Exploring opportunities for diversification of smallholders' rice-based farming systems in the Senegal River Valley

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HIGHLIGHTS

- Farmers in Senegal River Valley outlined their objectives and cropping practices.
- Farmers sought to combine rice cultivation with high-value vegetable cropping.
- Vegetable crops were more profitable than rice, but also more labour demanding.
- Trade-offs existed between profit vs. reduction of labour burden and pollution.
- Farmers' choices were influenced by external drivers of policies and services.

GRAPHICAL ABSTRACT
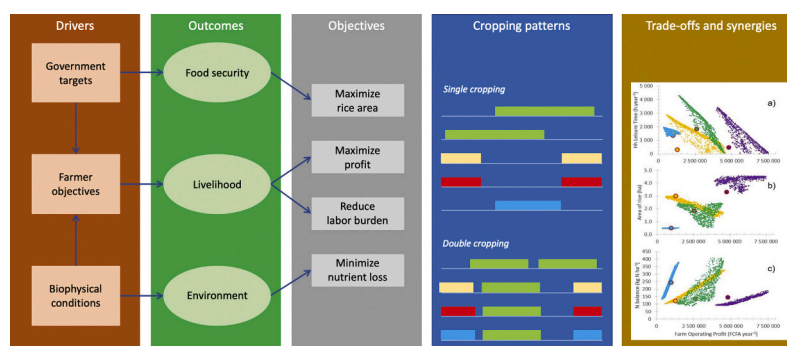
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ABSTRACT

CONTEXT: Policy-based or technological interventions are more likely to be effective if aligned with farmers' objectives, constraints, and decision-making processes.
OBJECTIVE: The objective of this study was to explore trade-offs and synergies of farming systems in response to innovative rice cultivation activities by understanding current farming systems, main drivers impacting farm management and farmers' perspectives on rice intensification. Understanding these interrelations is key in rice production areas, where smallholder farmers largely depend on growing rice to subsist.
METHODS: A rapid system analysis was conducted interviewing 20 farmers in 4 villages along the Senegal River Valley (SRV) to obtain a general view on farm functioning and farmers' perspectives on farming systems. A detailed system analysis with four farmers was subsequently conducted to provide an insight into the underlying processes regulating farm management. A multi-objective optimization model was used to quantitatively

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evaluate and explore farm performances based on four selected indicators representing: rice production, household agricultural profit, household labour and farm nutrient balance.

RESULTS AND CONCLUSIONS: The results of this study showed that government programmes and farmers' Unions were strongly influencing farmers' decision-making in agricultural production. Farmers also reported that although rice was still essential for their livelihoods, there were transitions towards less rice production in the wet season with short duration rice varieties and more vegetable production. Both farmers' interviews and the modelling results suggested that farmers would be unlikely to increase or even maintain the area of rice double cropping, which has been strongly promoted by the Senegalese government. Instead, farmers would rather keep investing in vegetable production.

SIGNIFICANCE: This modelling study shows the consequences of policy-based and technological interventions for farming systems and may inform both policy makers and farmers in situations where objectives are strongly divergent. Hence, modelling outcomes may be used to inspire discussion and innovation in order to align the government priority of ensuring national food security and farmers' objectives and constraints in the SRV.

1. Introduction

Agricultural interventions, whether policies or technological innovations, can become more effective and sustainable if aligned with farmers' objectives, constraints and decision-making processes (Ajayi et al., 2007; Meijer et al., 2014). This alignment is particularly pressing in rice-based agricultural regions where recent food crises, increasing agricultural input costs, climate change and growing water scarcity ask for viable sustainable rice production methods (Djaman et al., 2017; Krupnik et al., 2012a; Seck et al., 2013). A particular example is Senegal, where rice is the staple food for millions of people (Tanaka et al., 2015) but still national rice production has been insufficient to meet consumption needs, which are expected to increase further in the coming decades (Saito et al., 2015b; Seck et al., 2013). As the national population increases and the economic transformation of Senegal keeps evolving (Van den Broeck and Maertens, 2017), the Senegalese government still seeks to increase rice production levels to achieve national rice self-sufficiency, in particular promoting the expansion of the area under irrigated rice cultivation by providing new land and using existing land for double cropping (MAER, 2014). Since rice is produced almost exclusively by smallholder farmers, increasing rice production is crucial to ensure food security while enhancing rural livelihoods (Krupnik et al., 2012b; Tanaka et al., 2015).

Although the Senegal River Valley (SRV) is the major rice production area in the country, where the cereal is only grown in irrigated lowland systems, smallholder farmers still face many challenges to intensify rice production. Despite innovative opportunities and agricultural initiatives towards rice intensification promoted in the region, there is a substantial gap between attainable and actual yields obtained by smallholders in irrigated lowland rice production systems (Tanaka et al., 2015; van Oort et al., 2016). In the wet season, the delay in rice sowing dates has been identified as the major cause of the yield gap, increasing the risk of spikelet sterility caused by low temperatures at the end of the growing season (Tanaka et al., 2015). This delay has been attributed to late credit allocation, limited availability of machinery, suboptimal decisions on timing of irrigation (Krupnik et al., 2012b; Poussin et al., 2006; Poussin et al., 2005; Tanaka et al., 2015), inappropriate fertilizer applications and bird damage (Tanaka et al., 2015). These are persistent issues that highlight the existence of barriers in institutional arrangements and underlying social interactions surrounding smallholder farmers that directly affect their decisions and farm functioning (Diagne et al., 2013; Poussin et al., 2005; Soullier and Moustier, 2018; Tanaka et al., 2015). Consequently, from 2003 to 2016, the rice cultivation period shifted from wet to dry season, and farmers often prefer short duration rice varieties over medium duration varieties because the yield gain of a medium duration variety is insufficient to offset the extra cultivation costs (Busetto et al., 2019; van Oort et al., 2016). Concurrently, cultivation of vegetables, such as onion and tomato, during the cool dry season has been widely adopted in the valley due to their profitability (Tanaka et al., 2015). Some farmers even give priority to vegetable cultivation over timely sowing of rice (Krupnik et al., 2012b; van Oort

et al., 2016). The opportunities to diversify farm production and increase crop profitability are important criteria that guide farmers' decisions (Ellis, 2000; van Oort et al., 2016).

Previous studies in the SRV have mostly focused on constraints and opportunities for rice production with little to no attention for growing other crops, livestock husbandry or understanding decision-making at the farm and household levels (Diagne et al., 2013; Haefele et al., 2002a; Krupnik et al., 2012b; Poussin et al., 2006; Poussin et al., 2005; Tanaka et al., 2015; van Oort et al., 2016). Multi-objective optimizations using computational models are well suited to explore trade-offs and synergies within farming systems in response to multiple innovative farming goals and options (Groot et al., 2012) across diverse smallholder regions (Cortez-Arriola et al., 2014; Estrada-Carmona et al., 2020; Flores-Sanchez et al., 2011; Naudin et al., 2015; Naudin et al., 2012; Paul et al., 2015). On the other hand, multi-objective studies have been conducted in the SRV to assess irrigation scheme performances but such studies at farm-system level are lacking (García-Bolaños et al., 2011; van Oort et al., 2016). The objective of this study was to analyse whether farmers are faced with conflicting objectives on farm and that what extent their room to manoeuvre is limited or expanded by availability of on- and off-farm resources (including services) and policy drivers. Therefore, we explored trade-offs and synergies among socio-economic and environmental farm performance indicators as affected by innovative rice cultivation activities on the basis of a characterization of current farming systems, and we analysed the main drivers impacting farm management and the farmers' perspectives in rice intensification in the SRV. To achieve this, farmers' interviews were conducted and options for reconfiguration of cropping and farming systems were generated with a Pareto-based multi-dimensional optimization. This allowed us to explore the opportunity spaces for farm innovation, which were related to the socio-institutional room to manoeuvre.

