y., Yacouba, H., Barry, B., & Jamin, J. Y. (2011). L'agriculture irriguée dans le Sahel ouest-Africain. *Cahiers Agricultures, 20,* 24–33.

Bariau, O. (1993). *Etude socio-économique d'un terroir villageois près de Sikasso (Sud Mali): Importance du riz dans les systèmes de production*. Cercy-Pontoise: Institut Supérieur d'Outre-Mer (ISTOM).

Becker, M., & Johnson, D. E. (2001). Improved water control and crop management effects on lowland rice productivity in West Africa. *Nutrient Cycling in Agroecosystems, 59,* 119–127.

Blanchet, F., & Lidon, B. (1996). Logique de conception d'aménagements. Exemple de M'pégnesso. In: Ahmadi, N., Teme, B. (Eds.), *Aménagement et mise en valeur des basfonds au Mali, bilan et perspectives nationales, intérêt pour la zone de savane ouest-africaine*. Actes du séminaire, 21–25 Octobre 1996, Sikasso, Mali. Colloques, Cirad, Montpellier, France. 498 p.

Bricas, N., & Seck, P. A. (2004). L'alimentation des villes du Sud: Les raisons de craindre et d'espérer. *Cahiers Agricultures, 13,* 10–14.

De Bon, H., Parrot, L., & Moustier, P. (2010). Sustainable urban agriculture in developing countries. A review. *Agronomy for Sustainable Development, 30,* 21–32. https://doi.org/10.1051/agro:2008062.

Delarue, J. (2007). *Mise au point d'une méthode d'évaluation systémique de l'impact des projets de développement agricole sur le revenu des producteurs. Etude de cas en region kpèlè (République de Guinée)*. Thèse de doctorat, Institut National Agronomique Paris-Grignon, France.

Dembele, Y., Yacouba, H., Keïta, A., & Sally, H. (2012). Assessment of irrigation system performance in south-western Burkina Faso. *Irrigation and Drainage, 61,* 306–315. https://doi.org/10.1002/ird.647.

Djagba, J. F., Rodenburg, J., Zwart, S. J., Houndagba, C. J., & Kiepe, P. (2013). Failure and success factors of irrigation system developments in West Africa—A case study from the Ouémé valley in Benin. *Irrigation and Drainage, 63,* 328–339. https://doi.org/10.1002/ird.1794.

DNGR. (2012). *Base de données «Suivi-Evaluation PGA»*. Mise à jour du 22 octobre 2011.

Dossou-Yovo, E. R., Baggie, I., Djagba, J. F., & Zwart, S. J. (2017). Diversity of inland valleys and opportunities for agricultural development in Sierra Leone. *PLoS ONE, 12*(6), e0180059. https://doi.org/10.1371/journal.pone.0180059.

Dossou-Yovo, E. R., Zwart, S. J., Kouyaté, A., Ouédraogo, I., & Bakare, O. (2018). Predictors of drought in inland valley landscapes and enabling factors for rice farmers' mitigation measures in the Sudan-Sahel Zone. *Sustainability, 11,* 79. https://doi.org/10.3390/su11010079.

Erenstein, O. (2006). Intensification or extensification? Factors affecting technology use in peri-urban lowlands along an agro-ecological gradient in West Africa. *Agricultural Systems, 132–158,* 132. https://doi.org/10.1016/j.agsy.2005.12.005.

Erenstein, O., Oswald, A., & Mahama, S. (2006a). Determinants of lowland use close to urban markets along an agro-ecological gradient in West Africa. *Agriculture, Ecosystems & Environment, 117,* 205–217. https://doi.org/10.1016/j.agee.2006.03.033.

Erenstein, O., Sumberg, J., Oswald, A., Levasseur, V., & Koré, H. (2006b). What future for integrated rice-vegetable production systems in West African lowlands? *Agricultural Systems, 88,* 376–394. https://doi.org/10.1016/j.agsy.2005.07.006.

