European Journal of Agronomy 93 (2018) 95–112

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Research paper

Feeding the world while reducing farmer poverty? Analysis of rice relative yield and labour productivity gaps in two Beninese villages

Lise Paresys[a,b,*], Kazuki Saito[d], Santiago Dogliotti[c], Eric Malézieux[b], Joël Huat[b,d], Martin J. Kropff[e,f], Walter A.H. Rossing[a]

[a] Farming Systems Ecology, Wageningen University, PO Box 430, 6700 AK, Wageningen, The Netherlands
[b] CIRAD, UPR HORTSYS, F-34398 Montpellier, France
[c] Departamento de Producción Vegetal, Facultad de Agronomía, Universidad de la República,Av. Garzón 780, 11200 Montevideo, Uruguay
[d] Africa Rice Center (AfricaRice), 01 B.P. 2031, Cotonou, Benin
[e] Crop Systems Analysis, Wageningen University, PO Box 430, 6700 AK, Wageningen, The Netherlands
[f] CIMMYT, Apdo. Postal 6-641 06600 México, D.F., México

A R T I C L E I N F O

Keywords:
Rice
Yield gap
Labour productivity gap
Management practices
Labour-saving technologies

A B S T R A C T

Improvements in agricultural land and labour productivity are needed to meet the growing food demand and reduce farmer poverty in sub-Saharan Africa. The objectives of this study were to (i) quantify variation in labour inputs, yield and labour productivity among rice fields; (ii) elicit factors associated with this variation; and (iii) identify opportunities for improving yield and labour productivity. The study was carried out in two contrasting Beninese villages: Zonmon in the south and Pelebina in the north-west.

In Zonmon 82 irrigated rice fields were surveyed during the 2013 and 2014 dry seasons. In Pelebina 50 rainfed lowland rice fields were surveyed over three rainy seasons (2012–2014). Data on farmer field management practices and field conditions were recorded through interviews with farmers, on-farm observations and measurements. Stepwise regression analyses were used to identify variables associated with variation in yield, labour inputs and labour productivity.

Average yields were 4.8 ± 2.0 t ha^{-1} in Zonmon and 2.3 ± 1.2 t ha^{-1} in Pelebina. Average labour productivity, however, was larger in Pelebina (17 kg of paddy rice person-day^{-1}) than in Zonmon (8 kg of paddy rice person-day^{-1}). Relative yield gaps (43–48%) and labour productivity gaps (59–63%) were similar in the villages. There was no trade-off between yield and labour or labour productivity within the villages, suggesting that in many cases rice yields can be increased without additional labour inputs. The major labour-demanding farming operations were bird scaring in Zonmon and harvesting and threshing in Pelebina.

We identified opportunities to improve rice yield and labour productivity, given current farmer knowledge and resource endowment. Based on the statistical models fitted per village, increasing the average hill density would result in up to 1.2 t ha^{-1} more yield, and up to 4 kg person-day^{-1} greater labour productivity for Zonmon. Increasing the average field size and avoiding rice shading would result in up to 0.8 t ha^{-1} more yield, and up to 17.1 kg person-day^{-1} greater labour productivity for Pelebina. Further enhancing yield and labour productivity will require (i) introducing small-scale mechanisation and other labour-saving innovations, in particular for labour-demanding farming operations such as bird scaring in Zonmon and harvesting and threshing in Pelebina; and (ii) combining analyses of yields and labour productivities at field level with detailed analyses of labour use and labour productivity at farm level. We found that, on average, one hectare in Zonmon contributed twice as much to Beninese rice production than one hectare in Pelebina but with a two times smaller reward for farmer labour. This paradox of higher yields but lower labour productivity in such different rice growing environments and farming systems should be addressed in elaborating development policies.

* Corresponding author at: Farming Systems Ecology, Wageningen University, PO Box 430, 6700 AK, Wageningen, The Netherlands.
E-mail addresses: lise.paresys@wur.nl, lise.paresys@wanadoo.fr (L. Paresys), K.Saito@cgiar.org (K. Saito), ssandog@gmail.com (S. Dogliotti), eric.malezieux@cirad.fr (E. Malézieux), joel.huat@cirad.fr (J. Huat), M.KROPFF@cgiar.org (M.J. Kropff), walter.rossing@wur.nl (W.A.H. Rossing).

https://doi.org/10.1016/j.eja.2017.10.009
Received 22 March 2017; Received in revised form 17 October 2017; Accepted 18 October 2017
1161-0301/

1. Introduction

The first and the second Sustainable Development Goals address eradicating extreme poverty and achieving global food security by 2030. Achieving these goals requires improvement in agricultural land and labour productivity as a source of growth based on agriculture and improvement of farmers' livelihoods (Byerlee et al., 2008; Thirtle et al., 2003; UN, 2015a). This is especially the case for sub-Saharan Africa, which was identified as particularly affected by extreme poverty and undernourishment (UN, 2015b). Many recent studies focused on land productivity, i.e., crop yield gaps (Anderson et al., 2016; Beza et al., 2017; Hengsdijk and Langeveld, 2009; Ittersum et al., 2013; Silva et al., 2017; Stuart et al., 2016), while largely ignoring labour input and labour productivity. With growing land scarcity, increasing yield is needed to meet the growing food demand (Conceição et al., 2016; Koning et al., 2008; Nonhebel and Kastner, 2011). Increases in land productivity should, however, be accompanied by and may in specific cases be subsidiary to increases in farmer labour productivity as a key to reducing farmer poverty.

Labour productivity is commonly measured as the gross margin per worked hour or person-day (8-hour day) or approximated as the gross margin per worker (Byerlee et al., 2008; Freeman, 2008; ILO, 2015). In sub-Saharan Africa, 65% of the labour force is involved in agriculture (ILO, 2008) and agricultural labour productivity is the lowest in the world (Byerlee et al., 2008; Haggblade and Hazell, 2010; Thirtle et al., 2003; van den Ban, 2011). Low labour productivity in this region was attributed to low yields (Tittonell and Giller, 2013) and high labour requirements due to lack of use and access to animal or fuel-based mechanisation (Ashburner and Kienzle, 2011; Diao et al., 2016, 2014; Fonteh, 2010; Houmy et al., 2013; Onwude et al., 2016).

Increasing labour productivity may have several impacts. When labour rather than land is a major limiting factor for crop production, improvement in labour productivity may allow (i) an increase in the cultivated area by the family as a whole, which is an important determinant of farm income and food security (Sender and Johnston, 2004; Tittonell and Giller, 2013); (ii) an increase in area cultivated by individual household members, which determines individual development opportunities (Paresys et al., 2016); and/or (iii) a decrease in casual labour use and its associated costs (Diao et al., 2016; Leonardo et al., 2015). In a context of lack of good off-farm job opportunities, increased labour productivity may allow poor farmers not to sell their labour to other farms, getting them out of 'poverty traps' (Tittonell, 2014). Improvement in labour productivity may also simply free up time and improve farmer health and quality of life (De and Sen, 1992; Netting, 1993). Finally, it may free children from labour in favour of schooltime thus improving their future opportunities (Byerlee et al., 2008; Ellis and Freeman, 2016; Frelat et al., 2016; van den Ban, 2011; van der Ploeg, 2008; Woodhouse, 2010).

Rice is the most important food crop of the developing world and the staple food of more than half of world's population (Seck et al., 2012). In sub-Saharan Africa, rice consumption is growing fast and rice production needs to be increased in order to decrease or at least halt the increase in country dependencies on food imports (Demont, 2013; Saito et al., 2014). Increasing rice production is possible through increasing rice yield and through expansion of the area cultivated in wetlands, which are currently underexploited (Saito et al., 2013). This is the case for Benin, where by 2009 only between 12 and 15% of arable wetlands were under rice cultivation (Diagne et al., 2013; Gruber et al., 2009). Benin has one of the largest untapped potentials for irrigation in sub-Saharan Africa (Saito et al., 2013; Seck et al., 2012; You et al., 2011).

Wetland crops, rice included, are labour-demanding (Balasubramanian et al., 2007; Guirkinger et al., 2015; Selim, 2012). A recent study in two villages in Benin showed that labour availability constrains farm expansion in wetlands (Paresys et al., 2017). Land was not a limiting factor in these two villages. Consequently farmers tended to adopt land-demanding and labour-saving production activities: they maximized labour productivity by giving priority to upland crops rather than to wetland crops. Improving labour productivity on rice fields would stimulate the expansion to wetlands (Paresys et al., 2017). In order to understand the main causes of variability in yield, labour input and labour productivity among rice fields, and to identify opportunities for improving yield and labour productivity, we collected and analysed detailed survey data from rice fields of two Beninese case-study villages contrasting in terms of rice growing environments.

2. Materials and methods

2.1. Case-study villages

The selection of villages was based on a rapid regional assessment of the various wetland agro-ecosystems from south to north in Benin. Two case-study villages were selected that were close to an urban market and experienced markedly different agro-ecological and socio-economic conditions; Zonmon in the south and Pelebina in the north-west (Paresys et al., 2017). Farming systems and types of farms differed greatly between villages.

In Zonmon, food production mainly involved maize and cash crops included groundnut and rice. Based on data from a random sample of 38% of farms, rice accounted for 14% of the total farmed area during the 2012–2013 agricultural season (Paresys et al., 2017). Area under rice was a key distinguishing factor among farm types. Larger areas were found in the wealthier farms, i.e., in farms with larger labour availability, particularly due to hired labour.

In Pelebina, food production involved tubers (yam and cassava) and cereals (maize and sorghum). Cash crops mainly included cotton, soya and groundnut. Based on data from a random sample of 34% of farms, rice accounted for 1% of the total area farmed during the 2012–2013 agricultural season (Paresys et al., 2017). The area under rice was not a key distinguishing factor among farm types.

The access to inputs for rice cultivation and the rice growing environments differed between villages (Fig. 1). In Zonmon, agricultural services provided farmers with improved seeds (IR841) and credits for fertilizers and casual labour. Rice was mainly cultivated in the bottom and lower fringes of one lowland with a mixed flood regime, i.e., subjected to both rainwater runoff and floodwater of the Oueme river (Fig. 2). The rice cropping season started at the end of January, i.e., in the middle of the dry season and ended in mid-May, i.e., in the middle of the long rainy season. An irrigation scheme had been developed in 1975 under the Benin-China cooperation (Djagba et al., 2014). Although operated and maintained with difficulty by farmers (Totin et al., 2012), this scheme allowed intermittent irrigation from stream water on rice fields.