2. Methods

2.1. Study area

This study was conducted in two districts of the SRV region of Saint-Louis, Senegal (Fig. 1). Diama, in the west, is a municipality of Ndiaye district in the department of Dagana. The district is representative of the delta of the SRV (Tanaka et al., 2015), and Fanaye is a municipality of Thillé Boubacar which is a district in the department of Podor and is representative of the middle valley of the SRV (van Oort et al., 2016). The main vegetation of this region has been classified as woody steppe dominated by species of the genera *Acacia* and *Commiphora* (Keay, 1959). The climate is referred to as a Sahelian type, with three differentiated seasons: humid and hot (locally called the Wet Season, WS, about 200 mm rainfall) from July to October, dry and cool (Cool Dry Season, CDS) from November to February, dry and hot (Hot Dry Season, HDS) from March to June (Haefele et al., 2002b). In Diama, temperatures range from 11 °C to 44 °C (De Vries et al., 2011) and main soil type is Orthithionic Gleysol, with high salinity due to marine salt deposits in

the subsoil, allowing rice production while limiting vegetable cropping (Haefele et al., 2004; Haefele et al., 2002b). In Fanaye, temperatures range from 8 °C to 46 °C (De Vries et al., 2011), while the main soil type is Eutric Vertisol with a low or absent natural soil salinity, allowing rice-vegetable farming systems (Haefele et al., 2004, Haefele et al., 2002b). Most irrigation schemes have been developed on heavy clay and silty clay soils (Tanaka et al., 2015).

2.2. Farm selection

Two villages were selected in each district: Pont-Gendarme and Boundoum-Barrage in Diama, and Ndierba and Fanaye-Diéri in Fanaye. These were contrasting villages that included part of the SRV diversity in terms of cropping systems, landscapes, and soil type. In each selected village, five farmers were randomly selected and interviewed for the rapid system analysis. Subsequently, one farmer was selected per village to conduct a detailed analysis at farm level. The small number of farms allowed to describe farm functioning in detail, but no statistical analyses were conducted because of the small number of interviewed farmers and their diversity in terms of location, household head age and level of education, household size, income sources, farm area, cultivation choices, type of financing and rice self-sufficiency.

2.3. Farming system characterization

This study followed a two-step analysis (c.f., Flores-Sanchez et al., 2011). A rapid analysis to obtain both a general view on major drivers influencing farm management, and an overall description of farm functioning and the farmers' situation, objectives, and perspectives. Based on the first step, a more detailed system analysis was conducted to provide an insight in agronomic and socio-economic indicators at field and farm level, and in the underlying processes regulating farm management.

2.3.1. Rapid system analysis

In this step, 20 farmers were interviewed in November 2017. All interviews were conducted by the first author (Brosseau) and a translator who translated from Wolof to French. Interviews had both a structural and semi-structural component. The structural component comprised questions on: (1) household structure and situation; and (2) farming system functioning. The semi-structured component included questions on: (3) perceived problems and key assets; (4) socio-economic

environment and farmers' opinions; and (5) farmers' objectives (see Table S1 in Supplementary Material). This rapid survey was complemented with transect walks with farmers and technicians to observe variations in landscape and soil type, and to obtain an insight on access to infrastructure for transport and communication. Secondary data was also used to complement and corroborate the main findings of the farmers' interviews. The farmers' objectives noted during interviews were selected as indicators to measure farm performances in the subsequent step of detailed system analysis.

2.3.2. Detailed system analysis

From the initial group of twenty farmers, one per village was selected to participate in the detailed system analysis. Criteria to select these farmers were their location, ability to speak French to avoid translation bias, and farm specificity (e.g. farm size, self-financing capacity, cropping system). All interviews were conducted by the first author (Brosseau). Structured interviews were conducted in December 2017 about four main components: (1) household labour management; (2) cropping systems and management; (3) livestock production system and management; and (4) farm economics (see Table S2 in Supplementary Material). Farmers' fields were visited, and visual soil assessments were conducted to characterize soil quality (Shepherd, 2000).

2.4. Farm modelling and multi-objective optimization

Based on the detailed farmers' survey, the FarmDESIGN model was calibrated to quantitatively evaluate the performances of the selected farms (Groot et al., 2012). The model quantifies farm production, nutrient flows and cycles and economic profits. We used the initial typical farms information to generate alternative farm configurations that could optimize conservation and production. Inputs required for the model describe the biophysical environment, socioeconomics (production costs for activities and labour), type and crop products (agronomic inputs and outputs), herd composition and products (production costs and outputs), manure types and degradation rates, external sources of mineral nutrients (through animal food or fertilizers) and physical assets. A static farm balance model calculates a large range of indicators pertaining to nutrient and organic matter flows and balances, herd feed consumption and energy and protein balance, the manure balance, labour balance and economic results. The model can be freely downloaded from https://fse.models.gitlab.io/COMPASS/FarmDESIGN/.

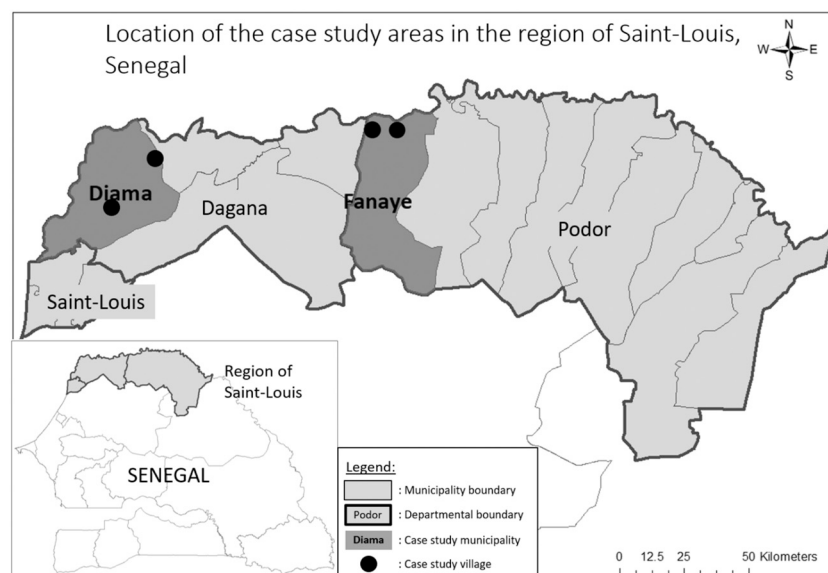The model uses an evolutionary algorithm to generate alternative

Fig. 1. Location of the study areas on the map of the region of Saint-Louis, Senegal.

configurations of agricultural production systems by adjusting land-use areas and inputs (crops, animals, manures, fertilizers, herbicides), and evaluating the responses of selected indicators. The aim of a multi-objective optimization is to create alternative farm configurations with respect to a selected set of farm parameters and objectives. It employs a Pareto-based Differential Evolution algorithm (Groot et al., 2012; Groot et al., 2010), which allows to explore the trade-offs between productive, socio-economic, and environmental performance indicators that are formulated as objectives. Four objectives were defined based on interviews with farmers and expert knowledge:

(1) maximize area of rice,
(2) maximize farm operating profit,
(3) maximize farmer leisure time by reducing the labour burden, and.
(4) minimize N balance to avoid nutrient losses.

Maximizing rice area could contribute to meeting the goals of the Senegalese government towards national rice self-sufficiency, and of smallholder farmers towards household rice self-sufficiency (MAER, 2014). In the optimization, the performance for the various objectives is adjusted through generating alternative farm configurations that involve reconfiguration of production activities pertaining to crop and livestock husbandry typical for the selected farm systems (see Tables S3 and S4 in Supplementary Material).

2.4.1. Production activities: cropping systems and livestock

Annual cropping patterns describing the use of fields involved either single cropping (one crop per field) or successions of two crops with at least one rice cultivation per year. To create a succession a rice crop grown in hot dry season (HDS) would be combined with rice or vegetable crops in either the CDS or WS seasons. Five single crops and four successions were considered in this study (Table 1). If a crop was not grown by a farmer, estimated values for requirements, costs and productivity were calculated based on information collected from other farmers.

To parameterise the model, yields of rice, tomato, okra and onion were asked from interviews and converted to productivity expressed in kg per hectare. With farmers renting assigned land in irrigation schemes developed by the government, farmers knew their exact crop area from official documents. They also knew most of their production quite accurately because all tomatoes were sold, and for rice local millers were paid on a product basis. Paddy rice was either sold or self-consumed.