Francis, G., Edinger, R., & Becker, K. (2005). A concept for simultaneous wasteland reclamation, fuel production, and socio-economic development in degraded areas in India: Need, potential and perspectives of *Jatropha* plantations. *Natural Resources Forum, 29,* 12–24.

Fu, R. H. Y., Abe, S. S., Wakatsuki, T., & Maruyama, M. (2010). Traditional farmer-managed irrigation system in central Nigeria. *Japan Agricultural Research Quarterly, 44,* 53–60. https://doi.org/10.6090/jarq.44.53.

Giertz, S., Steup, G., & Schönbrodt, S. (2012). Use and constraints on the use of inland valley ecosystems in central Benin: Results from an inland valley survey. *Erkunde, 66,* 239–253. https://doi.org/10.3112/erdkunde.2012.03.04.

Haile, A. M. (2007). *A tradition in transition, water management reforms and indigenous spate irrigation systems in Eritrea*. [Ph.D.], UNESCO-IHE Institute for Water Education. Delft: CRC Press.

Heong, K. L., & Escalada, M. M. (1999). Quantifying rice farmers' pest management decisions: Beliefs and subjective norms in stem borer control. *Crop Protection, 18,* 315–322.

Huong, P. T. T., Everaarts, A. P., Neeteson, J. J., & Struik, P. C. (2013). Vegetable production in the red river of Vietnam. I. Opportunities and constraints. *NJAS—Wageningen Journal of Life Sciences, 67,* 27–36.

Junk, W. J., Brown, M., Campbell, I. C., Finlayson, M., Gopal, B., Ramberg, L., et al. (2006). The comparative biodiversity of seven globally important wetlands. *Aquatic Sciences, 68,* 400–414. https://doi.org/10.1007/s00027-006-0856-z.

Kasem, S., & Thapa, G. B. (2011). Crop diversification in Thailand: Status, determinants, and effects on income and use of inputs. *Land Use Policy, 28,* 618–628.

Katic, P. G., Namara, R. E., Hope, L., Owusu, E., & Fujii, H. (2013). Rice and irrigation in West Africa: Achieving food security with agricultural water management strategies. *Water Resources and Economics, 1,* 75–92. https://doi.org/10.1016/j.wre.2013.03.001.

Komakech, H. C., Mul, L. M., van der Zaag, P., & Rwehumbiza, F. B. R. (2011). Water allocation and management in an emerging spate irrigation system in Makanya catchment, Tanzania. *Agricultural Water Management, 98,* 1719–1726.

Lamagat, J.-P. (1980). Région sud du Mali: bilan des observations hydrologiques. In: ORSTOM (Ed.). *ORSTOM*, *Bamako, Mali* (p 15).

Lawrence, P., & Van Steenbergen, F. (2005). Improving community spate irrigation. In: *Report OD 154 release 1.0*. London, HR Wallingford/DFID/META META.

Legoupil, J. C., Lidon, B., Maraux, F., Blanchet, F., & Lammer, T. B. (1997). *Etudes hydrologique et hydraulique des bas-fonds pour leur aménagement et l'intensification des systèmes de cultures. Communication présentée à l'atelier annuel 1997 du Consortium bas-fonds, Yamoussoukro, Côte d'ivoire* (p. 33). Montpellier: Cirad.

Liao, C., & Brown, D. (2018). Sustainable intensification of agriculture for synergistic outcomes in food production, ecosystem services, and smallholder livelihoods. *Current Opinions in Environmental Sustainability, 32,* 53–59. https://doi.org/10.1016/j.cosust.2018.04.013.

Lidon, B., Kouyate, A. M., Diaw, B., Fusillier, J. L., Djagba, J. F., Simpara, M. B., Diakité, C. H., Hamadoun, A., Yossi, H., & Huat, J. (2012). Fiches signalétiques d'un échantillon de bas-fonds du cercle de Sikasso Mali: Diagnostic régional de la mise en valeur des bas-fonds dans le cercle de Sikasso. Cotonou: WARDA [Africa Rice Center], 58 p.

