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Intensification of an irrigated rice system in Senegal: Crop rotations, climate risks, sowing dates and varietal adaptation options

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ABSTRACT

Feeding the future world population requires increased crop production. Here, we investigate the intensification option of increasing production by increasing cropping intensity and choice of varieties with different crop duration. We developed a model to generate, compare and visualise opportunities for single/double/triple cropping systems consisting of irrigated rice and optionally a vegetable. The model was applied in a case study in the Senegal River valley. Results showed that with appropriate choice of sowing dates, severe cold sterility in rice can be avoided, also in rice–rice crop rotations. At optimal sowing dates, simulated total long term average potential yields of single, double and triple cropping yields were 10.3, 19.0 and 18.9 t/ha respectively (total of 1,2 and 3 yields). With a hypothetical completely cold tolerant variety, yields could increase to 11.2, 20.2 and 20.9 respectively. Simulated Triple crop yields are hardly any higher than those of a double crop with two medium duration varieties. Delay in sowing due to late availability of resources (machinery, irrigation water allocation within a scheme, credits for pump fuel) is a known problem in the region. Therefore we also simulated how much delay was possible (width of the sowing windows) whilst still allowing for double cropping. We found enough delay was possible to allow for a rice–rice or a rice-vegetable crop. A rice-rice-vegetable triple cropping system would only be possible without delays and with a very short duration vegetable of 2 months. Most promising options to increase production are through shifting the sowing date to facilitate double cropping, adoption of medium duration varieties and breeding for cold tolerant varieties.

1. Introduction

Global demand for agricultural crop production is expected to roughly double by 2050 (Kastner et al., 2012). The challenge of meeting demands of a growing population can be met by increasing yields on existing land, bringing new land into cultivation or imports from other parts of the world (Van Oort et al., 2015b). The options for bringing new land into cultivation may be limited, as often the suitable lands are already in use (Hall and Richards, 2013; Young, 1999). Reliance on imports can be a solution only when pressure on land and water is less in exporting countries. Although the relation between high import dependency and poverty, price fluctuations and food riots or political instability is complex and dependent on many factors (Natalini et al., 2015), a number of studies suggest that such relations do exist (Sternberg, 2012; Weinberg and Bakker, 2015; Wischnath and Buhaug, 2014). To increase production, most researchers advocate increasing yields on existing land, referred to as intensification. The two main intensification options are: (1) closing the yield gap and (2) increasing the number of days in the year in which the land is used for crop cultivation (Cassman et al., 2003; Foley et al., 2011; Garnett et al., 2013; Pretty et al., 2011; Ramankutty and Rhemtulla, 2012; van Ittersum et al., 2013). Breeding can contribute to this through the development

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of high yielding and stress tolerant varieties (Evenson and Gollin, 2003) and varieties with "optimal" phenology.

In irrigated areas an important question for breeders is whether they should select for shorter duration varieties which would enable growing two or even three crops per year, or alternatively breed for medium/long duration varieties that yield more per individual crop but possibly restrict options for growing two or three crops per year. The same question is relevant for farmers, who decide on what varieties to include in their crop rotations. The answer to this question on short versus medium duration varieties depends on how many days exist within the year with a favourable climate. At high latitude locations only one crop may be possible per year because of low temperatures and low radiation levels in the colder half of the year. There, extending the length of the growing season of a single crop may have more prospects. Or, when a yield plateau is reached at a certain crop duration, an intensification option is growing a vegetable crop or cover crop in autumn, after harvesting a winter cereal in summer. Moving closer to the equator the number of favourable days increases and so the choice between single/double/triple cereal cropping becomes more pertinent; all three should be considered. Clearly, when researching options for intensification we should take into consideration the climate. We should not only look at intensification options for individual crops but also implications for the viability of crop rotations.

Ideotyping has in the past (Dingkuhn et al., 1991) and more recently again (Rötter et al., 2015) been proposed as a method in which crop growth models can be used to identify the optimal combination of morphological and/or physiological traits in a crop, for optimizing performance in a particular biophysical environment and crop management package. Ideotyping to date has remained very much focussed on individual crops. There have been no ideotyping studies in which trait optimisation has been conducted in the crop rotation context. A few models have been proposed for comparing crop rotations (Dogliotti et al., 2003; Huong et al., 2014) but with these it is difficult to simulate in detail climatic risks and effects of varietal differences. With other models such as APSIM and DSSAT crop rotations can be simulated and climatic risks quantified (Jones et al., 2003; Keating et al., 2003) (Holzworth et al., 2014; Jones et al., 2003), but these models do not allow for easily generating and comparing very large numbers of cropping calendar options and varietal traits. What is missing is a model that allows for generating and comparing large numbers of crop rotation × ideotype options whilst at the same time also simulating climatic risks of crops in these rotations.