Table 1
Cropping patterns observed on farms and used in the multi-objective modelling of rice-based farming systems in the Senegal River Valley. WS: wet season, HDS: hot dry season, CDS: cool dry season.

	1st crop	Initial month	Final month	2nd crop	Initial month	Final month
Single crops	Rice WS	Jul/Aug	Nov/Dec			
	Rice HDS	Feb/Mar	Jun/Jul			
	Onion CDS	Oct/Nov	Mar/Apr			
	Tomato CDS	Oct/Nov	Mar/Apr			
	Okra WS	Jun-Aug	Oct/Nov			
Successions	Rice HDS	Feb/Mar	Jun/Jul	Rice WS	Jul/Aug	Nov/Dec
	Rice HDS	Feb/Mar	Jun/Jul	Onion CDS	Oct/Nov	Mar/Apr
	Rice HDS	Feb/Mar	Jun/Jul	Tomato CDS	Oct/Nov	Mar/Apr
	Rice HDS	Feb/Mar	Jun/Jul	Okra WS	Jun-Aug	Oct/Nov

Rice bran and husk from the paddy rice saved for self-consumption were fed to animals. The whole broken rice was self-consumed. In the model a constraint was set allowing the household level rice self-sufficiency to increase, but not to decrease compared with the current situation. Tomato, okra, and onion bulbs were the only vegetable crop products, and were assumed to be totally exported from the farms.

Animal production was also considered in the model. The feed evaluation system was based on animal dry matter intake capacity, and requirements of metabolizable energy (ME), crude protein (CP) and fibrous material for ruminants. The feed balance was calculated for the whole year without distinction between seasons, since no major differences in feeding strategies were observed during dry and rainy seasons. Animals were either located in an open yard or were grazing off-farm. Animal physical features were based on Tourrand (2000). Animal ME and CP requirements were calculated on the basis of needs for body maintenance, growth and production (e.g. meat production) and were derived from Šebek and Gosselink (2006). Meat products were assumed to be sold.

2.4.2. Labour management

Most interviewed farmers expressed the desire and ambition to free up time to participate in family and community events. Therefore, the maximization of household leisure time (Ditzler et al., 2019) was included as objective. At the farm level, labour requirements were calculated as the sum of crop labour, animal labour, and farm maintenance labour. Labour should be provided by the household or hired labour. FarmDESIGN distinguished regular and casual labour (Groot et al., 2012). Regular labour referred to skilled family members working on-farm all year around and hired skilled labour, who could be either temporarily or permanently employed in the farm. Regular labour was needed for weeding, fertilizers, and pesticides applications, sowing, irrigation, and other soil preparation work. Regular labour was also required for animal husbandry (e.g. feeding, medical care), herd management (e.g. keeping), and farm maintenance (Groot et al., 2012). Casual labour was provided by family members occasionally helping in the fields (e.g. women, children) and by temporally hired unskilled workers. Casual labour was needed during labour peaks, such as vegetable transplanting and harvests. Grass collection for the livestock also required casual labour. Regular labour had a higher cost than casual labour. Contract work was not accounted in any labour but quantified as a financial cost (Groot et al., 2012).

2.4.3. Farm economics

Economic performance was expressed through farm operating profit. Profit maximization tended to enhance smallholders' household economic prosperity. It was calculated as the difference between the gross margins of crops and animals and the costs of manures, crop protection products, farm equipment, and hired regular and casual labour (Groot et al., 2012). Crop gross margin was affected by crop products fresh yields, price, cultivated area, cultivation costs, and contract work costs. Cultivation costs were the sum of seed costs, irrigation costs, and other costs (e.g. union fees, assurance, etc.). Bank fees and interests were included for farmers with access to credit. For rice, contract work costs were the sum of soil preparation, harvest and post-harvest operations, and transportation costs. For vegetables, only soil preparation costs were accounted in contract work costs (and transportation costs for onion). Harvest costs were included in labour costs and transportation was free for tomato and okra. Fertilizers and pesticides were subsidised up to 50% of their price. Farm equipment referred to all equipment owned by farmers (e.g. motor pump, scooter, cart, hand spray).

2.4.4. Nitrogen balance

Environmental performance was expressed through the farm nitrogen (N) balance (kg ha^{-1}), which reflects nitrogen losses in the environment based on farm-level inputs and outputs. N inputs comprised crop and animal product imports for the household, fertilizer imports,

symbiotic and non-symbiotic fixation, and deposition. N outputs comprised crop and animal product exports and manure exports. A nitrogen balance larger than zero implied a surplus supply of nitrogen that could be lost in the environment.

3. Results

3.1. Rapid system analysis

3.1.1. Main drivers influencing farmers' decisions

Farmers reported various drivers influencing their options and decisions on agricultural activities (Table 2). Farmers perceived that rice intensification was driven by political and financial incentives (e.g. credits and subsidies), and supported by agronomic research and assistance (e.g. with the SAED: Société d'Aménagement et d'Exploitation des terres du Delta et des vallées du fleuve Sénégal et de la Falémé), but could be hampered by low involvement of the government (i.e. lack of investments). Compared to rice, certainty about product prices and accessible funding mechanisms were seen as crucial drivers for increasing vegetable cultivation. However, the integration of vegetable production in the farm was largely limited by the decisions made at Farmers Union level (e.g. farm machinery management, credit distribution) and the defective organisation of the supply chain. The farmers stated that the low production levels of crops and post-harvest losses originated primarily from lack of well-functioning machinery, storage facilities (especially for vegetables), poor infrastructure and insufficient tillage and field preparation techniques. Farmers also explained the ongoing shift of rice cultivation from WS to HDS due to biophysical and environmental constraints (see Section 3.1.2).

3.1.2. Farm functioning and farmers' perspectives

Interviewed farmers reported earning a low income that hardly covered the household expenses throughout the year. They also relied on bank credits to purchase inputs for rice and tomato production (e.g. seeds, fertilizers, pesticides, irrigation costs), and soil preparation costs (only for tillage, while ploughing and levelling were self-financed).

Farmers also mentioned that rice was mainly grown for household self-consumption but still a significant part of the production had to be sold to reimburse cultivation costs and cover household expenses. In other words, rice production levels defined whether farmers could pay their credits while ensuring household food security. Farmers preferred to use short duration rice varieties such as Sahel 108 to mitigate biophysical risks that could jeopardize successful crop harvest (e.g. early rains at the end of the HDS, early cold at the end of the WS), and/or to alleviate the negative impact of delayed sowing. Most farmers used certified seeds due to their overall quality. Farmers reported transitioning from growing rice in WS to HDS because of the restoration of irrigation systems by the mid 1990's, higher yields, and avoiding WS limitations including cold weather, difficult field access because of the rain, and pest and bird pressure on rice production.

Vegetables were a popular alternative to the low-profit rice production. Vegetable production enabled farmers to increase their total income and to spread that income throughout the year, ensuring household food security. Main vegetables included onion (*Allium cepa*) and tomato (*Solanum lycopersicum*), but also okra (*Abelmoschus esculentus*), watermelon (*Citrullus lanatus*), and aubergine (*Solanum melongena*). Most farmers used certified seeds. Tomatoes were generally sold through sale contracts. Onions were sold on local markets, providing a direct income to farmers but lowering onion prices at harvest peak (David-Benz and Seck, 2018). In response, some farmers harvested onions prematurely to be first on the market, while others waited for the price to increase (David-Benz and Seck, 2018). Long-term storage onion varieties were preferred to avoid post-harvest losses.

Farmers listed several considerations for a viable vegetable cultivation in the region. Salinity in the Delta could prohibit vegetable growth, but if salinity was absent, lighter soils could be an advantage for onion

Table 2
Main drivers influencing farmers' options and agricultural activities in the Delta and Middle Valley of the Senegal River Valley. Data: 20 interviews of the rapid system analysis.