In Pelebina, rice seeds were either bought on local markets or self-produced. Original variety names could not be identified. Rice fields were scattered across 11 different lowlands. The rice cropping season started at the end of June, i.e., at the beginning of the rainy season and ended at the beginning of December, i.e., at the beginning of the dry season. Water on rice fields was not controlled.

2.2. Field survey

We determined the total number of farms for each village with the help of village authorities using social mapping (Rim and Rouse, 2002): 134 farms in Zonmon and 146 farms in Pelebina (Paresys et al., 2017). In Pelebina, we surveyed all rice fields found in the village during the 2012, 2013 and 2014 rainy seasons. In Zonmon, we surveyed all rice fields in a random sample of 21 farms during the 2013 and 2014 dry seasons. In total, we surveyed 50 rice fields found in 26 farms in Pelebina and 82 rice fields found in 21 farms in Zonmon (Table 1).

At the start of the growing season, we conducted semi-structured interviews with farmers to (i) identify whether rice fields were family rice fields, i.e., fields controlled by the family management unit to

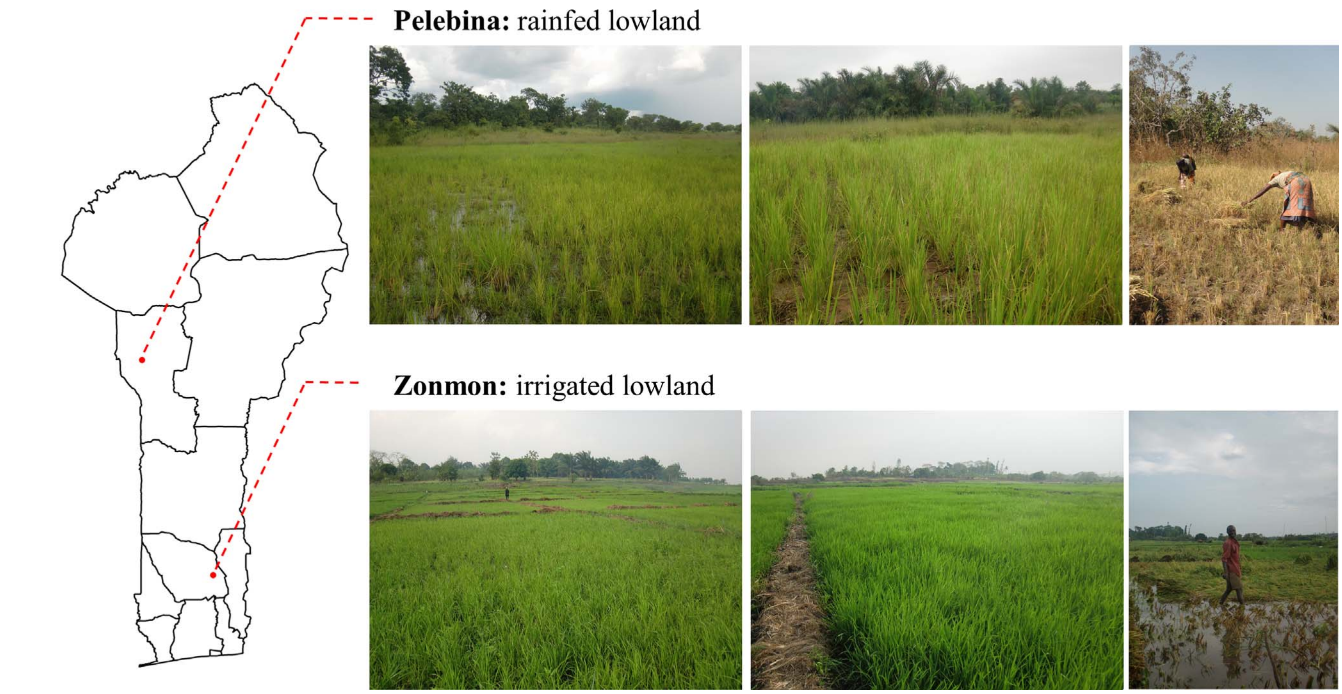

Fig. 1. Location of case-study villages and photo impressions of the rice growing environments.

satisfy family needs, or individual rice fields, i.e., fields controlled by one family member to satisfy individual needs (Paresys et al., 2017); (ii) evaluate their experience with rice cultivation; (iii) identify the soil type and the flooding period (by rainwater runoff in Zonmon and Pelebina as well as floodwater of the Oueme river in Zonmon) on fields; and (iv) identify the preceding crop.

During the growing season, we conducted semi-structured interviews with farmers on a bimonthly basis to monitor their management practices, evaluate the duration and timing of farming operations as well as to identify the workers involved in each farming operation until harvest. We cross-validated interview data by our own on-field observations.

On each field, we staked five randomly selected 1 × 1 m plots after transplanting (in Zonmon) or sowing (in Pelebina) for additional

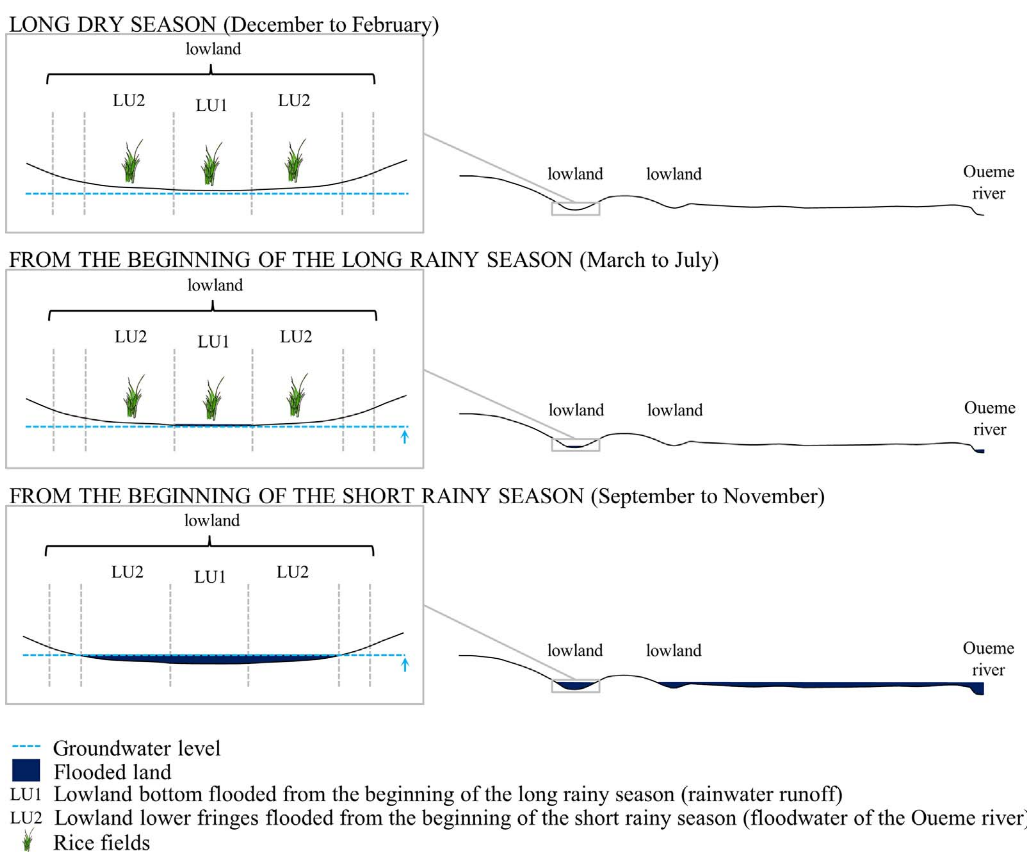

Fig. 2. Flooding period and flood regime for the major landscape units (LU) where rice was cultivated in Zonmon.

Table 1
Number of farms, farmers and rice fields sampled for each studied season and over the study period.

	Zonmon		Pelebina		
	2013 dry season	2014 dry season	2012 rainy season	2013 rainy season	2014 rainy season
Number of farms	18	13	18	12	8
Number of farmers	22	14	23	16	8
Numer of rice fields	61	21	23	19	8
Total number of farms	21		26		
Total number of farmers	21		34		
Total number of rice fields	82		50		

observations and to estimate rice yield. We made observations at harvest, including hill density; weed cover below the rice canopy; weed cover above the rice canopy; rat damage; bird damage; and water level. Weed cover was scored from 0 to 4 using the following classes: no weeds (0); weed cover below 10% (1, low infestation); weed cover between 10 and 30% (2, moderate); weed cover between 30 and 60% (3, high); weed cover above 60% (4, very high). We harvested plots at the same time as fields were harvested by farmers and we weighed rice total aboveground biomass using a hand-held scale. We estimated filled grain weight and grain moisture content on a subsample of about 1 kg.

2.3. Calculations and statistical analyses

Rice yields were corrected to 14% moisture content. Labour productivity was calculated as the ratio of the yield to the amount of labour used in person-days (8-hour days). Relative yield and labour productivity gaps (Ernst et al., 2016) were estimated for each village following Stuart et al. (2016) and Tanaka et al. (2015):

$$\textit{Relative yield gap} = (Y_L - Y_A)/Y_L \quad (1)$$

$$\textit{Relative labour productivity gap} = (LP_L - LP_A)/LP_L \quad (2)$$

where Y_L and LP_L are the locally attainable yield and labour productivity levels defined as the average yield and labour productivity of the highest decile; Y_A and LP_A are the average yield and labour productivity from the full sample of rice fields; and $Y_L - Y_A$ and $LP_L - LP_A$ are the exploitable yield and labour productivity gaps.

Stepwise regression analyses with Bayes Information Criterion (BIC) were used to select and identify variables associated with variation in labour for each (group of) farming operation(s) as well as variables associated with variation in yield. Candidate independent variables for each regression analysis are displayed and numbered in Table 2. Regression models used in stepwise procedures are displayed in Appendix A. Variables identified by stepwise procedures were subsequently used as candidate independent variables to identify variables associated with variation in labour productivity (Fig. 3). When necessary, Box-Cox transformation of the dependent variable was performed to satisfy normality assumptions and homogeneity of variance of residuals (Barker and Shaw, 2015; Box and Cox, 1964). Collinearity diagnoses were performed according to Belsley's guide (1991).