In this study, we analyse the scope for intensification at a site in Senegal, near the town of Fanaye, representing the middle valley of the Senegal River in the Sahel. The study area has three seasons: a cold dry season (Nov.–Feb.), a hot dry season (Mar.–Jun.) and a warm wet season (Jul.–Oct). The area is sparsely populated and ample irrigation water is available. Important crops are rice, tomato and onion. These crops are grown for home consumption and for the market. Scope for rice intensification in this study area has been extensively studied in the 1990s as reported in the book by (Miezan et al., 1997). Reflecting on the various contributions to this book, (Matlon, 1997), noted a number of knowledge gaps including the need to look more broadly for other options and not only at rice–rice double cropping. The second gap in the research reported in the book by (Miezan et al., 1997) as noted by Matlon (1997) was the lack of adequate consideration of the farmers' perspective.

Since these critical comments by (Matlon, 1997), there have been more studies on the farmers' perspective. Causes of yield gaps were identified as poor supply of labour, unavailability of machinery, lack of credits to purchase inputs (fertiliser, herbicides, certified seeds), inappropriate timing of fertiliser application and poor timing of allocation of irrigation water within the irrigation scheme as important constraints (Haefele et al., 2002; Krupnik et al., 2012; Tanaka et al., 2015). The original analysis of scope for rice–rice double cropping by Dingkuhn (1995) was later followed up by (Poussin et al., 2006, 2005) who considered labour organisation of different operations in rice cropping within an irrigation scheme. Three challenges that have not been taken up are (1) broader systematic exploration of options for intensification including vegetables, (2) link to ideotyping where not only sowing dates of the 2–3 crops in the rotation are varied, but also crop traits such as crop duration and tolerance to cold-induced sterility and (3) analysis of flexibility: is double or triple cropping also possible if sowing of crops is delayed, for instance due to lack of machinery, seeds or water allocation? If so, how much delay is possible?

The only previous study which did look in a systematic manner into options for intensification was by Dingkuhn (1995). Dingkuhn compared single and double rice cropping options. Specifically for our study area, he concluded that double cropping is "possible but subject to severe time constraints". These time constraints were caused by the difficulty of fitting two crops in one year, a required period between the two crops and the need to avoid periods with heat and cold sterility. It is interesting therefore in such a site to investigate if twenty years later the situation has changed and opportunities for double cropping have increased. Since the 1990s, a number of developments have taken place on the ground that call for new cropping calendar research: (1) double cropping has expanded at this site especially in the last 5 years with government promoting rice production (Diagne et al., 2013) and (2) several additional short duration varieties have been introduced. At the time of Dingkuhn (1995), medium variety Jaya was most popular, with a duration for direct seeded rice ranging from 118 to 192 days depending on sowing date (Sié et al., 1998). Since then, short duration variety Sahel108 with a duration from sowing to maturity of 96–155 days (direct seeded rice) has become a popular variety among farmers (Tanaka et al., 2015). Also science has advanced since the 1990s. Recently new research on phenology (van Oort et al. (2011)) and sterility (Julia and Dingkuhn (2012, 2013)) has been incorporated into the ORYZA2000 crop growth model (Van Oort et al. (2015a)) which allows for simulating not only sterility risk but also yield. One of the findings of this latest study was that good yields can still be obtained at moderate levels of sterility (say <30%); this is possible only if enough spikelets and biomass have been formed at flowering. For a source limited crop, a limited reduction in the sink size (=fertilised spikelets) has no effect on yield. This finding suggests that the previous selection of "safe" sowing windows by Dingkuhn (1995), based on simulated sterility was perhaps too strict.

Farmers face many constraints and research should consider their objectives and constraints. It is impossible to include all farmers' perspectives here. And it can also be interesting to move beyond the current situation, to systematically explore what would be possible if farmers' constraints would be alleviated. We address all the above mentioned issues in the following way in this paper. Firstly, we include in a rudimentary way a vegetable in our analysis of possible crop rotations. Secondly, we consider two different farmers' objectives: yield maximisation and maximisation of yield per unit time. Thirdly, we investigate not only optimal sowing dates but also sowing windows. These sowing windows tell us how much temporal flexibility there is in the cropping calendar. We developed a model for constructing cropping calendars, which was linked to the ORYZA2000 model for rice. For the vegetable crop, we simply blocked a part of the year. With this part of the year blocked, we used ORYZA2000 to simulate potential yields as a function of sowing dates of the rice crop(s).

The biggest steps in intensification can be made by increasing the number of crops grown per year (cropping intensity). Smaller steps in intensification can be made by growing medium instead of short duration varieties. Both intensifications are considered in this