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Unravelling the causes of variability in crop yields and treatment responses for better tailoring of options for sustainable intensification in southern Mali

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A B S T R A C T

Options that contribute to sustainable intensification offer an avenue to improve crop yields and farmers' livelihoods. However, insufficient knowledge on the performance of various options in the context of smallholder farm systems impedes local adaptation and adoption. Therefore, together with farmers in southern Mali we tested a range of options for sustainable intensification including intensification of cereal (maize and sorghum) and legume (groundnut, soyabean and cowpea) sole crops and cereal-legume intercropping during three years on on-farm trials. There was huge variability among fields in crop yields of unamended control plots: maize yielded from 0.20 to 5.24 t ha^{-1}, sorghum from 0 to 3.53 t ha^{-1}, groundnut from 0.10 to 1.16 t ha^{-1}, soyabean from 0 to 2.48 t ha^{-1} and cowpea from 0 to 1.02 t ha^{-1}. This variability was partly explained by (i) soil type and water holding capacity, (ii) previous crop, its management and the nutrient carry-over and (iii) inter-annual weather variability. Farmers recognized three soil types: gravelly soils, sandy soils and black soils. Yields were very poor on gravelly soils and two to three times greater (depending on the crop) on black soils. Yields were also poor at the end of the typical crop rotation, i.e., after sorghum and millet, and 1.3–1.7 times greater (depending on the crop) after the fertilized crops maize and cotton. We diagnosed a number of cases of technology failure where no improvement in yield was observed with hybrid varieties of maize and sorghum and rhizobial inoculation of soyabean. Regardless of soil type and previous crop, mineral fertilizer improved yields by 34–126% depending on the crop. Targeting options to a given soil type and/or place in the rotation enhanced their agronomic performance: (i) the biomass production of the cowpea fodder variety was doubled on black soils compared with gravelly soils, (ii) the additive maize/cowpea intercropping option after cotton or maize resulted in an average overall LER of 1.47, no maize grain penalty, and 1.38 t ha^{-1} more cowpea fodder production compared with sole maize. Soil type and position in the rotation, two indicators easy to assess by farmers and extension workers, allowed the identification of specific niches for enhanced agronomic performance of legume sole cropping and/or intercropping.

1. Introduction

Farmers in Southern Mali grow cotton for income generation, cereals for food self-sufficiency and keep livestock for a wide variety of reasons, including draught power, manure, meat, milk and buffer against risk (Falconnier et al., 2015b; Kanté, 2001). Due to market uncertainty and increasing land pressure, agriculture needs to adapt to the decline in cotton profitability (Coulibaly et al., 2015) and reduced availability of fodder for livestock (Breman, 1992; De Ridder et al., 2004; Leloup, 1994). Sustainable intensification offers an avenue to improve farmers' livelihood and is based on three principles (Vanlauwe et al., 2014): (i) production of more food, feed and/or fuel from the same amount of land, labour and/or capital (ii) maintenance of healthy soils and reduction of negative environmental impacts and (iii) resilience to climate shocks and stresses. Two strategies are often mentioned to contribute to

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sustainable intensification. Firstly, Integrated Soil Fertility Management (ISFM), which assembles locally-adapted practices based on the use of improved crop varieties together with combined fertilizer, organic resource management and other soil amendments (e.g., lime) can enhance crop productivity and contribute to maintenance of healthy soils (Vanlauwe et al., 2015). Secondly, crop diversification through cereal-legume rotations or cereal-legume intercropping can reduce yield variability and improve overall farm productivity (Franke et al., 2014; Snapp et al., 2010). The options we tested all fall under one of these two strategies and can thus contribute to sustainable intensification. Although many studies report increased crop productivity in trials with such practices (Kaizzi et al., 2012; Otinga et al., 2013; Pitan and Odebiyi, 2001; Rurinda et al., 2013), local adaptation to diverse smallholder farm systems and conditions has received less attention. Indeed smallholder farming in SSA exhibits wide variability in household resource endowment and in soil fertility (Giller et al., 2011), resulting in huge ranges in yields within the same agro-ecological zone or even within individual farms (Baudron et al., 2012; Ronner et al., 2015; Zingore et al., 2007). Large numbers of on-farm trials are required to unravel the relationships between the farmers' socio-ecological context and the performance of interventions. For example, 63 on-farm trials in semi-arid Zimbabwe showed that no tillage and insufficient mulch favoured crusting of sandy soils, thereby reducing water infiltration and decreasing cotton yields compared with ploughing (Baudron et al., 2012). Ojiem et al. (2007) used 27 trials to demonstrate that soil fertility status impacted the contribution of forage and grain legumes species to soil fertility improvement through biological nitrogen fixation.