Differences in the amount of labour required for each (group of) farming operation(s) were assessed using Friedman tests followed by Nemenyi tests. Differences in the average total amount of labour required for rice production, yield and labour productivity between villages were assessed using Kruskal-Wallis tests. Differences in recorded variables among groups of rice fields (e.g., weed cover below and above the rice canopy associated with different frequencies of weeding) were assessed using Kruskal-Wallis tests followed by Dunn tests with Bonferroni as p value adjustment method.

3. Results

3.1. Description of rice cropping systems

In Zonmon, rice cultivation started with field cleaning, i.e., clearing weeds and residues of the preceding crop, together with bund making. In most fields, residues were piled onto the bunds (Table 2). Subsequently, the land was usually prepared by combining manual tillage and puddling. After land preparation, rice was transplanted. Farmers worked on a field-by-field basis, resulting in a range of transplanting dates across their fields. On average, farmers managed 2 fields with different transplanting dates and these fields were usually adjacent to each other. The first weeding operation was completed within 40 days after transplanting (DAT) in most fields. Weed control consisted of hand-weeding and/or applying herbicide. A single hand-weeding operation was the most frequent weeding method. Fertilizers, comprising urea and/or a compound NPK fertilizer, were applied in most fields right after weeding and only once. Bird damage during the ripening phase was controlled by chasing away birds. From dawn until nightfall workers would scare the birds by shouting and running after them. Harvesting and threshing methods were manual for all farmers.

In Pelebina, rice cultivation started either with field cleaning and/or land preparation. In slightly more than half of the fields, rice was preceded by tubers (yam or cassava) cultivated on mounds and thus, weeds and/or crop residues could be directly incorporated into the soil while breaking the mounds (Table 2). Herbicides were used prior to land preparation in around one third of the fields. Rice was usually sown on hills, occasionally broadcasted or sown in rows and never transplanted. Weed control consisted of hoe-weeding and/or applying herbicide. A single hoe-weeding operation was the most frequent weeding method; herbicides were used in 44% of fields. No bird control activities were performed. Harvesting and threshing methods were manual for all farmers.

3.2. Variation in labour use

The average amount of labour required for rice production was 727 person-days ha^{-1} in Zonmon and 168 person-days ha^{-1} in Pelebina (Table 3), i.e., 4 times less than in Zonmon ($p < 0.001$). Labour use in Zonmon varied from 267 to 2413 person-days ha^{-1}, while in Pelebina it varied from 40 to 410 person-days ha^{-1}. In Zonmon, bird scaring was the most labour-demanding operation, accounting for nearly half of the total labour input. Weeding was less labour-demanding than field cleaning and bund making, or than land preparation and transplanting (Table 3). In Pelebina, labour requirements were similar and relatively low for sowing and weeding, and intermediate for field cleaning and land preparation.

In Zonmon, the amount of labour used for field cleaning and bund making was less (i) on fields where no residues were found compared to fields where residues were found and piled on bunds; (ii) on never-flooded fields compared to fields flooded from the beginning of the long rainy season; (iii) and on individual fields compared to family fields.

The amount of labour used for field cleaning and bund making was positively related to the proportion of casual labour. The amount of labour used for land preparation and transplanting was less (i) on fields where land was not prepared compared to fields where tillage was combined with puddling; (ii) when farmers had more experience with rice cultivation and (iii) when fields were larger. Labour used for land preparation and transplanting increased on fields where there was no tillage and only puddling compared to fields where tillage was combined with puddling. Labour used for land preparation and transplanting was positively correlated to the proportion of casual labour. The amount of labour used for weeding was less (i) on fields where herbicides were applied once compared to fields that were hand-weeded once; and (ii) when fields were larger. More labour was required for weeding on fields where hand-weeding was done twice compared to once. Labour used for weeding was positively correlated to the proportion of casual labour. The amount of labour used for bird scaring was less (i) at greater hill density and (ii) when fields were larger. Labour used for bird scaring was more (i) on fields where rice was preceded by market gardening in the rotation, and (ii) on rice fields preceded by sugarcane or maize (other crops) compared to fields where rice was preceded by rice (Table 4). We found no effect of yield on the amount of labour used for harvesting and threshing. The amount of labour used for harvesting and threshing was less (i) in 2014 compared to 2013; (ii) when fields were larger; and (iii) at greater weed cover below the rice canopy.

In Pelebina, the amount of labour used for field cleaning and land preparation was lower (i) on individual fields compared to family fields; (ii) when fields were larger; and (iii) on fields where land was tilled compared to fields where mounds were broken. The amount of labour used for sowing was higher (i) on fields where rice was preceded by market gardening and (ii) on fields where rice was preceded by rice compared to fields where rice was preceded by tubers. The amount of labour used for weeding was lower (i) on individual fields compared to family fields; (ii) on fields on sandy soils compared to fields on sandy-clay soils; and (iii) when fields were larger. Labour used for weeding increased (i) on fields where hoe-weeding was done twice or (ii) three times compared to fields that were hoe-weeded once (Table 5). The amount of labour used for harvesting and threshing increased with yield ($r^2 = 0.09$, $p < 0.05$) but we found no effect of candidate variables on this amount of labour.

3.3. Variation in rice yield

The average rice yield was 4.8 ± 2.0 t ha^{-1} in Zonmon and 2.3 ± 1.2 t ha^{-1} in Pelebina, i.e., half of that in Zonmon ($p < 0.001$). Average yields of the top decile were 8.4 and 4.4 t ha^{-1}, resulting in a relative yield gap of 43 and 48% for Zonmon and Pelebina, respectively (Fig. 4A). There was no clear relationship between labour use and yield in both villages ($p = 0.27$ for Zonmon and $p = 0.42$ for Pelebina). Yields were not higher at larger labour allocation to rice.

In Zonmon yields were higher (i) at greater hill density and (ii) on larger fields. Yields were lower (i) at higher rat damage; and (ii) at later harvesting dates (Table 4). The inclusion of weed cover below and above the rice canopy as explanatory variables in the regression of yield did not modify the above-mentioned results.

In Pelebina, yields were higher on fields where residues were burned or exported compared to fields where residues were incorporated into the soil; (ii) in 2014 compared to 2012; and (iii) when fields were larger. Yields were lower (i) on fields where land was not prepared compared to fields where mounds were broken; (ii) at greater weed cover above the rice canopy; (iii) at greater bird damage; and (iv) at later sowing dates (Table 5).

3.4. Variation in labour productivity

The average labour productivity was 8 ± 5 kg person-day^{-1} in Zonmon and 17 ± 12 kg person-day^{-1} in Pelebina (Fig. 4B). Observed variation in labour productivity was affected by both labour use (r^2 0.42 in Zonmon and r^2 0.30 in Pelebina, $p < 0.001$) and yield (r^2 0.55 in Zonmon and r^2 0.53 in Pelebina, $p < 0.001$) in both villages (Fig. 4B and C). The higher yields obtained in Zonmon did not compensate for the larger labour input, resulting in lower labour productivity compared to Pelebina ($p < 0.001$). The estimated relative labour productivity gaps were similar, i.e., 59% in Zonmon and 63% in Pelebina. Relative labour productivity gaps were larger than relative yield gaps in both villages.

In Zonmon, five variables had a significant effect on labour productivity (Table 4). Yield and consequently labour productivity decreased with increasing rat damage. Labour productivity was less for fields where rice was preceded by market gardening, sugarcane or maize (other crops) as labour for bird scaring was more than for fields where rice was preceded by rice. Finally, labour productivity increased with an increase in field size and hill density, as yield increased while labour used for land preparation and transplanting, weeding and/or bird scaring decreased with increases in both variables.

In Pelebina, three variables had a significant effect on labour productivity (Table 5). Similar to Zonmon, labour productivity increased with increases in field size as yields were higher on larger fields while labour used for field cleaning and land preparation and weeding was less. Labour productivity decreased with an increase in weed cover above the rice canopy as yield decreased with increases in weed cover above the rice canopy. Finally, labour productivity was lower at greater bird damage as yield decreased with increases in bird damage.

4. Discussion

In order to understand the main causes of variability in yield, labour input and labour productivity among rice fields, and to identify opportunities for improving yield and labour productivity, we studied a total of 132 fields during two or three growing seasons in two villages illustrative of rainfed and irrigated lowlands in Benin. Our results showed a huge variation between and within villages in rice yield, labour input and labour productivity, which suggests the existence of ample opportunities to improve farmer benefits from rice production and its attractiveness as a cash crop within smallholder farm systems in Benin.

4.1. Strategies to reduce labour

The literature reveals a large variation in labour used for rice cultivation depending on management practices, rice growing environments and levels of mechanisation (Kriesemer, 2013; Ministère des Affaires étrangères et al., 2003). Our data were consistent with those reported in the literature, i.e., 20–140 person-days ha^{-1} for manual land preparation (Ministère des Affaires étrangères et al., 2003; Ndiaye, 2011; Pingali et al., 1997); (ii) 30–60 person-days ha^{-1} for transplanting (Krupnik et al., 2012; Ministère des Affaires étrangères et al., 2003; Senthilkumar et al., 2008); (iii) 80 person-days ha^{-1} for hand-weeding (Senthilkumar et al., 2008) and 30–60 person-days ha^{-1} for hoe-weeding (Ministère des Affaires étrangères et al., 2003); (iv) 20–90 person-days ha^{-1} for harvesting (Ministère des Affaires étrangères et al., 2003; Ndiaye, 2011; Pingali et al., 1997; Senthilkumar et al., 2008); and (v) 7–10 person-days ha^{-1} for threshing (Ministère des Affaires étrangères et al., 2003). Field cleaning, i.e., clearing weeds and residues of the preceding crop was not mentioned in the literature we reviewed. Our observations in Zonmon indicate that the amount of labour required for bird scaring by one adult on a field of average size (0.14 ha) and a ripening phase of IR841 of 30 days (IRRI, 2007) is 210 person-days ha^{-1}. This indicative value is much higher than the average of 23 person-days ha^{-1} reported for irrigated rice farmers in the Senegal River Valley (Mey et al., 2012).