Lidon, B., Legoupil, J. C., Blanchet, F., Simpara, M., & Sanogo, I. (1998). *Le diagnostic rapide de pré-aménagement (Diarpa). Un outil d'aide à l'aménagement des zones de bas-fonds. Agriculture et développement* no 20-Décembre 1998 (p. 20).

Loos, J., Abson, D. J., Chappell, M. J., Hanspach, J., Mikulcak, F., Tichit, M., et al. (2014). Putting meaning back into "sustainable intensification". *Frontiers in Ecology and the Environment, 12,* 356–361. https://doi.org/10.1890/130157.

Mawois, M., Aubry, C., & Le Bail, M. (2011). Can farmers extend their cultivation areas in urban agriculture? A contribution from agronomic analysis of market gardening systems around Mahajanga (Madagascar). *Land Use Policy, 20,* 434–445. https://doi.org/10.1016/j.landusepol.2010.09.004.

McCartney, M., Rebelo, L.-M., Senaratna Sellamuttu, S., de Silva, S. (2010). Wetlands, agriculture and poverty reduction. Colombo, Sri Lanka: International Water Management Institute (IWMI). 31 p. (IWMI Research Report 137). https://doi.org/10.5337/2010.230.

Metzger, L., & Günther, I. (2015). Making an impact? The relevance of information on aid effectiveness for charitable giving. A laboratory experiment. *CRC-PEG Discussion Papers, 182,* 18. https://doi.org/10.3929/ethz-a-010492382.

Paresys, L., Malézieux, E., Huat, J., Kropff, M. J., & Rossing, W. A. H. (2018). Between all-for-one and each-for-himself: On-farm competition for labour as determinant of wetland cropping in two Beninese villages. *Agricultural Systems, 159,* 126–138. https://doi.org/10.1016/j.agsy.2017.10.011.

Parrot, L., Dongmo, C., Ndoumbe, M., & Poubom, C. (2008). Horticulture, livelihoods and urban transition in Africa: Evidence from South-West Cameroon. *Agricultural Economics, 39,* 245–256.

Pretty, J., Toulmin, C., & Williams, S. (2011). Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability, 9,* 5–24. https://doi.org/10.3763/ijas.2010.0583.

R Development Core Team. (2011). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. (ISBN 3900051-07-0) http://www.R-project.org/.

Raunet, M. (1985). Bas-fonds et riziculture en Afrique. *L'agronomie tropicale, 40*(3), 181–201.

Rebelo, L.-M., McCartney, M. P., & Finlayson, C. M. (2010). Wetlands of Sub-Saharan Africa: Distribution and contribution of agriculture to livelihoods. *Wetlands Ecology and Management, 18,* 557–572.

Rodenburg, J., Zwart, S. J., Kiepe, P., Narteh, L. T., Dogbe, W., & Wopereis, M. C. S. (2014). Sustainable rice production in African inland valleys: Seizing regional potentials through local approaches. *Agricultural Systems, 123,* 1–11. https://doi.org/10.1016/j.agsy.2013.09.004.

Rogé, P., Diarisso, T., Diallo, F., Boiré, Y., Goïta, D., Peter, B., et al. (2017). Perennial grain crops in the West Soudanian Savanna of Mali: Perspectives from agroecology and gendered spaces. *International Journal of Agricultural Sustainability*. https://doi.org/10.1080/14735903.2017.1372850.

Saïdou, A., Tossou, R. C., Kossou, D., Sambieni, S., Richards, P., & Kuyper, T. W. (2007). Land tenure and sustainable soil fertility management in central Benin: Towards the establishment of a cooperation space among stakeholders. *International Journal of Agricultural Sustainability, 5,* 195–212.

Sakané, N., Alvarez, M., Becker, M., Böhme, B., Handa, C., Kamiri, H., et al. (2011). Classification, characterisation, and use of small wetlands in East Africa. *Wetlands, 31,* 1103–1116. https://doi.org/10.1007/s13157-011-0221-4.

Sakané, N., van Wijk, M. T., Langensiepen, M., & Becker, M. (2014). A quantitative model for understanding and exploring land use decisions by smallholder agro-wetland households in rural areas of East Africa. *Agriculture, Ecosystems & Environment, 197,* 159–173. https://doi.org/10.1016/j.agee.2014.07.011.