In southern Mali, past research has identified a range of options for sustainable intensification including (i) maize-legume intercropping in which leguminous fodder is produced without penalizing maize grain yields (Bengaly, 1998), (ii) hybrid sorghum varieties that yield more than local landraces under fertilized conditions (Rattunde et al., 2013) and (iii) improved varieties of cowpea that allow grain production whilst also providing good quality fodder (Dugje et al., 2009). Yet little is known of the agronomic performance of these different options across the wide array of soil types, rotations and seasons that are encountered in the prevailing crop-livestock farming system. Hence, for better advice to farmers, information is needed on the niches where these options perform best. Such information needs to be easy to use and to assess by local farmers and farm advisors. Furthermore, numerous papers report on specific crop (maize, cowpea, soyabean) experiments, but very few studies encompass the complete set of farmers' crops in multi-year on-farm trials. However, such experimental setup is required to produce relevant information for farmer decision-making, which takes into account the management of the entire cropping system and the risk and trade-offs associated with certain decisions. Together with local farmers we therefore experimented with five crops (maize, sorghum, soyabean, cowpea and groundnut), two intercrops (maize/cowpea and sorghum/cowpea) and a whole range of options including hybrid varieties, combined additions of mineral fertilizer and manure, rhizobial inoculation of soyabean, improved varieties of cowpea and groundnut and intercropping patterns. After a series of participatory rural appraisals to understand and define farmers' constraints and opportunities, experiments to test these options were co-designed by researchers and farmers. Farmers tested the options in their fields over three consecutive seasons. The on-farm trials formed part of a larger participatory farming system re-design process (Falconnier et al., 2015a), which for example accommodated for annual adjustments in the set of trials.

In this paper we (i) assess the agronomic performance of a range of intensification options across a range of farmers' fields; (ii) explore the causes of the variability in farmers' yields and in the effects of the options on productivity; and (iii) define simple rules on where and when the intensification options perform best. In doing this, we explored the hypotheses that (i) soil type and characteristics, previous crop and its management, and seasonal rainfall variability explain the variability in farmers' yields and treatment effects; and (ii) better matching of intensification options with the environment (previous crop, soil type) increases the likelihood of increased crop yield.

2. Material and methods

2.1. Study area

The study area is located in Koutiala district in the cotton zone of Southern Mali, between the 800 mm and 1000 mm isohyets. The region is characterised by a uni-modal rainy season that starts in May and ends in October, with total rainfall fluctuating from 600 to 1400 mm. The population is relatively dense compared with the rest of the country, reaching 70 people km^{-2} (Soumaré et al., 2008). Farmers distinguish three main soil types with a vernacular name related to landscape position and texture (Blanchard, 2010; Kanté, 2001): "gravelly soils" at higher elevation, "sandy soils" in the middle and "black soils" in the lowest part of the catena. All soils are classified as Lixisols (FAO, 2006). Dominant crops are cotton, maize, sorghum, millet and groundnut. Farmers rely largely on cotton, maize and livestock for income and on maize, sorghum and millet as staple foods. The most common rotations are: (i) cotton and maize rotations, (ii) cotton and maize followed by sorghum and/or millet and (iii) sorghum and millet rotations. In all cases, organic and mineral fertilizers are applied solely on cotton and maize (Blanchard, 2010). The major livestock are cattle, sheep and goats. On average, farmers own 10 Tropical Livestock Units (TLU) of 250 kg with a wide range from 0 to 54 TLU (Falconnier et al., 2015b). Besides milk and meat, animals provide draught power for timely farming operations to cope with the erratic distribution of rainfall, while application of livestock manure in the fields has positive feedbacks on crop productivity (Kanté, 2001).

2.2. On-farm trials

We carried out on-farm trials during three consecutive cropping seasons (2012–2014). Participating farmers originated from nine neighbouring villages of the Koutiala district: M'Peresso, Nitabougouro, Nampossela, Finkoloni, Try, Koumbri, Kaniko and Kani. A total of 372 trials were planted by 12, 111 and 132 farmers in 2012, 2013 and 2014 respectively. Trials were not repeated in the same location. The first season was an inception year with only 12 participating farmers, while in the second and third season the network of participating farmers expanded. Seven different trials on options with sole crops and intercrops were co-designed by researchers and farmers to explore the opportunities discussed in participatory rural appraisals. Treatments included: (i) a maize and (ii) a sorghum hybrid and local variety, with and without combined mineral fertilizer and manure application (iii) soyabean without any amendments, with rhizobial inoculation and/or P fertilizer with manure, (iv) a grain variety and a fodder variety of cowpea with and without P fertilizer (v) an improved and a local groundnut variety, (vi) the cowpea grain and fodder varieties intercropped with maize or (vii) sorghum, with an additive and a substitutive intercropping pattern. Farmers indicated which improved varieties for maize and sorghum they were interested in for testing. As farmers were eager to test groundnut options, the groundnut trial was added in the third year.

Each sole crop trial was comprised of four plots of 6 × 8 m each: a control plot, two plots to test the effect of the first and second factor