In Zonmon the average labour input was 4 times larger than in

Table 2
Candidate independent variables for regression analyses of rice yield and labour use in Zonmon and Pelebina. Means ± standard deviations are displayed for continuous variables while proportions are displayed for categorical variables. Reference categories are indicated in italics.

Zonmon			n	Pelebina			n
X_1	Field size (ha)	0.14 ± 0.20	82	X_1	Field size (ha)	0.19 ± 0.14	50
	Preceding crop				Preceding crop		
	Rice	40	33	X_2	Tubers	54	27
X_2	Fallow	29	24		*Rice*	32	16
X_3	Market gardening	28	23	X_3	Fallow	6	3
X_4	Other (maize, sugercane)	2	2	X_4	Market gardening	8	4
	Residues management				Residues management		
	Exported	78	64		*Incorporated*	56	28
X_5	Burned	18	15	X_5	Burned	34	17
X_6	No residues	4	3	X_6	Exported	10	5
					Herbicide application prior to land preparation		
				X_7	Yes	34	17
					No	66	33
	Land preparation method				Land preparation method		
	Tillage + puddling	73	60		*Mound breaking*	52	26
X_7	No land preparation	16	13	X_8	Tillage	42	21
X_8	Tillage	4	3	X_9	Ridging	2	1
X_9	Puddling	7	6	X_{10}	No land preparation	4	2
					Sowing method		
					Hill sowing	90	45
				X_{11}	Broadcasting	6	3
				X_{12}	Sowing in rows using a rope	4	2
X_{10}	Plant age at transplanting (days)	16 ± 7	82				
X_{11}	Transplanting date (Julian days)	30 ± 38	82	X_{13}	Sowing date (Julian days)	174 ± 29	50
X_{12}	Hill density (hills m^{-2})	26 ± 5	82	X_{14}	Hill density (hills m^{-2})	14 ± 6	50
	First weeding date (DAT)				First weeding date (DAS)		
X_{13}	No weeding	9	7	X_{15}	No weeding	6	3
X_{14}	10–20	12	10	X_{16}	0 − 20	18	9
	20–30	33	27	X_{17}	20–40	22	11
X_{15}	30–40	23	19		*40–60*	38	19
X_{16}	> 40	23	19	X_{18}	> 60	6	3
	Frequency of weeding				Frequency of weeding		
X_{17}	No weeding	9	7	X_{19}	No weeding	6	3
	Hand-weeding once	57	47		*Hoe-weeding once*	58	29
X_{18}	Herbicide once	5	4	X_{20}	Herbicide once	12	6
X_{19}	Hand-weeding twice	12	10	X_{21}	Hoe-weeding twice	10	5
X_{20}	Herbicide once + Hand-weeding once	13	11	X_{22}	Herbicide once + Hoe-weeding once	10	5
X_{21}	Herbicide once + Hand-weeding twice	4	3	X_{23}	Hoe-weeding three times	4	2
X_{22}	Applied N (kg ha^{-1})	54 ± 45	82				
X_{23}	Applied P (kg ha^{-1})	13 ± 14	82				
X_{24}	Applied K (kg ha^{-1})	9 ± 10	82				
	First fertilizer application date (DAT)						
X_{25}	No fertilizer application	11	9				
X_{26}	0 − 20	6	5				
	20–40	35	29				
X_{27}	40–60	35	29				
X_{28}	> 60	12	10				
	Frequency of fertilizer application				Frequency of fertilizer application		
X_{29}	No fertilizer application	11	9		*No fertilizer application*	96	48
	Once	65	53	X_{24}	Once	4	2
X_{30}	Twice	20	16				
X_{31}	Three times	5	4				
	Partial netting						
	Yes	57	47				
X_{32}	No	43	35				
X_{33}	Casual labour (%)	30 ± 26	82	X_{25}	Casual labour (%)	9 ± 19	50
X_{34}	Harvesting date (Julian days)	132 ± 40	82	X_{26}	Harvesting date (Julian days)	338 ± 12	50
X_{35}	Rice cycle length (DAT)	103 ± 13	82	X_{27}	Rice cycle length (DAS)	164 ± 27	50
	Type of management unit				Type of management unit		
	Family	77	63		*Family*	62	31
X_{36}	Individual	23	19	X_{28}	Individual	38	19
X_{37}	Experience with rice cultivation (years)	2 ± 1	82	X_{29}	Experience with rice cultivation (years)	10 ± 9	50
	Sampling year				Sampling year		
	2013	74	61		*2012*	46	23
X_{38}	2014	26	21	X_{30}	2013	38	19
				X_{31}	2014	16	8
	Soil type				Soil type		
X_{39}	'Ado' (sandy-loam soil)	4	3	X_{32}	'Burum' (sandy soil)	36	18
X_{40}	'Veyssa' (sandy soil)	1	1		*'Vete' (sandy-clay soil)*	56	28
	'Kozo holo' (loamy soil)	60	49	X_{33}	'Sewer' (loamy soil)	8	4
X_{41}	'Kozo dide' (heavy clay soil)	35	29				

(continued on next page)

Table 2 (*continued*)

	Zonmon		n		Pelebina		n
	Flooding period				Flooding period		
X_{42}	Never flooded	5	4	X_{34}	Never flooded	30	15
	Flooded from the long rainy season	71	58		*Flooded during the rainy season*	70	35
X_{43}	Flooded from the short rainy season	22	18				
X_{44}	Always flooded ('Towewe' pond)	2	2				
	Soil moisture at transplanting				Soil moisture at sowing		
	Wet	57	47	X_{35}	Dry	2	1
X_{45}	Standing water	43	35		*Wet*	92	46
				X_{36}	Standing water	6	3
X_{46}	Weed cover below the rice canopy at harvest (score)	1.2 ± 0.6	80	X_{37}	Weed cover below the rice canopy at harvest (score)	2.1 ± 0.6	50
X_{47}	Weed cover above the rice canopy at harvest (score)	0.4 ± 0.5	80	X_{38}	Weed cover above the rice canopy at harvest (score)	0.5 ± 0.7	50
X_{48}	Bird damage at harvest (% of panicles)	3.4 ± 4.3	82	X_{39}	Bird damage at harvest (% of panicles)	3.7 ± 5.8	50
X_{49}	Rat damage at harvest (% of panicles)	2.7 ± 4.4	82	X_{40}	Rat damage at harvest (% of panicles)	1.4 ± 3.3	50
X_{50}	Water level at harvest (cm)	9 ± 13	82	X_{41}	Water level at harvest (cm)	0 ± 2	50

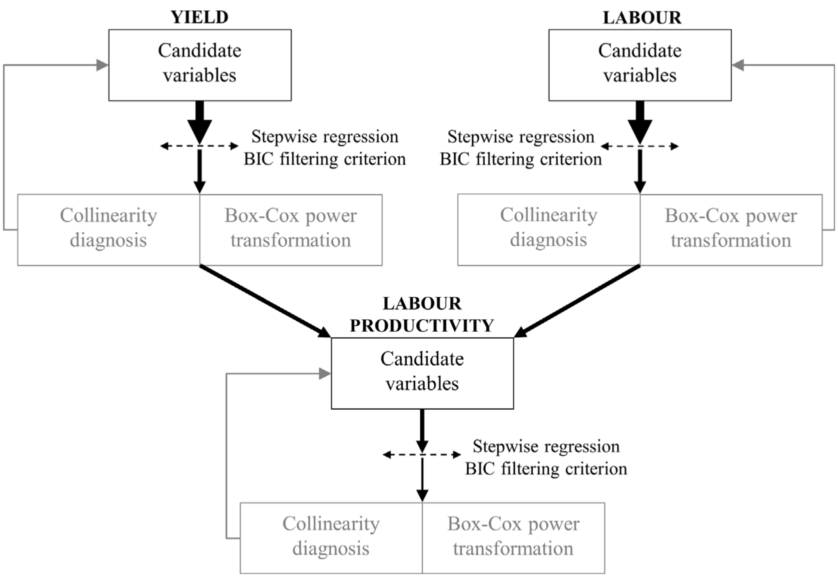

Fig. 3. Overview of the steps used in regression analyses. Steps for testing and validating statistical assumptions are indicated in grey.

Pelebina, with lower and higher labour input fields differing 2146 person-days ha^{-1}. Since there is room to reduce labour input without reducing yield (Table 4 and Fig. 4A), reducing labour input in Zonmon appears the best strategy to increase labour productivity and rice area in this village. Increasing the average hill density up to 34 hills m^{-2} would be viable and based on our regression models, would reduce labour by 49 person-days ha^{-1} through its effect on bird-scaring (Table 6). Using post-emergence herbicides instead of one hand-

Table 3
Labour requirement (average ± standard deviation) for each (group of) farming operation(s). Medians are displayed in italics. Different letters indicate differences in labour requirements among farming operations at the 5% level.

	Zonmon						Pelebina				
	Labour (person-days ha^{-1})			Casual labour (person-days ha^{-1})			Labour (person-days ha^{-1})			Casual labour (person-days ha^{-1})	
Farming operation	% of total	Mean ± SD	Median	Mean ± SD	Median	Farming operation	% of total	Mean ± SD	Median	Mean ± SD	Median
Field cleaning + bund making	15	109 ± 88	89 c	60 ± 72	28 c	Field cleaning + land preparation	23	39 ± 28	32 bc	6 ± 12	0 a
Land preparation + transplanting	17	126 ± 78	115 c	74 ± 75	58 c	Sowing	18	31 ± 26	21 b	1 ± 6	0 a
Weeding	9	66 ± 61	50 b	29 ± 49	0 b	Weeding	22	36 ± 34	26 b	0 ± 1	0 a
Fertilizer application	0	2 ± 2	2 a	0 ± 0	0 a	Fertilizer application	0	0 ± 2	0 a	0 ± 0	0 a
Bird scaring	45	324 ± 280	240 d	49 ± 235	0 ab						
Harvesting + threshing	14	100 ± 62	82 bc	20 ± 39	0 b	Harvesting + threshing	37	62 ± 34	52 c	0 ± 0	0 a
Total	100	727 ± 352	667	231 ± 315	132	Total	100	168 ± 86	146	7 ± 16	0

Table 4
Results of regression analyses for Zonmon. Reference categories are displayed in italics.