Category	Driver	Consequence/ effect on cropping systems	% farmers mentioning the driver
Political	Access to irrigation systems	Intensify rice cultivation in HDS	100%
	Pressure towards rice self-sufficiency	Promote rice double cropping	100%
	Lack of engagement from the government	Slow intensification progress	30%
Economic	Tomatoes sold through pre-harvest sale contracts	Increase household income/ Intensify tomato cultivation	90%
	High-profit livestock production	Financial conflict of interest with crop production	80%
	Onions sold on local markets	Direct income/ Uncertainty of price and sale/Limit onion cultivation	75%
	Low-profit rice production	Low income/ Increase interest for vegetable cultivation	35%
Financial	Subsidies for rice cultivation	Intensify rice cultivation	100%
	Access to bank credit through Farmers' Unions	Intensify rice cultivation	90%
	Farmers' low financial capacity/ No individual credit	High risk on investment/ Reliance on Farmers' Unions/ Limit vegetable cultivation	75%
	High interest rates	No insurance of household food security/Search for alternative income sources	50%
Technical	Agronomic research for rice cultivation	Use of certified seeds/ Intensify rice cultivation	100%
	Lack/ Poor condition of machinery	Yield penalties	80%
	Poor condition of infrastructures	Yield penalties/ Post-harvest losses/ Limit vegetable cultivation	50%
	Lack of storage facilities	Post-harvest losses/ Limit vegetable cultivation	50%
Organisational	Reliance on Farmers' Unions	Limited window for decision-making and planning	60%
	Defective organisation of the supply chain	Limited window to integrate (more) vegetables	30%
Production variability	Higher rice yields in HDS	Shift of rice cultivation period from WS to HDS	85%
	WS limitations for rice cultivation		80%
	Biophysical risks and delays	Use of short duration rice varieties	70%
	Light soil preparation/ Rare levelling/ ploughing	Yield penalties	25%

production compared to the heavy clay soils near Fanaye. Vegetable cultivation was also constrained by farmers' low financial capacity, which explained the relatively small cultivated areas. Proximity to buyers (e.g. agro-industries, merchants) was necessary to ensure the sale

of the harvest while reducing post-harvest losses. Finally, market price fluctuations regulated selling prices and thus crop profitability. Despite farmers' willingness to diversify crop production, growing new crops is risky and self-financed. Farmers mentioned they lacked the necessary technical, financial, and organisational support to integrate (more) vegetables in their cropping systems.

Livestock husbandry represented a central but resource-demanding component for these farmers. Animal production was a growing business but often not considered a major farming activity. Sheep were valuable cultural assets, notably due to the religious context; Islam is the predominant religion in the study area. Goats were sometimes preferred over sheep due to their autonomy but were less valuable. Donkeys and horses provided draught power and transport. Small ruminants and equines were generally raised on-farm, fed with rice residues (e.g. bran and husks) supplemented with concentrates and other vegetation. Cattle were kept and fed outside the village by paid ranchers, and mainly used as financial backup. Farmers employed field keepers to avoid cattle entering in their fields by the end of the HDS where feed and water were scarce (De Mey et al., 2012). Animal manure was rarely collected, occasionally applied on vegetable nurseries.

Off-farm and social activities (e.g. family, community and religious events) were also influencing farmers' decisions on labour allocation. Some farmers had other significant sources of income, occupying a function such as farmers' representative, SAED agent, or water pump station agent.

3.2. Detailed system analysis

3.2.1. Farm descriptions

The four selected farmers presented striking similarities in terms of agricultural limitations and objectives. Main limitations included: lack of machinery (for land preparation and/or harvests) causing delays in sowing and yield losses; limited access to cropland; and high pest and disease pressure (especially birds reducing rice yields). Main objectives comprised: increase of agricultural income, growing interest towards cropping system diversification with more vegetables and livestock production; and decrease of farm workload to find or keep off-farm jobs and participate in family and community events.

However, the four selected farmers combined different cropping and livestock activities, but they focused on a particular crop. They also differed in terms of farming structure and objectives (Table 3). We refer to the four farmers interviewed as: "Mixed-onion farmer", "Specialised rice farmer", "Mixed-tomato farmer" and "Mixed-rice farmer".

The mixed-onion farmer was a young farmer in the Delta region who recently inherited a 0.5 ha farm. The household comprised three members with only one working on-farm, although his neighbours often helped him. His main source of income was onion production with a two years rotation (rice HDS – rice WS – rice HDS – onion/tomato CDS). They were not self-sufficient and had to buy extra rice. He proudly owned 2 to 4 sheep for self-consumption and extra income. In addition to the main

limitations listed above, his agricultural limitations also included high credit interest rate and costs of extra labour.

The specialized-rice farmer owned 1 ha of land to grow rice for the whole year, and he also rented 2 ha in HDS. Out of the seven household members, he was the only working full time on the farm, although his wife also helped for the harvest, threshing and sales, besides raising the children. He also hired a worker almost full time. His main source of income was rice production. Each season, he reimbursed his credit, kept enough rice to feed his household until the next harvest, and sold the remaining part. They raised three sheep for household consumption and kept two zebus. He also guarded the village water pump station during the weekend for extra income. His limitations also included lack of infrastructure to access field and lack of proper rice storage facilities.

The mixed-tomato farmer was proudly a self-financed producer located in the middle valley. His household comprised 25 members. He was the only family member working full time on-farm, but his three brothers also supported him and he also hired external labour. He owned 4.35 ha and each field hosted a specific crop avoiding cropping calendar overlaps. When fields were not used for cropping, they were left in fallow. He grew rice on 2.3 ha in HDS and occasionally used a part of this area to grow rice in WS. In addition, he rented 1 ha extra in HDS to grow rice. In CDS, tomato and onion were grown on 0.5 and 0.75 ha, respectively. Finally, okra was grown on 0.8 ha in WS. His main source of income was tomato production. His household was self-sufficient in rice. They managed around 15 sheep for household consumption and for sales, and 20 zebus as savings. He also owned a thresher which he rented out to nearby farmers in exchange of 10% of their harvest. His limitations also included soil fertility decline, poor maintenance of water channels, and low selling price for rice. He also wished to extend his cropped area.

The mixed-rice farmer was also located in the middle valley. His household comprised 18 members, but only he and his younger brother were working full-time on the farm. The four women also participated in the vegetable harvest and were mostly busy with children. He also hired external labour during the harvesting season. He owned 1.3 ha and rented 1.15 ha. Rice was grown on 1.85 ha in HDS, tomato and onion were respectively grown on 0.35 and 0.14 ha in CDS, and okra was grown on 0.11 ha in WS. That particular season he did not grow rice, leaving these fields in fallow. Still, his main source of income was rice production. After credit reimbursement, most of the rice production was sold to provide an income. As a result, the household could be fed with his own production only up to six months after the harvest. Three sheep and poultry were raised for household consumption and/or extra income, and 4 zebus were kept as savings. His limitations also included difficulty to sell rice and tomato products for a good price.

3.3. Underlying processes of farmers choices

The FarmDESIGN quantitative analysis on the current performance of the four selected farms was divided into two levels: a farming and a

Table 3
Household characteristics of the four case study farms from the Senegal River Valley.

Farmer	Location	Household size		Age of household head	*Education level household head*	Family members working on the farm	Household workforce	Main source of income	Main type of financing	Rice self-sufficiency
		Adult	Child	(year)		#	(h year^{-1})			(months)
Mixed-onion	Pont du Gendarme	2	1	26	University	1	2190	Onion	Credit	1 to 4
Specialized-rice	Boundoum Barrage	2	5	45	Primary	1 (+1)[a]	2080 (+470)[a]	Rice	Credit	8 to 10
Mixed-tomato	Ndierba	20	5	42	University	4	4137	Tomato	Self-financed	10 to 12
Mixed-rice	Fanaye Diéri	8	10	39	Primary	2 (+4)[a]	4380 (+1220)[a]	Rice	Credit	4 to 6

[a] Values between brackets represent household casual labour.

cropping system analysis.