Sakurai, T. (2002). Land tenure systems and adoption of water control technologies in lowland rice production. In Sakurai, T., Furuya, J., Tagaki, H. (Eds.), *Economic analyses of agricultural technologies and rural institutions in West Africa—Achievements, challenges and application to rice farming research. Proceedings of JIRCAS international workshop. Japan International Research Center for Agricultural Sciences, Tsukuba, Japan* (pp. 107–125).

Sakurai, T. (2006). Intensification of rainfed lowland rice production in West Africa: Present status and potential green revolution. *The Developing Economies, 44,* 232–251. https://doi.org/10.1111/j.1746-1049.2006.00015.x.

Senthilkumar, K., Bindraban, P. S., de Boer, W., de Ridder, N., Thiyagarajan, T. M., & Giller, K. E. (2009). Characterising rice-based farming systems to identify opportunities for adopting water efficient cultivation methods in Tamil Nadu, India. *Agricultural Water Management, 96,* 1851–1860. https://doi.org/10.1016/j.agwat.2009.08.007.

Senthilkumar, K., Tesha, B. J., Mghase, J., & Rodenburg, J. (2018). Increasing paddy yields and improving farm management: Results from participatory experiments with good agricultural practices (GAP) in Tanzania. *Paddy and Water Environment, 16,* 749–766.

Singbo, A., & Oude Lansink, A. (2010). Lowland farming system inefficiency in Benin (West Africa): Directional distance function and truncated bootstrap approach. *Food Security, 2,* 367–382. https://doi.org/10.1007/s12571-010-0086-z.

Thomson, A. M., Ellis, E. C., Ricardo Grau, H., Kuemmerle, T., Meyfroidt, P., Ramankutty, N., et al. (2019). Sustainable intensification in land systems: Trade-offs, scales, and contexts. *Current Opinion in Environmental Sustainability, 38,* 37–43. https://doi.org/10.1016/j.cosust.2019.04.011.

Totin, E., Leeuwis, C., Van Mierlo, B., Mongbo, R. L., Stroosnijder, L., & Kossou, D. K. (2014). Drivers of cooperative choice: Canal maintenance in smallholder irrigated rice production in Benin. *International Journal of Agricultural Sustainability, 12,* 334–354. https://doi.org/10.1080/14735903.2014.909644.

Touré, A., Becker, M., Johnson, D. E., Koné, B., Kossou, D., & Kiepe, P. (2009). Response of lowland rice to agronomic management under different hydrological regimes in an inland valley of Ivory Coast. *Field Crops Research, 114,* 304–310. https://doi.org/10.1016/j.fcr.2009.08.015.

Traoré, F., Bayoko, A., Konaté, S., Coulibaly, A., & Diarra, B. (2004). *Etude des perspectives de changement climatique au Mali* (pp. 196–204). Mali: Bamako.

Verhoeven, J. T. A., & Setter, T. L. (2010). Agricultural use of wetlands: Opportunities and limitations. *Annals of Botany, 105,* 155–163. https://doi.org/10.1093/aob/mcp172.

Vitale, J. D., & Sanders, J. H. (2005). New markets and technological change for the traditional cereals in semi-arid sub-Saharan Africa: The Malian case. *Agricultural Economics, 32,* 111–129.

White, F. (1983). The vegetation of Africa. A descriptive memoir to accompany the UNESCO/AETFAT/UNSO vegetation map of Africa. *Natural Resources Research, 20,* 1–356.

Williamson, S., Little, A., Arif Ali, M., Kimani, M., Meir, C., & Oruko, L. (2003). Aspects of cotton and vegetable farmers' pest management decision-making in India and Kenya. *International Journal of Pest Management, 49,* 187–198.

Windmeijer, P., & Andriesse, W. (1993). *Inland valleys in West Africa: An agro-ecological characterization of rice growing environments*. Wageningen: International Institute for Land Reclamation and Improvement.

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