	Field cleaning + bund making (person-days ha^{-1})		Land preparation + transplanting (person-days ha^{-1})		Weeding (person-days ha^{-1})		Bird scaring (person-days ha^{-1})		Harvesting + threshing (person-days ha^{-1})		Yield (kg ha^{-1})		Labour productivity (kg person-day^{-1})	
Transformation	ln(Y + 0.001)		ln(Y)		sqrt(Y)		ln(Y)		ln(Y)		sqrt(Y)		ln(Y)	
Multiple R-squared	0.9191		0.6277		0.5973		0.4087		0.3133		0.3500		0.5656	
Intercept	4.4798	***	4.8000	***	7.4194	***	6.3990	***	4.9830	***	56.8950	***	1.1780	**
Type of management unit (*Family*)														
Individual	−0.5497	**												
Sampling year (2013)														
2014									−0.6348	***				
Experience with rice cultivation			−0.1632	***										
Weed cover below the rice canopy									−0.2682	*				
Rat damage at harvest											−1.3333	***	−0.0489	**
Field size			−0.0001	***	−0.0004	*	−0.0002	***	−0.0001	*	0.0016	*	0.0002	***
Flooding period (*Flooded from the long rainy season*)														
Never flooded	−1.3906	***												
Flooded from the short rainy season	−0.1767													
Always flooded ('*Towewe*' pond)	0.6863													
Preceding crop (*Rice*)														
Fallow							−0.0739						−0.1904	
Market gardening							0.6246	***					−0.7328	***
Other							0.8087	*					−1.1820	**
Residues management (*Exported*)														
Burned	−0.0289													
No residue	−11.6415	***												
Land preparation method (*Tillage + puddling*)														
No land preparation			−0.6049	***										
Tillage			−0.1605											
Puddling			0.7433	***										
Hill density							−0.0320	*			1.0023	**	0.0403	**
Frequency of weeding (*Hand-weeding once*)														
No weeding					−7.7609	***								
Herbicide once					−5.9860	***								
Hand-weeding twice					3.5358	***								
Herbicide once + Hand-weeding once					−0.7875									
Herbicide once + Hand-weeding twice					3.1703									
Harvesting date											−0.1041	**		
Casual labour	0.0075	*	0.0106	***	0.0280	*								

Asterisks indicate level of significance: $p < 0.10$ (.), $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

Table 5
Results of regression analyses for Pelebina. Reference categories are displayed in italics.

	Field cleaning + land preparation (person-days ha^{-1})		Sowing (person-days ha^{-1})		Weeding (person-days ha^{-1})		Yield (kg ha^{-1})		Labour productivity (kg person-day^{-1})	
Transformation	ln(Y)		Y		Y		sqrt(Y)		sqrt(Y)	
Multiple R-squared	0.3324		0.2547		0.7128		0.6053		0.4349	
Intercept	3.6540	***	30.5991	***	18.9680		66.9305	***	3.3664	***
Type of management unit (*Family*)										
Individual	−0.4539	*			−19.2139	*				
Sampling year (*2012*)										
2013							5.5847			
2014							12.7306	*		
Soil type (*'Vete', sandy-clay soil*)										
'*Burum*' (sandy soil)					−19.1335	*				
'*Sewer*' (loamy soil)					−18.0372					
Weed cover above the rice canopy							−6.9309	**	−0.5753	*
Bird damage at harvest							−0.8813	**	−0.0722	*
Field size	−0.0002	**	−0.0047	.	−0.0052	*	0.0026	*	0.0005	***
Preceding crop (*Tubers*)										
Rice			17.5288	*						
Fallow			5.0092							
Market gardening			37.9857	**						
Residues management (*Incorporated*)										
Burned							13.9658	***		
Exported							11.5234	*		
Land preparation method (*Mound breaking*)										
Tillage	0.7375	***					5.7296			
Ridging	0.5364						−11.7678	.		
No land preparation	0.1951						−18.3504	*		
Sowing date							−0.1770	**		
Frequency of weeding (*Hoe-weeding once*)										
No weeding					−16.9685					
Herbicide once					−15.3183					
Hoe-weeding twice					72.0079	***				
Herbicide once + Hoe-weeding once					19.3659					
Hoe-weeding three times					45.9041	**				
Rice growing cycle length					0.2084	.				

Asterisks indicate level of significance: $p < 0.10$ (.), $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***)

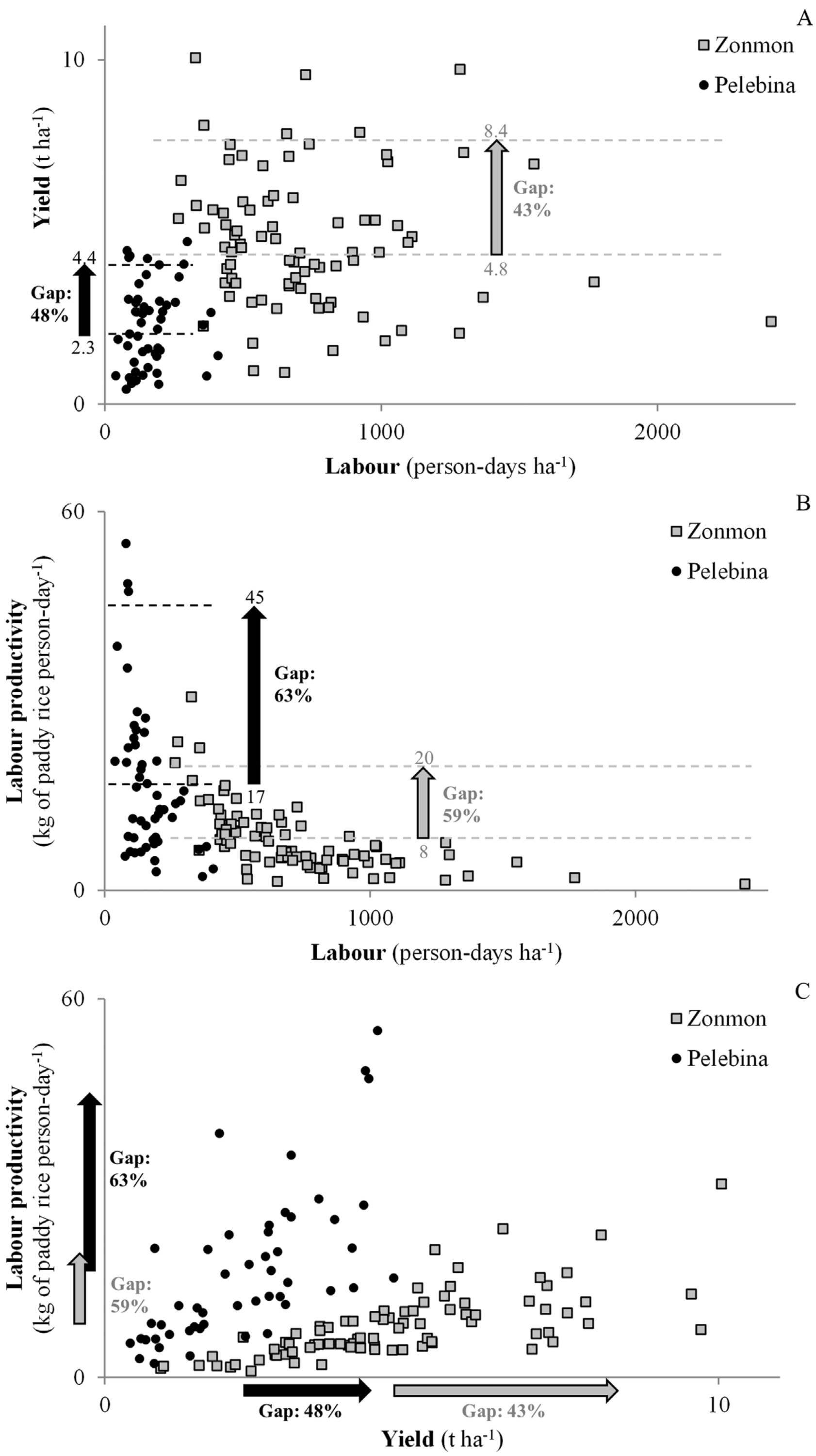

Fig. 4. Yield and labour productivity gaps in the case-study villages. A. Relationship between yield and labour. B. Relationship between labour productivity and labour. C. Relationship between labour productivity and yield. Yield and labour productivity gaps are symbolised by arrows (black arrows for Pelebina and grey arrows for Zonmon) and are expressed as a percentage of the average highest yield and labour productivity decile. Average yield and average labour productivity are displayed at the bottom of arrows. Average highest yield decile and average highest labour productivity decile are displayed at the top of arrows.

weeding operation was an affordable alternative (2 800 FCFA on a field of average size) which would reduce labour by 56 person-days ha^{-1}, but may pose risk to human health and wildlife (Culliney, 2005). As village authorities delimited an area dedicated to rice production, most rice fields were already grouped in the same area of the lowland, which increased bird scaring efficiency. Some farmers even associated themselves with their neighbours and took turns at bird scaring to decrease the labour needed. Skills exchange with experienced farmers may speed up farmers' learning processes and reduce labour by 34 person-days ha^{-1}. Doing away with casual labour would reduce labour by 64 person-days ha^{-1} but casual labour was probably used because of a lack of family labour. Cultivating large areas (0.3 ha on average per farmer) with limited labour available led to working on a field-by-field basis for the labour-demanding field cleaning and bund making, and land preparation and transplanting. Working on a field-by-field basis was not a strategy to deal with climatic uncertainty (Milgroom and Giller, 2013) but a strategy to maximize the area with early transplanting. This strategy resulted in a range of transplanting dates and field sizes for fields managed by the same farmer. Therefore, increasing the average field size and constraining bird scaring to the critical period for bird

Table 6
Ranking of variables based on the effect of a change in their value from the average to the average highest or lowest decile (for continuous variables) or from the base category to an alternative category (for categorical variables) on the amount of labour used in Zonmon and related comments. Calculations were made using the regression models of labour for field cleaning and bund making, labour for land preparation and transplanting, labour for weeding, and labour for bird scaring.