3.3.1. Farming system analysis

The four selected farming systems showed large differences of yields, labour requirements, cultivation costs, and fertilizer use (Table 4). Higher observed onion yields in the Delta could be explained by the lighter soils compared with the middle valley, and better crop management and/or timing of harvest. In addition, the mixed-onion farmer applied large quantities of urea to maximize yields and harvested the bulbs prematurely to benefit from higher market prices. In this way, he avoided overlaps in the cropping calendar between the cultivation of vegetables in CDS and rice in HDS. Variations in labour requirements could be explained by differences in terms of bird control strategy and manual weeding intensity. Rice cultivation costs were higher for the mixed-onion and specialized-rice farmers than for the other farmers due to differences in crop management strategy including soil preparation, type of harvest and threshing. All farmers used the amounts of fertilizers recommended by the SAED on rice (see Table S5 in Supplementary Material), except for the specialized-rice farmer who applied 50 kg ha^{-1} of urea extra. However, rice was the crop with the least economic profit per unit of area.

Rice in HDS produced higher yield than rice in WS resulting in higher margin per hectare. This could explain the ongoing shift of rice cultivation from WS towards the HDS. Manual harvest and threshing were more common than mechanical harvest (with combine harvester). Manual harvest costed 75,000 to 90,000 FCFA/ha in HDS against 50,000 FCFA/ha in WS. While threshing costed 10% of the total amount of rice produced, mechanical harvest (including threshing) costed 18%. Bird control by members of the farmers' household was the most time-consuming activity related to rice cultivation.

Onion and tomato were the most profitable crops. Although tomato seemed to be slightly more profitable than onion with low cultivation costs, it was time-consuming due to (daily) crop monitoring, manual weeding, multiple fertilizers and pesticides applications, and labour peaks at transplanting and harvest. Onion could outperform tomato if grown in appropriate conditions. Onion had the highest cultivation costs due to its costly seeds. Onion was also time-consuming with some labour peaks at transplanting and harvest. Large quantities of fertilizer were applied on both vegetables. Okra yields (and profitability) were very variable according to crop management strategy. Okra had low cultivation costs, but it was very time-consuming due to the demanding harvests. Nevertheless, farmers' estimation of okra production data tended to be less accurate than other crops because multiple harvests were required during the growing season, it was self-financed, and it was sold on informal markets.

3.3.2. Cropping systems analysis

The contribution of the individual cropping systems to the selected four objectives (area under rice production, farm operating profit, farmer leisure time and N balance) are presented in Fig. 2. For example, less N fertilizer was applied on rice than vegetables, and fertilizers with low N content were usually applied on tomato. For onion, N balance differed among farmers depending on their financial capacity and experience with the crop. Large amounts of N fertilizer were applied on okra, resulting in a high N balance.

Single crops were less time consuming than successions (Figs. 2a & 2b). Depending on farmers' management practices, tomato or onion were the two most labour-consuming crops. Rice as single crop potentially allowed for more leisure time than the other cropping patterns. Since labour costs were not accounted in credits, it made sense for a

Table 4

Farm characteristics of the four case study farms. Data based on interviews conducted in December 2017.

Farmer	Crops							Fertilizers			Animals	
	Type	Season	Area	Yield	Cultivation costs	Margin	Labour	Urea	DAP	9–23-30	Type	No
			(ha)	(t FM ha^{-1})	(K FCFA ha^{-1})	(K FCFA ha^{-1})	(h ha^{-1})	(kg ha^{-1})	(kg ha^{-1})	(kg ha^{-1})		#
Mixed-onion	Rice WS	Aug/Sep - Nov/Dec	0.5	5.6	404	348	684	300	100	–	Donkey	1
	Rice HDS	Mar/Apr - Jul/Aug	0.5	8.0	472	642	756	300	100	–	Sheep	3
	Onion CDS	Oct - Feb/Mar	0.3	32.3	545	3487	1416	833	333	–		
	Tomato CDS	Oct – Mar	0.2	37.5	238	1712	883	250	–	850		
	Cultivated area		*0.5*									
Specialized-rice	Rice WS	Jul/Aug - Nov/Dec	1.0	6.8	474	473	580	350	100	–	Donkey	1
	Rice HDS	Feb/Mar - Jun/Jul	3.0	8.0	522	593	580	350	100	–	Sheep	3
											Zebu	2
	Cultivated area		*3.0*								Poultry	3
Mixed-tomato	Rice WS	Aug – Nov/Dec	1.0	6.4	313	578	672	300	100	–	Donkey	2
	Rice HDS	Mar – Jul	3.3	7.3	304	714	468	300	100	–	Horse	1
	Onion CDS	Oct - Mar/Apr	0.75	14.7	505	1335	923	200	–	667	Lamb	5
	Tomato CDS	Oct – Mar	0.5	30.9	230	1403	1293	200	250	650	Sheep	10
	Okra WS	Jun - Aug/Sep	0.8	2.3	211	351	829	750	250	–	Zebu	15
	Cultivated area		*5.35*									
Mixed-rice	Rice HDS	Mar – Jul	1.85	6.3	336	570	450	292	95	–	Horse	1
	Onion CDS	Oct - Mar/Apr	0.14	16.7	540	1549	1229	536	714	–	Lamb	5
	Tomato CDS	Oct – Mar	0.35	38.7	251	1762	1409	214	171	571	Sheep	3
	Okra WS	Jun - Aug/Sep	0.11	7.2	191	1419	3806	1636	455	–	Zebu	4
											Poultry	41
	Cultivated area		*2.45*								Goat	16

Yields are expressed in Fresh Matter (FM). At the time of data-analysis, 16 May 2018, FCFA 1000 = EUR 1.52 = USD = 1.79. (FCFA: Franc Communauté financière d'Afrique ('Financial Community of Africa Franc')).
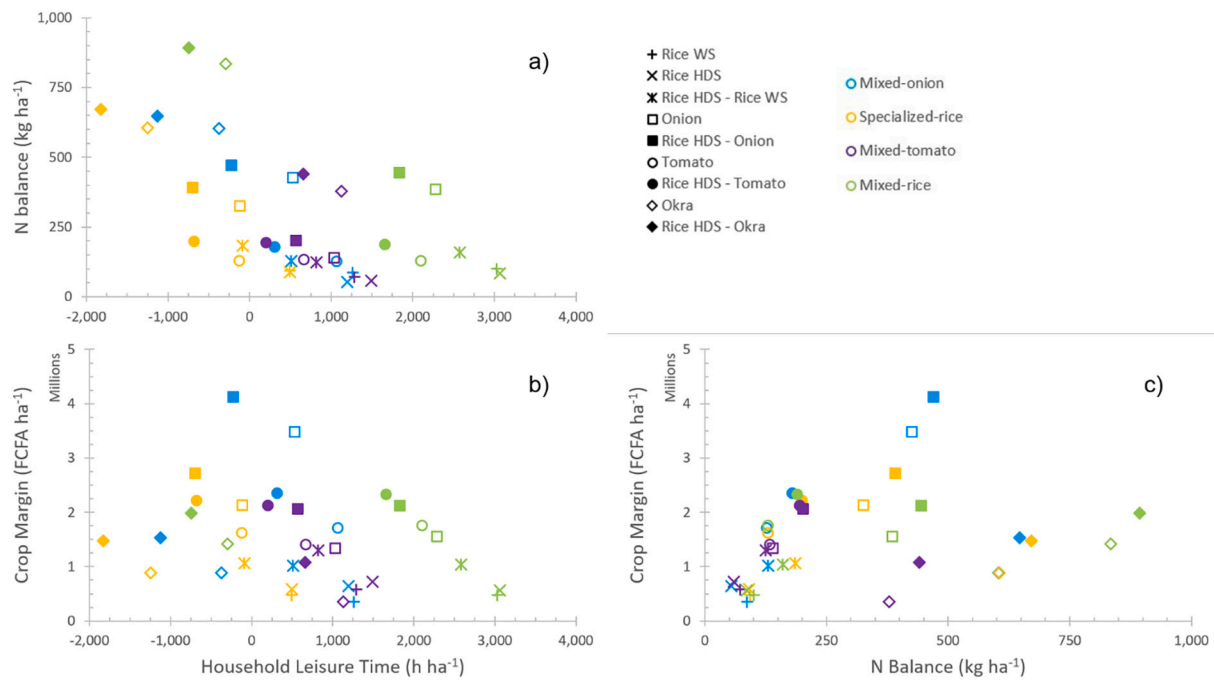
Fig. 2. Analysis of N balance, crop margin, and household leisure time at cropping-system level for the four case study farms: FarmDESIGN outputs before multi-objective optimization. For each cropping system, household leisure time was calculated as the difference between total household available time minus the labour required to grow one hectare of the related crop(s). Negative leisure time occurred for time-intensive crops which required to hire extra labour. Each colour represents a farm, and each marker represents a single crop or a crop succession.

farmer to prioritize the less time-consuming crops and to favour their own labour. Crop successions were always more profitable than single crops. The rice-rice cropping system was still less profitable than a single onion or tomato. Overall, crops ensuring high margins tended to be the most time-consuming (e.g. onion, tomato), and showed the highest N balance (e.g. onion, okra). Crops showing low N balances tended to be

the less profitable and less labour intensive (e.g. rice).