Variables	Change in variable value from the average or from the base category	Effect on labour input (person-days ha^{-1})	Comments
Field size (m^2)	+3546	−166	Greater incentives to complete farming operations in a timely manner on larger fields because the task was perceived of major importance; Free-riding on smaller fields because the task was perceived as of minor importance; Economies of scale on larger fields (e.g., not less than a full-time worker could be allocated to small fields for bird-scaring)
Exported residues	No residue	−111	Flooding after harvest (rainwater runoff and floodwater of the Oueme river) together with early field cleaning after the dropping of the water level helped controlling the amount of weeds (Rodenburg and Johnson, 2009) and crop residues
Flooded from the long rainy season	Never flooded	−83	More difficult work in the muddy soils of fields flooded from the long rainy season
Casual labour (%)	−30	−64	Moral hazard (Holmstrom, 1982), i.e., low effort on the part of casual labourers
Hand-weeding once	No weeding	−59	Lower weed pressure on non-weeded fields (no difference in the weed cover below and above rice canopy and in the first weeding date among fields with different frequencies of weeding; *p* values of 0.89, 0.16 and 0.15, respectively)
Hand-weeding once	Herbicide once	−56	Similar weed pressure on fields where herbicides were applied than on fields that were hand-weeded once
Hill density (hills m^{-2})	+8	−49	Birds are attracted to zones with plant densities much lower than in the immediate vicinity (de Mey and Demont, 2013; Tréca, 1977). At greater plant densities, farmers can respond to lower bird pressure by delaying the start of bird-scaring or decreasing the number of workers involved
Tillage + puddling	No land preparation	−49	No specific conditions identified for fields where land was not prepared (no relationship found between no land preparation and flooding period, soil type, residues management and preceding crop)
Family fields	Individual fields	−47	Less labour available on individual fields; Family fields may experience free-riding (Guirkinger and Platteau, 2014)
2013 as the sampling year	2014 as the sampling year	−45	More rainfall at the beginning of the rainy season, i.e., at harvesting time in 2013 compared to 2014 caused rice lodging, which made harvesting more labour-demanding
Experience with rice cultivation (years)	+2.3	−34	
Weed cover below the rice canopy	+1.1	−24	Competition with weeds led to a smaller number of panicles per m^2 (data not shown, $p = 0.07$); Farmers did not harvest areas with very high weed cover; Higher weed cover below the rice canopy was associated with lower water level at harvest ($p < 0.01$) and thus, with easier harvesting conditions
Hand-weeding once	Hand-weeding twice	+67	Higher weed pressure on fields that were hand-weeded twice
Tillage + puddling	Puddling	+119	Tillage made puddling faster: when subsequent to tillage, farmers used a small hoe to break soil clods while without tillage, farmers used a machete which was much more labour-demanding to break the dense root systems and mash the soil; Puddling was done without tillage on fields where the water level was too high to till the soil
Rice as the preceding crop	Market gardening as the preceding crop	+185	Earlier start of bird-scaring, i.e., during the flowering phase ($p = 0.08$) because fields where market gardening was the preceding crop were adjacent to fields where rice was the preceding crop, which were transplanted earlier ($p = 0.06$) and managed by the same farmers
Rice as the preceding crop	Other crops as the preceding crop	+266	Higher bird pressure on isolated fields and the farmers' response to this by putting forward the start of bird-scaring or increasing the number of workers involved

damage (ripening phase) would first require reducing the transplanting period by saving labour for field cleaning and bund making as well as for land preparation and transplanting. Additional investments in the irrigation scheme would be needed to improve water management before and during the rice cropping season. At present, the amount of weeds and crop residues cannot be controlled as (i) the flooding period is not controlled; and (ii) the period between the dropping water level and the start of field cleaning depends on the yearly collective digging of the main irrigation canal on the sandy fringes. Besides, the presence of a permanently flooded pond at the bottom of the lowland (*Towewe* pond) makes drainage difficult, not to say impossible on fields located near the bottom of the lowland. And yet, draining fields just before cleaning operations would (i) avoid working in muddy soils and thus, reduce labour by 83 person-days ha^{-1}; and (ii) allow tillage before puddling and thus, reduce labour by 119 person-days ha^{-1} on the 7% of fields where the water level was too high to till the soil. Finally, no land preparation instead of tillage and puddling may reduce labour by 49 person-days ha^{-1} but we did not study water use efficiency on rice fields and puddling is usually recommended to reduce water loss (IRRI, n.d.).

In Pelebina, the variation observed in labour input was also high in percentage but the spread between lower and higher labour input fields was only 370 person-days ha^{-1}. Still, there are opportunities to increase labour productivity by reducing labour input. Based on our regression models, sowing rice after tubers cultivated on mounds would require less labour for sowing and was already done in slightly more than half of the fields. Increasing the average field size up to 0.5 ha and sowing rice on sandy soils instead of sandy-clay soils would reduce labour by 27 person-days ha^{-1} and 19 person-days ha^{-1}, respectively (Table 7). These alternatives would be feasible as fallows were available through ownership and borrowing (Paresys et al., 2017) and rice fields were usually adjacent to fallows. Increasing field size from the current average size of 0.19 ha up to 0.5 ha would imply an increase in labour demand of 7.6 person-days at farm level, spread on the whole growth period of the crop. Increasing field size would not imply increasing the demand of cash spent on purchasing chemical inputs at farm level

Table 7
Ranking of variables based on the effect of a change in their value from the average to the average highest or lowest decile (for continuous variables) or from the base category to an alternative category (for categorical variables) on the amount of labour used in Pelebina and related comments. Calculations were made using the regression models of labour for field cleaning and land preparation, labour for sowing, and labour for weeding.

Variables	Change in variable value from the average or from the base category	Effect on labour input (person-days ha^{-1})	Comments
Family fields	Individual fields	−29	Less labour available on individual fields; Family fields may experience free-riding (Guirkinger and Platteau, 2014)
Field size (m^2)	+2 957	−27	Greater incentives to complete farming operations in a timely manner on larger fields because the task was perceived of major importance; Free-riding on smaller fields because the task was perceived as of minor importance; Economies of scale on larger fields
'Vete', sandy-clay soil	'Burum' (sandy soil)	−19	Sandy soils are light and relatively easy to work while sandy-clay soils are hard under dry conditions and very sticky under wet conditions
Tubers as the preceding crop	Rice as the preceding crop	+18	The soil was tilled when rice was the preceding crop whereas mounds were broken when tubers were the preceding crop. In case of tillage, sowing included breaking soil clods, i.e., preparing a seedbed where the rice was to be sown. In case of mound breaking, soil structure enabled sowing rice without any additional operation; As preceding crop and not land preparation was selected by the stepwise procedure, there was an additional effect of preceding crop on sowing, which was probably related to crop residues
Mound breaking	Tillage	+29	Relatively light soil on mounds; Less activity as the soil was not turned over
Tubers as the preceding crop	Market gardening as the preceding crop	+38	See 'Rice as the preceding crop'
Hoe-weeding once	Hoe-weeding three times	+46	Either higher weed pressure on fields that were hoe-weeded twice or three times or hoe-weeding later and just once was an efficient labour-saving strategy to control weeds (no difference in the weed cover below and above rice canopy among fields with different frequencies of weeding; p values of 0.89, 0.16, respectively; first weeding completed earlier on fields weeded more than once; $p < 0.001$)
Hoe-weeding once	Hoe-weeding twice	+72	

because currently most farmers do not use these inputs. Resulting increases in rice areas at village level would not affect lowland land use substantially. In 2012, rice was grown by 23 farmers on only 4.2 ha. Assuming that all 23 farmers increase their field size to 0.5 ha, we estimated that the proportion of fallow land in the lowlands of Pelebina would decrease from 64% (Paresys et al., 2017) to 59%.

4.2. Strategies to improve yield

We found a yield difference of almost 4 and 2 t ha^{-1} between the average and the top yielding fields in Zonmon and Pelebina, respectively, and we were able to relate part of that yield difference to crop management practices in both villages.

In Zonmon, the average yield (4.8 t ha^{-1}) was identical to that found by Tanaka et al. (2013) in the same region of Benin and larger to that of 3.7 t ha^{-1} found in irrigated lowlands in the sub-humid zone of sub-Saharan Africa (Niang et al., 2017; Tanaka et al., 2017). The average yield of the top decile (8.4 t ha^{-1}) was close to the potential yield of 9.1 t ha^{-1} simulated for irrigated systems of Guinea savanna (Becker et al., 2003). According to our regression model in Zonmon, yield would be improved by 1.2 t ha^{-1} by increasing the average hill density up to 34 hills m^{-2} (Table 8). Rat damage was not controlled and may be reduced like in nearby villages by individual actions (Tanaka et al., 2013) and/or collective actions (Palis et al., 2007; Thi My Phung et al., 2013), the former being less efficient but probably easier to be adopted than the latter. Increasing the average field size and earlier transplanting (second half of December) would improve yield by 1.5 t ha^{-1} but would first require saving labour for field cleaning and bund making as well as for land preparation and transplanting. If such labour savings may allow earlier transplanting or help farmers to transplant seedlings onto large rice fields, farmers cultivating more than one field may choose to cultivate large fields on land which they perceived to be more productive and small fields on land which they perceived to be less productive. Thus, simultaneously transplant seedlings on the combination of large and more productive and small and less productive fields may overall not have the expected positive impact on the average yield at farm level. Increasing field size would then only have a positive impact for farmers having extra productive land available. Finally, late harvesting was probably due to competition in labour allocation between rice fields and upland fields at the beginning of the rainy season (Paresys et al., 2017).