3.4. Multi-objective optimization

The FarmDESIGN quantitative exploration was divided into an assessment of trade-offs and an analysis of potential alternative farm
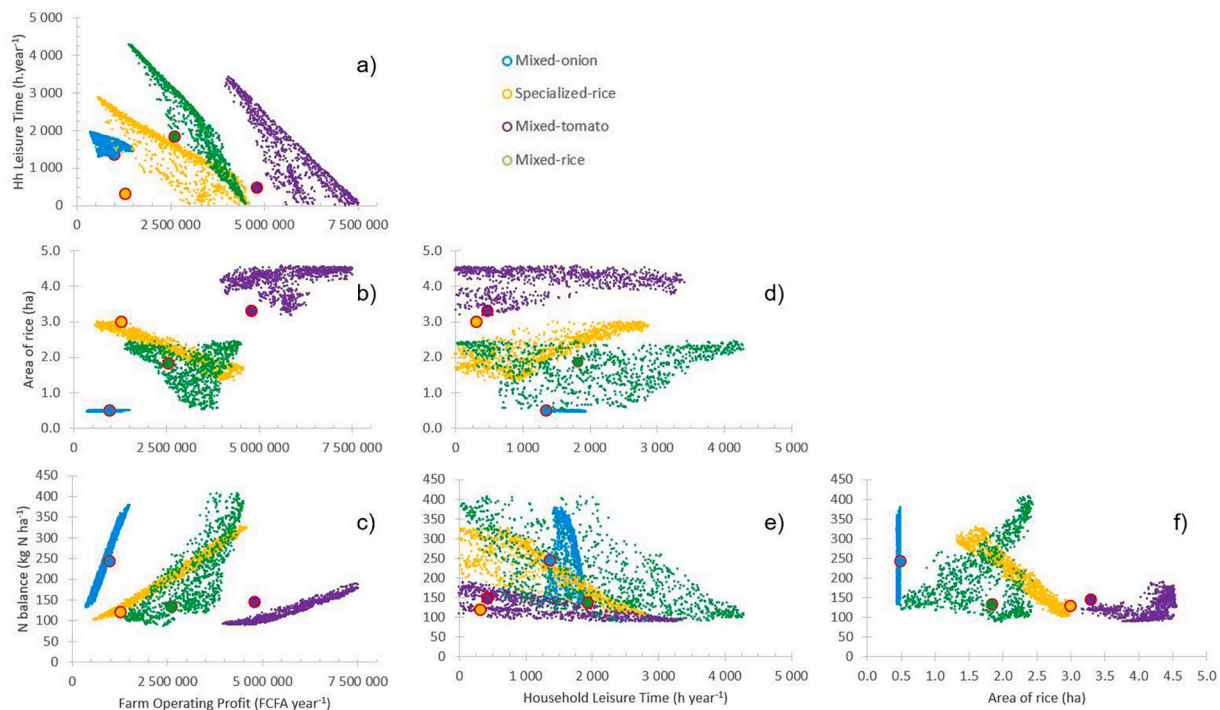

Fig. 3. Trade-off between the four objectives (rice area, profit, leisure time and N balance) for four farmers ("Mixed-onion farmer", "Specialized-rice farmer", "Mixed-tomato farmer", and "Mixed-rice farmer"). Point clouds show Pareto frontiers after multi-objective optimization. Each colour represents a farm. Each dot represents a new farming system configuration. The large symbols represent the current performance for the four farming systems.

configurations.

3.4.1. Trade-offs among farm performance indicators

Fig. 3 shows the opportunity spaces for farm adjustments relative to the initial situation for each of the farms. These results from the multi-objective optimization, wherein farm management variables are adjusted and the associated changes in farm performance indicators assessed and optimized. Multiple potential trade-offs between the four selected objectives were observed (Fig. 3). For all farmers, household leisure time would decrease when farm profit increased (Fig. 3a). The mixed-tomato farmer had the largest farm area and could potentially reach the highest farm operating profit. The specialized-rice farmer could increase his operating profit by shifting rice production to vegetable and rice-vegetable production. The larger the farm, the higher the potential room for increasing farm profit (Fig. 3b). But the higher the profit, the higher the N balance (Fig. 3c). This high N balance was particularly marked for the mixed-onion farmer, who had already used relatively high levels of fertilizers in his small vegetable production. On the other hand, there was no clear relation between area under rice production and household leisure time (Fig. 3d).

Similarly, for the Pareto-optimal solutions, the N balance tended to decrease while household leisure time increased for all farmers (Fig. 3e). The relation between N balance and area under rice was mixed (Fig. 3f). For the specialized-rice farmer, a larger area under rice meant lower N balance because the single rice or rice-rice production had low N losses. For the mixed-rice and the mixed-tomato farmer, a larger area under rice could decrease N balance through the integration of a single rice instead of a single vegetable, or could increase N balance through the adoption of rice-vegetable successions.

Compared to the initial farm configurations (large symbols, Fig. 3), the optimization results for the mixed-onion farmer showed that the options for improvements in the various indicators were quite limited. This reflected that he was already combining his crops and rotations in a very efficient small farm leaving little room for improvement. The optimization results for the other farms showed that performances could be enhanced. In the next section, we describe the changes needed to achieve these potential better performances in detail.

3.4.2. Exploration of alternative farm configurations

Maximizing or minimizing the 4 objectives lead to different farm configurations for each of the 4 farmers.

For the mixed-onion farmer, the ideal cropping system included: rice-tomato, rice-onion, rice-rice, and rice in HDS (see Fig. S1 in the Supplementary Material). Rice-onion generated more profit than any other crop, but also higher N losses. Rice-tomato could be favoured over rice-onion to lower N balance while providing relatively high margins. The expansion of rice in HDS and rice-rice would increase leisure time and reduce N losses but decrease farm profit.

For both the specialized-rice farmer and the mixed-tomato farmer, the ideal cropping system was: onion, rice-onion, and rice in HDS (see Figs. S2 and S3). Rice in HDS generated the most leisure time and the least N losses but also the least farm profit. The expansion of onion and rice-onion would provide the highest profit, but also the highest N losses, and the least leisure time.

For the mixed-tomato farmer, the single onion could be grown too to allow lower N balance than rice-onion while providing high returns. Rice-tomato had higher margins, but the extra labour needed when compared with rice-onion was proportionally greater than the corresponding extra returns.

For the mixed-rice farmer, the optimal cropping system was: rice in HDS, tomato, and rice-onion (see Fig. S4). Rice in HDS generated the most leisure time and the least N losses but also the least farm profit, whereas rice-onion generated the highest profit, but also the highest N losses, and the least leisure time. Tomato could be favoured over rice-onion to lower N balance while providing high returns.

3.4.3. Similarities and differences between farmers

For each of the 4 farmers and for each of the 4 objectives, key features of the farming system (allocation of land and labour, farm expenses) would change compared with the current situation, but the explorations showed curious similarities and differences (Table 5).