In Pelebina, the average yield (2.3 t ha^{-1}) was within the range of that found by Danvi et al. (2016) in the same region of Benin and close to that of 2.1 t ha^{-1} found in rainfed lowlands in the sub-humid zone of sub-Saharan Africa (Niang et al., 2017; Tanaka et al., 2017). The average highest yield decile (4.4 t ha^{-1}) was within the range of 3.8–4.4 t ha^{-1} found in an experiment in the same region of Benin (Worou et al., 2013). It was 70% of the potential yield of 6.6 t ha^{-1} simulated in rainfed systems (Van Oort et al., 2015) and was around half of the potential yield of 9.1 t ha^{-1} simulated in irrigated systems of Guinea savanna (Becker et al., 2003). According to our regression model in Pelebina, burning residues or exporting residues instead of incorporating them would improve yield by 1.2 t ha^{-1} or 0.9 t ha^{-1}, respectively (Table 8). On the one hand, compared to exporting residues, burning residues would allow K recycling on rice fields. On the other hand, compared to burning residues, exporting residues would avoid emissions of carbon dioxide and their adverse effect on the environment (Sidhu et al., 1998) and may avoid nutrient losses if residues are recycled on other fields (e.g., incorporated or used in mulch form for drained fields where N is applied, or used in compost form). Increasing the average field size up to 0.5 ha would improve yield by 0.6 t ha^{-1} and would be feasible as fertile land was available through ownership and borrowing. Besides, increasing field size would not imply substantial changes in labour and chemical inputs at farm level and in lowland land use at village level (see 4.1). Avoiding rice shading, i.e., removing the weed cover above the rice canopy would improve yield by 0.2 t ha^{-1}. Land should be prepared, as was the case on most fields. Moving forward the average sowing date to between the end of April and the beginning of May as well as introducing bird control may be constrained by labour availability and allocation at farm level as rice was cultivated during the rainy season when the labour demand by upland fields was high (Paresys et al., 2017).

Table 8
Ranking of variables based on the effect of a change in their value from the average to the average highest or lowest decile (for continuous variables) or from the base category to an alternative category (for categorical variables) on yield and related comments. Calculations were made using the regression models of yield fitted per village.

Variables		Change in variable value from the average or from the base category	Effect on yield (kg ha^{-1})	Comments
Zonmon	Hill density (hills m^{-2})	+8	+1 181	The average highest decile of hill density was 34 hills m^{-2}, a value equivalent to a spacing of 17.2 cm × 17.2 cm, which is narrower than the recommended spacing of 20 cm × 20 cm (Bell et al., 2017; Nwilene et al., 2008)
	Field size (m^2)	+3546	+785	Farmers may decide to allocate more labour, i.e., to cultivate larger fields, to land which they perceived to be more productive (Tittonell and Giller, 2013);We found a direct relationship between field size and yield and not an inverse relationship as established between farm size and land productivity for Africa (Ali and Deininger, 2015; Frelat et al., 2016; Woodhouse, 2010) as (i) there may be no relationship between rice field size and farm size in this study; (ii) in Zonmon, farmers cultivated more than one field and small fields were usually cultivated in addition to large fields; (ii) agricultural production on farms was not rice-based but relied on a diversity of crops (Paresys et al., 2017)
	Harvesting date (Julian days)	−51	+743	Earlier harvesting was associated with earlier transplanting (high correlation between harvesting date and transplanting date, *r* 0.95) and transplanting earlier has been found to be associated with greater yield (Stuart et al., 2016); In addition, on-time harvesting, i.e., harvesting when rice reached the maturity date avoided grain losses (Mejía, 2003)
	Rat damage (% of panicles)	−2.7	+506	Effect also reported by Tanaka et al. (2013) in the same region of Benin. In Zonmon, however, rat damage was not controlled.
Pelebina	Incorporating residues	Burning residues	+1 161	Burning residues may avoid N immobilization and reduction of N uptake and crop growth (Thuy et al., 2008; Xu et al., 2010), especially as N was not applied in 26 of 28 fields (93%) (Huang et al., 2013); Accumulation of phytotoxic substances as 75% of fields (21 of 28) were flooded during the rainy season and never drained (Bijay-Singh et al., 2008; Gao et al., 2004)
	2012 as the sampling year	2014 as the sampling year	+1 043	Year 2014 considered as a relatively normal year; In 2012, some rice fields were flooded after sowing due to an excess in rainfall; In 2013, there was a lack of rainfall during the month of June.
	Incorporating residues	Exporting residues	+930	See ‘Burning residues’; K recycling when residues were burned compared to K depletion when residues were exported may explain differences in magnitude and significance level between the two residues management practices.
	Sowing date (Julian days)	−63	+889	See ‘Harvesting date’ in Zonmon
	Field size (m^2)	+2 957	+586	See ‘Field size’ in Zonmon
	Bird damage (% of panicles)	−3.7	+234	Bird damage not controlled in Pelebina; Rice fields vulnerable to birds as often located in remote areas and surrounded by attractive fallows (de Mey and Demont, 2013)
	Weed cover above the rice canopy	−0.5	+228	Shading decreased grain production (Caton et al., 2001; Efthimiadou et al., 2009; Zimdahl, 2004)
	Mound breaking	No land preparation	−932	Negative effect of no land preparation on N uptake and crop growth as fields were located in sandy and sandy-clay soils and N was not applied (Huang et al., 2015, 2012)

Table 9
Ranking of variables based on the effect of a change in their value from the average to the average highest or lowest decile (for continuous variables) or from the base category to an alternative category (for categorical variables) on labour productivity. Calculations were made using the regression models of labour productivity fitted per village.

	Variables	Change in variable value from the average or from the base category	Effect on labour productivity (kg ha^{-1})
Zonmon	Field size (m^2)	+3 546	+8.6
	Hill density (hills m^{-2})	+8	+4.0
	Rat damage at harvest (% of panicles)	−2.7	+1.5
	Rice as the preceding crop	Market gardening as the preceding crop	−5.3
	Rice as the preceding crop	Other crops as the preceding crop	−7.1
Pelebina	Field size (m^2)	+2 957	+15.0
	Weed cover above the rice canopy	−0.5	+2.1
	Bird damage at harvest (% of panicles)	−3.7	+2.1

4.3. Strategies to improve labour productivity

4.3.1. The need to prioritise labour-saving technology development

We found a striking difference in labour productivity between the two case-study villages. The average labour productivity and the average labour productivity of the top decile were two times higher in Pelebina than in Zonmon, although the average yield and the average yield of the top decile in Pelebina were half of those in Zonmon (Fig. 4A–C). The difference in labour productivity may be explained by differences in rice growing environments. In Zonmon, rice was cultivated during the dry season, which required irrigation. Irrigation implied bund making, puddling, transplanting rather than sowing, and hand-weeding rather than hoe-weeding. Field cleaning and harvesting may be more labour-demanding in an environment where fields are flooded and drainage is not controlled. Bird pressure may be higher on rice fields at a period of time when other cereals are not grown. Combined, this may have caused rice cultivation in Zonmon to require more labour than in Pelebina and thus, resulted in lower labour productivity.

In both case-study villages, within-village variation in yield and labour productivity indicated there was room for farmers to learn from other farmers' practices. Practices to improve labour productivity on rice fields included practices to increase yield as well as practices to decrease the amount of labour used. In each village, we found a synergy between gains in labour productivity and gains in yield (Fig. 4C). In other words, practices increasing yield did not imply additional labour (i.e., earlier transplanting and on-time harvesting in Zonmon; earlier sowing in Pelebina) or even reduced the labour input (i.e., increasing field size and hill density in Zonmon; increasing field size in Pelebina). In the literature, failures in the uptake of yield-enhancing, potentially yield-enhancing or yield-sustaining practices have been attributed to labour constraints (Asfaw and Lipper, 2015; Baudron et al., 2015; Byerlee et al., 2008; Gabre-madhin and Haggblade, 2004; Gebremedhin et al., 2003; Leonardo et al., 2015; Nicol et al., 2011; Ortega et al., 2016; Vissoh et al., 2004) while some successes were attributed to labour savings (Diao et al., 2016; Franke et al., 2010; Gabre-madhin and Haggblade, 2004; Haggblade and Hazell, 2010; Vandeplas et al., 2008). These results are supported by our findings and point to the need to combine yield analyses with analyses of labour use and labour productivity and to focus on labour-saving approaches rather than on yield-increasing approaches if they demand more labour.

Using detailed local agronomic information allowed us to identify best viable practices. Based on our regression model, labour productivity would be improved by 4 kg person-day^{-1} by increasing the average hill density up to 34 hills m^{-2} in Zonmon and by 17.1 kg person-day^{-1} by increasing the average field size up to 0.5 ha and avoiding rice shading in Pelebina (Table 9). Beyond these local best viable practices there is still room to improve labour productivity on rice fields. Research has been carried out on factors impacting labour use efficiency for weeding (N'Cho, 2014; Ogwuike et al., 2014) as well as labour-saving technologies for weeding such as herbicides (Gianessi, 2013; Lawrence and Dijkman, 1997) and mechanical weeders (Gongotchame et al., 2014; Rodenburg et al., 2015). Weeds, dates of weeding and weeding frequencies, however, were not identified as variables explaining yield and labour productivity in Zonmon, suggesting weeds were well controlled by farmers. Besides, weeding was less labour-demanding than (i) field cleaning and bund making, or than land preparation and transplanting and greatly less labour-demanding than bird scaring in Zonmon; and (ii) harvesting and threshing in Pelebina.

In Zonmon, saving on the amount of labour used for field cleaning and bund making as well as for land preparation and transplanting may (i) allow earlier transplanting; (ii) help farmers decrease differences in transplanting dates among their rice fields, or even to transplant seedlings onto large rice fields, which in return would save labour, in particular labour used for bird scaring, and based on our regression model, would increase labour productivity by up to 8.6 kg person-day^{-1} (Table 9). In addition, the amount of casual labour may be decreased (Table 3) and consequently, the gross margin of rice production may be increased.

In Asian rice systems, the adoption of mechanical power reduced labour requirements, costs and ensured the timely completion of land preparation (Biggs and Justice, 2015; Pingali, 2007). In sub-Saharan African rice systems, mechanical power for land preparation (e.g. power tillers in Zonmon) or threshing (e.g. threshers in Pelebina) may be adopted provided that technologies are made affordable, adapted to the growing environment and spare parts are made available (Seck et al., 2012). Failures in the adoption of large-scale equipment such as tractors (Diao et al., 2016, 2014; Fonteh, 2010; Onwude et al., 2016) suggest that massive introduction of purchased large-scale equipment must be avoided (Mmari and Mpanduji, 2014; Seck et al., 2012). Instead, building on the gradual and so-called 'silent revolutions' that occurred in some Asian countries (Biggs and Justice, 2015), small-scale equipment should be targeted. Research and development agencies should engage in testing and adapting equipment (Biggs and Justice, 2015; Seck et al., 2012) and local manufacturing and maintenance of equipment needs to be stimulated (Curfs, 1976; Douthwaite and Gummert, 2010; Onwude et al., 2016; Seck et al., 2012).