The exploration of alternative farm configurations produced some similar results among the selected farmers in terms of crop profitability, nutrient losses, and rice area. First, rice-vegetable and/or vegetable (with onion as main source of income) generated higher profit than rice either single or double cropping. By prioritizing these crops, both total farm labour and expenses would increase due to the additional household on-farm labour (except for the mixed-onion farmer), hired labour and its associated costs (except for the mixed-rice farmer), and cultivation costs. Second, rice in HDS caused the least N losses and household workload. By specializing in this crop, total farm labour would decrease due to the decrease of household farm labour. Although cultivation costs would decrease, total farm expenses could increase or decrease depending on the additional hired labour and its associated costs. Finally, rice in HDS and/or rice-vegetables maximized rice area. By prioritizing these crops, total farm labour would increase (except for the mixed-onion and specialized-rice farmers), and total farm expenses would rise (except for the mixed-onion) due to the additional cultivation costs and/or hired labour and its associated costs.

These explorations also showed major differences among farmers in terms of household on-farm labour, hired labour and total expenses. First, when maximizing profit, household on-farm labour requirements increased for most farmers but decreased for the mixed-onion farmer. This farmer could replace household labour by external labour because the additional hired labour costs were outperformed by onion cultivation. Second, when maximizing profit, hired labour increased for most farmers but decreased for the mixed-rice farmer, who could replace external labour by household labour. Third, when minimizing household on-farm labour and N losses, total expenses decreased for the mixed-tomato and mixed-onion farmers but increased for the specialized-rice and mixed-rice farmers. For the latter two farmers, the reductions of crop cultivation costs were outperformed by the increase of labour costs. Fourth, when maximizing rice area, total farm labour increased for the mixed-tomato and mixed-rice farmers but stayed stable for the mixed-onion and specialized-rice farmers, who already prioritized rice area in their current cropping system. Finally, when maximizing rice area, total farm expenses increased for most farmers, but decreased for the mixed-onion farmer, who could deal with the workload without additional hired labour.

4. Discussion

4.1. Drivers of farmers' decisions

Farmers' perceptions on the major factors influencing agricultural decisions reflect their political and institutional context. Support for rice expansion and intensification relates to the ongoing effort of the Senegalese government to achieve national rice self-sufficiency (MAER, 2014) by investing in agricultural finance and agronomic research for rice, implementation of credits and subsidies for fertilizers, pesticides, and machinery (Demont and Rizzotto, 2012; MAER, 2014).

These efforts led to an accelerated expansion of the area under rice cultivation (Busetto et al., 2019; Saito et al., 2015b). These national efforts shaped farmers' options and agricultural practices through complex institutional arrangements. Farmers were often gathered in farmers groups and unions (Bonnefond, 1982). Union representatives, who often collaborated with the government, took key decisions (Bonnefond, 1982) including: buying farm machinery and arranged their usage schedule among farmers (Gay and Dancette, 1995; MAER, 2014), and being intermediaries between farmers and banks to obtain credits to purchase essential crop inputs (Gay and Dancette, 1995). Hence, farmers' options in agricultural investment largely depended on these

Table 5

Optimum farm configurations according to the favoured objective. Data based on farming system optimization using FarmDESIGN. Differences in total farm area, compared to the current configuration, result from the optimization.

Farmer	Farm configuration	Land distribution			Labour distribution		Farm expenses	Main income source
		Rice	Vegetable	Rice-vegetable	Household	Hired		
		(ha)	(ha)	(ha)	(h/year)	(h/year)	(M FCFA/year)	
Mixed-onion	Current	0.25	–	0.25	848	246	674	Onion
	(Max) Farm operational profit	0.05	–	0.45	752	485	759	Onion
	(Min) Nitrogen balance	0.35	–	0.10	352	493	643	Rice
	(Max) Household leisure time	0.34	–	0.11	239	594	663	Rice
	(Max) Area of rice	0.25	–	0.25	842	251	672	Onion
Specialized-rice	Current	3.00	–	–	2246	1440	2888	Rice
	(Max) Farm operational profit	0.48	1.32	1.19	2387	3097	3928	Onion
	(Min) Nitrogen balance	2.87	0.01	0.01	–	3673	3239	Rice
	(Max) Household leisure time	2.87	0.01	0.01	–	3673	3239	Rice
	(Max) Area of rice	3.00	–	–	2098	1560	2939	Rice
Mixed-tomato	Current	3.30	2.05	–	2683	2741	3749	Tomato
	(Max) Farm operational profit	1.03	0.81	3.47	3121	4261	5504	Onion
	(Min) Nitrogen balance	3.94	1.20	0.03	653	3845	3574	Rice
	(Max) Household leisure time	4.07	0.83	0.04	–	4345	3998	Rice
	(Max) Area of rice	3.09	0.78	1.47	1365	4281	4782	Onion
Mixed-rice	Current	1.85	0.60	–	3771	234	1420	Rice
	(Max) Farm operational profit	0.49	0.11	1.85	5544	57	2330	Onion
	(Min) Nitrogen balance	1.97	0.39	0.01	3174	384	1482	Rice
	(Max) Household leisure time	2.18	0.05	0.03	1311	1886	1977	Rice
	(Max) Area of rice	1.83	0.01	0.61	2147	1881	2408	Rice

institutional and financial service arrangements.

An important factor not explicitly addressed in the modelling study is risk management by farmers. Farmers acknowledged that crop cultivation under irrigation and the integration of (more) vegetables in rice-based cropping systems could be affected by risks related to labour availability and affordability, technical know-how for new crops, marketing opportunities, and financial risks when credits would be granted. Some of these uncertainties can be captured in risk indicators based on yield and price variability used in farm modelling (e.g., Mandryk et al., 2014; Kozicka et al., 2020); this would require multi-year datasets that were not available for our case study. Risks related to off-farm uncertainties could be addressed by multi-objective optimization under uncertainty (Choi et al., 2008; Crespo et al., 2010), but difficulties in estimation of the degree of uncertainty that farmers face due to different drivers would complicate interpretation.

4.2. Farming systems description

The results of the quick system analysis captured major agricultural drivers and trends of smallholder rice production in Senegal. Specifically, these results showed that a more efficient rice cultivation, and especially rice double cropping, highly depended on the Unions' capacity to timely provide machinery to the farmers. Since farmers mostly relied on the few available machines of the Unions, some farmers could benefit from the availability of Union machinery while others suffered yield penalties caused by delayed planting. This aligns with similar studies, where farmers also mentioned machinery unavailability as one of the main causes of delayed sowing (Diagne et al., 2013; Tanaka et al., 2015). In fact, agricultural machinery covered less than 50% of farmers' needs in the SRV because a considerable number of agricultural machines were broken down or unsuitable to the local biophysical conditions (MAER, 2014). These results support the claim that rice production intensification in the SRV still requires more adequate mechanization (Diagne et al., 2013; MAER, 2014).

The quick system analysis confirmed farmers' preferences and benefits of growing rice in HDS. Previous studies also observed a similar shift of rice cultivation from the WS to the HDS season because of more favourable weather conditions leading to higher yields (Busetto et al., 2019; Djaman et al., 2017; Saito et al., 2015b), and lower disease pressure (Djaman et al., 2017; Tanaka et al., 2015).

Finally, this study also documented why and how the interviewed farmers were diversifying crop production by growing more profitable options such as vegetables and investing on livestock production. This supports previous findings showing how despite various constraints, farmers diversified cropping systems enabling them to increase the production potential of lowland systems in the SRV (Bado et al., 2018; Gay and Dancette, 1995; Haefele et al., 2013), rising and diversifying their income, spreading risk, and ensuring food security (Bonnefond, 1982; Gay and Dancette, 1995; PNUE, 2005).

4.3. Farming system exploration

Modelling outcomes suggested three focal points for policy based and technological interventions: improving soil management, intensifying and diversifying sustainable cropping systems, and adjusting funding mechanisms.