Bird scaring was the most labour-demanding operation in Zonmon, accounting for around half of the total labour input. In this village, the Oueme river transcended its banks at the beginning of the short rainy season and flooded part of the village territory. Thus, during the short rainy season, farmers focused on cultivating groundnut and cowpea on sandy hills and on fishing. Acrylic nets used for fishing were recycled on rice fields for protection against birds. Farmers' interest for partial netting, i.e., netting part of the sides or top of fields, was reflected by a 37% increase in use of nets from the 2013 to the 2014 dry season. Farmers observed that partial netting helped in diverting and gathering birds together on a particular side of the fields. Although we did not find a quantitative effect of partial netting on yield and on the amount of labour used for bird scaring, it may have had a qualitative effect, i.e., it may have made the task less laborious. Previous studies showed that complete enclosure of rice fields during the ripening phase can effectively reduce bird damage (Ajayi et al., 2007; Bishop et al., 2003) and its implementation may be tested in Zonmon. Nets were available on the market and acrylic nets were relatively affordable. Research should not only evaluate trade-offs between costs and gains of complete enclosure netting of a rice field but also consequences at a whole farm level as labour demand for bird scaring competed with labour demand for upland fields at the beginning of the long rainy season (Paresys et al., 2017),

4.3.2. The need to optimise labour allocation at farm level

In addition to rice growing environments, differences in labour productivity between the two villages may be explained by differences in labour allocation at a farm level during the rice growing season and thus, of labour availability for rice production. In Zonmon, rice was cultivated during the dry season, when the labour demand on upland fields was low. In Pelebina, rice was cultivated during the rainy season, when the labour demand on upland fields was high. Herbicides were used prior to land preparation and around a third of rice fields were located in never flooded areas. Even on the two thirds of fields flooded during the rainy season, farmers chose not to control water levels, i.e., bunds were not made, puddling was not performed, transplanting was not used, and weeding was done using a hoe. Finally, birds were not controlled. In Pelebina, farmers may have developed highly labour-productive strategies in order to be able to add rice production to major cash crop (cotton and legume) and staple crop (tubers and cereals) production in uplands.

Our research supports the hypothesis that farmers' practices, yields and labour productivities at field level are shaped by the availability and allocation of resources, including labour, at farm level (Beza et al., 2017; Dzanku et al., 2015; Leonardo et al., 2015; Rusinamhodzi et al., 2016; Tittonell and Giller, 2013; Vissoh et al., 2004; Wijk et al., 2009). Based on our regression model in Pelebina, rice labour productivity was 2.1 kg person-day^{-1} higher when there was no bird damage (Table 9). The absence of bird control may be explained by labour constraints and priority given to upland fields at a farm level. In Zonmon, the use of casual labour was probably due to a lack of family labour and late harvesting was probably due to competition in labour allocation between rice fields and upland fields at the beginning of the rainy season. This points to the need to combine rice field analyses with analyses of labour use and labour productivity for farms with different levels of resource endowment and resource use strategies (Paresys et al., 2017). Such farm level analyses would provide new insights on how to further enhance rice yield and labour productivity, while maximising total farmer income.

5. Conclusion

The common analysis of relative yield gap at the field level was extended with an analysis of the relative labour productivity gap and variability in labour input in two villages illustrative of rainfed and irrigated lowlands in Benin. The approach was based on the assumptions that increases in farmer labour productivity constitute a key to reducing farmer poverty, and that increases in rice labour productivity is a key to stimulating expansion to wetlands.

Relative yield and labour productivity gaps were similar in the two villages (43–48% and 59–63%, respectively), but with great variation between and within the villages (4.8 ± 2.0 t ha^{-1} in Zonmon and 2.3 ± 1.2 t ha^{-1} in Pelebina, and 8 ± 5 kg person-day^{-1} in Zonmon and 17 ± 12 kg person-day^{-1} in Pelebina, respectively). We found no trade-off between yield and labour or labour productivity within the villages, suggesting that in many cases rice yields can be increased without additional labour inputs. We identified opportunities to reduce labour, improve yield and labour productivity based on current farmer knowledge and resource endowment.

Rice yield and labour productivity could be improved considerably with the locally available technologies and knowledge. Further enhancing yield and labour productivity will require (i) introducing small-scale mechanisation and other labour-saving innovations, in particular for labour-demanding farming operations such as bird scaring in Zonmon and harvesting and threshing in Pelebina; and (ii) combining analyses of yields and labour productivities at field level with detailed analyses of labour use and labour productivity at farm level.

When comparing fields within the same village, we found that both labour use and yield affected labour productivity. However, when comparing case-study villages, we found that higher yields do not always result in higher labour productivity. Cultivating irrigated rice during the dry season in Zonmon with improved donated seeds and credited fertilizers resulted, on average, in higher yields but lower labour productivity compared to cultivating rainfed rice in Pelebina with self-produced seeds and without fertilizers. In other words, one hectare in Zonmon contributed twice as much to Beninese rice production compared to one hectare in Pelebina but with a two times smaller reward for farmer labour. Such differences in labour productivity would even be more striking when taking costs of chemical inputs and casual labour into account. The paradox of higher yields but lower labour productivity in such different rice growing environments and farming systems should be addressed in elaborating development policies. In villages similar to Pelebina, policies could focus on yield-increasing approaches that do not demand more labour (e.g., donated seeds and credited fertilizers) while in villages similar to Zonmon, policies could focus on labour-saving approaches that do not decrease yield (e.g., small-scale mechanisation).

Acknowledgements

We thank Seidou Ouorou Aliou and Gildas Edjrokinto for their contribution as translators and assistants in Pelebina and in Zonmon, respectively. We thank Giscard Hounha and Rémi Hountchonou for their contribution to recording data through on-farm observations in Pelebina and in Zonmon, respectively. We thank Charles Djigbenoude for his contribution to estimating filled grain weight and grain moisture content of rice samples. We are grateful to the rice farmers who participated in our research. We thank village authorities and villagers for the warm welcome they have given us. We acknowledge the comments of two anonymous reviewers and the editor that helped us to improve the manuscript. This work was supported by the European Commission through the International Fund for Agricultural Development and the project "Realizing the agricultural potential of inland valley lowlands in sub-Saharan Africa while maintaining their environmental services Phase 2" [COFIN-ECG-65-WARDA]; and the Wageningen University INREF Fund (especially, Mr. Wim Andriesse and Mr Pieter Windmeijer).

Appendix A

Regression models used in the stepwise procedure

For Zonmon, regression models took the following forms:

$$Yield_i = \beta_0 + \sum_{j=1}^{50} \beta_j X_{ji} + \varepsilon_i,\ i = 1,\ \dots, \mathrm{n} \tag{A.1}$$

$$Field\ cleaning\ \&\ bund\ making_i = \beta_0 + \sum_{j=1}^{6} \beta_j X_{ji} + \beta_{33} X_{33i} + \sum_{j=36}^{44} \beta_j X_{ji} + \varepsilon_i,\ i = 1,\ \dots, \mathrm{n} \tag{A.2}$$

$$Land\ preparation\ \&\ transplanting_i = \beta_0 + \sum_{j=1}^{12} \beta_j X_{ji} + \beta_{33} X_{33i} + \sum_{j=36}^{45} \beta_j X_{ji} + \varepsilon_i,\ i = 1,\ \ldots,\mathrm{n} \tag{A.3}$$

$$Weeding_i = \beta_0 + \sum_{j=1}^{31} \beta_j X_{ji} + \sum_{j=33}^{45} \beta_j X_{ji} + \varepsilon_i,\ i = 1,\ \ldots,\mathrm{n} \tag{A.4}$$

$$Bird\ scaring_i = \beta_0 + \sum_{j=1}^{45} \beta_j X_{ji} + \varepsilon_i,\ i = 1,\ \ldots,\mathrm{n} \tag{A.5}$$

$$Harvesting\ \&\ threshing_i = \beta_0 + \sum_{j=1}^{50} \beta_j X_{ji} + \varepsilon_i,\ i = 1,\ \ldots,\mathrm{n} \tag{A.6}$$

where *Yield*$_i$, *Field cleaning & bund making*$_i$, *Land preparation & transplanting*$_i$, *Weeding*$_i$, *Bird scaring*$_i$, and *Harvesting* & *threshing*$_i$ are the dependent variables; $X_{1i}, X_{2i}, \ldots, X_{50i}$ are the candidate independent variables as numbered in Table 2; $\beta_0, \beta_1, \ldots, \beta_{50}$ are the parameters to be estimated; ε_i is the error term; and n the number of sampled fields.

For Pelebina, regression models took the following forms:

$$Yield_i = \beta_0 + \sum_{j=1}^{41} \beta_j X_{ji} + \varepsilon_i,\ i = 1,\ \ldots,\mathrm{n} \tag{A.7}$$

$$Field\ cleaning\ \&\ land\ preparation_i = \beta_0 + \sum_{j=1}^{10} \beta_j X_{ji} + \beta_{25} X_{25i} + \sum_{j=28}^{34} \beta_j X_{ji} + \varepsilon_i,\ i = 1,\ \ldots,\mathrm{n} \tag{A.8}$$

$$Sowing_i = \beta_0 + \sum_{j=1}^{14} \beta_j X_{ji} + \beta_{25} X_{25i} + \sum_{j=36}^{36} \beta_j X_{ji} + \varepsilon_i,\ i = 1,\ \ldots,\mathrm{n} \tag{A.9}$$

$$Weeding_i = \beta_0 + \sum_{j=1}^{31} \beta_j X_{ji} + \beta_{33} X_{33i} + \sum_{j=36}^{45} \beta_j X_{ji} + \varepsilon_i,\ i = 1,\ \ldots,\mathrm{n} \tag{A.10}$$

$$Harvesting\ \&\ threshing_i = \beta_0 + \sum_{j=1}^{41} \beta_j X_{ji} + \varepsilon_i,\ i = 1,\ \ldots,\mathrm{n} \tag{A.11}$$

where *Yield*$_i$, *Field cleaning* & *land preparation, Sowing*$_i$, *Weeding*$_i$, and *Harvesting* & *threshing*$_i$ are the dependent variables; $X_{1i}, X_{2i}, \ldots, X_{41i}$ are the candidate independent variables as numbered in Table 2; $\beta_0, \beta_1, \ldots, \beta_{41}$ are the parameters to be estimated; ε_i is the error term; and n the number of sampled fields.

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