4.3.1. Better soil management and conservation

The nutrient balance of the current farm management and configuration showed high potential N and P soil losses, and soil K mining in the four studied farms. Significant surpluses on the N balance were obtained, particularly for vegetables where farmers often bought more fertilizers than recommended hoping for high yields. For rice, interviewed farmers applied the amount of N and P fertilizers (156 kg N ha^{-1}, 46 kg P ha^{-1}) recommended by the SAED (2012), which exceeded the recommended doses (120 kg N ha^{-1}, 26 kg P ha^{-1}, 50 kg K ha^{-1}) reported in literature (Bado et al., 2010; Haefele et al., 2002b), resulting in N and P soil losses calculated in the model. This pattern has also been described by Haefele et al. (2013) who showed that fertilizer N losses in similar rice systems ranged from 50% to 82% of the applied amount. These results confirmed that instead of depleting N and P, current (intensive) irrigated rice and vegetable cultivation are generating large surpluses (Haefele et al., 2004). The potential K mining obtained in the nutrient balance can strongly reduce rice production, although Haefele et al. (2004) suggested that the high soil K reserves in the SRV region could buffer large negative K balances for decades. These results support the need for decision support tools at a site or production system level to increase fertilizer nutrient efficiency and rice productivity while reducing potential negative environmental impacts (Saito et al., 2019; Tsujimoto et al., 2019). This could specifically include concepts of site-specific nutrient management, integrated crop management, system of rice intensification, or nutrient management decision-support for rice in

the SRV (Bado et al., 2018; Haefele et al., 2013; Krupnik et al., 2012b; Krupnik et al., 2012a; Saito et al., 2015a).

4.3.2. Beyond rice production

Both farmers' interviews and the modelling results suggested that under the current conditions farmers would be unlikely to increase or even maintain the area of rice double cropping, which has been strongly promoted by the Senegalese government (MAER, 2014). Besides the mixed-onion farmer who was already growing rice twice a year in half of his small farm, none of our multi-objective optimization alternatives showed an increase of the area of rice double cropping. Alternative simulations were run maximizing specifically the area of rice double cropping, but the model prioritized the land allocation to grow vegetables which performed better in terms of household income and labour than rice-rice. This prioritization was related to the functioning of the model which used non-weighing Pareto-based methods to optimize the selected objectives (Groot et al., 2012). Since rice double cropping performed lower in terms of farm profit and household labour (also N balance for the mixed-rice farmer), it was expected that its area would not largely increase. Additional explorations could be made to test if using another indicator (i.e. household rice self-sufficiency) would have a different outcome in terms of rice production. Nevertheless, these results also suggested that governmental programmes should also consider farmers' objectives and limitations to better align their goal to achieve national food security (Ajayi et al., 2007; Meijer et al., 2014).

4.3.3. Support for sustainable vegetable production

In contrast to rice cultivation, both farmers' interviews and the modelling results showed that under the current conditions farmers would be likely to keep investing in vegetable production. However, there was hardly any technical or financial support for sustainable vegetables cultivation, as it was the case for tomato, for which the interviewed farmers did not know recommendations on sowing densities. Similarly, Huat and David-Benz (2000) described that tomato farming practices in the SRV were highly variable compared to the recommended practices. For onion production, David-Benz and Seck (2018) confirmed this observation by describing a very low quality of local onions despite the increasing production levels. van Oort et al. (2016) also reported this asymmetry of support between rice and vegetable production in the SRV, while other authors have also listed the main limitations of vegetable production: lack of technical, financial and institutional support, and poor dissemination of agronomic information (David-Benz and Seck, 2018; Gay and Dancette, 1995; MAER, 2014). All these results supported the call for strong agronomic research and support assistance for farmers in the vegetable sector (MAER, 2014).

4.4. Aligning government and farmers objectives

The present study clearly showed that there is some conflict between farmers' objectives and government policies towards national rice self-sufficiency. Vegetable crops were more profitable than rice, but also more labour demanding, having higher N losses to the environment, and self-financed. Moreover, vegetables grown in semi-dry irrigated environments suffer little from diseases which thrive in humid environments, so the SRV seems very well suited for vegetable cropping (although issues of salinity do occur) (Barbiéro et al., 2004; Mishra et al., 2014; van Oort, 2018; Whipps and Budge, 2000). Therefore, profit-oriented farmers were more likely to extend the area of vegetables rather than rice, to hire labourers during labour peaks, and to discharge large quantities of nutrients in the surroundings. In contrast, farmers with low investment capacity may favour rice to ensure household food security.

To date, most of the government's ambition to reach rice self-sufficiency in Senegal has been achieved through expansion of the area under irrigated rice cultivation by providing new land and using existing land for two instead of one rice crop per year (MAER, 2014).

Rather than trying to force options that are not farmers' priority, it might be more effective to align policy-based or technological interventions with farmers' constraints and preferences. It is necessary that policy makers account for the ongoing trend of increasing vegetable cultivation and livestock production while seeking for other options to increase rice production that benefit both farmers' livelihoods and the national food security. For example, policies could aim at promoting rice varieties best adapted to the hot dry season and farming practices aiming at increasing rice yields in this particular season.

The results also indicate a need for more policy support for vegetable cropping (David-Benz and Seck, 2018; Huat and David-Benz, 2000; MAER, 2014; van Oort et al., 2016). Several issues became clear that deserve more attention from policy making, including need for tools to improve nutrient and water management, soil conservation, limit chemical input use (i.e. fertilizers and pesticides), better transport, infrastructure and post-harvest facilities, and dissemination of agricultural information and market fluctuations (David-Benz and Seck, 2018; Krupnik et al., 2012b; Krupnik et al., 2012b).

4.5. Methodological considerations

In this study, some key assumptions had to be made in terms of farmer selection and modelling analyses. Firstly, relatively few farmers were selected to account for the potential variability in farming systems in the study area, but they were not representative of the entire farming population and therefore these results should not be extrapolated to the entire SRV. Secondly, assumptions on farm characteristics and farmers' decisions had to be made in the modelling calibration. For example, soil characteristics were not included in the exploration for optimal cropping systems, which could influence crop selection (e.g. no vegetables in soils with high salinity). Additionally, FarmDESIGN did not simulate dynamic response of crop yield to soil nutrient availability or other management operations (Groot et al., 2012). If necessary, this limitation could be overcome by linking FarmDESIGN with dynamic crop simulation models such as APSIM and CropSyst, or technical coefficient generators such as TechnoGIN (Keating et al., 2003; Ponsioen et al., 2006; Stöckle et al., 2003). Another modelling assumption was that double cropping had a very narrow time span between the two crops, overlapping in some growing periods. In contrast, some farmers preferred to either harvest vegetables prematurely or sow rice later on (David-Benz and Seck, 2018; van Oort et al., 2016), reducing vegetable quality or inducing large rice yield gaps (David-Benz and Seck, 2018; Tanaka et al., 2015). A cropping calendar construction (CCC) model could be used to investigate new cropping options before running FarmDESIGN (Groot et al., 2012; van Oort et al., 2016). Finally, potential changes in livestock husbandry were not included in the modelling, despite the fact that sheep farming had become a profitable business, and that integrated crop-livestock can be a more sustainable farming system (Lemaire et al., 2019). Future studies could also include animal and fodder production to explore farming system options in the SRV.

5. Conclusions

The livelihoods of smallholder farmers in the SRV depended on the combination of diverse farm and off-farm activities, of which rice production was the most important one. The two main objectives that were shared by the interviewed farmers were to ensure household food security and to increase farm profitability. Farmers also considered labour as an essential resource that needed to be carefully divided among farm activities, family, community and religious events, and off-farm job opportunities. Farmers reported how their decision-making was often limited by biophysical, financial, organisational, and technical constraints as well as market price fluctuations. Under the current circumstances, vegetable cropping generated more profit than rice production although it was self-financed, inefficient, and required more workforce.

Both farmers' interviews and the modelling results suggested that farmers would be unlikely to increase or even maintain the area of rice double cropping, which has been strongly promoted by the Senegalese government. Instead, farmers would rather keep investing in vegetable and livestock production. To align government priority of ensuring national food security and farmers' objectives and constraints in the SRV, policy-based and technological interventions may focus on an integral agronomic research and support assistance for farmers in the vegetable and livestock sector, while exploring with farmers complementary alternative to ensure national food security.

Declaration of Competing Interest

No conflict of interest.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2021.103211.

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