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Identification of the main constraints for upland rice crop in direct-seeding mulch-based cropping systems under the high altitude conditions of the Madagascar highlands

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Abstract

In the Madagascar highlands, increasing demand for rice combined with increasing land pressure in the lowlands led to the development of upland rice. To tackle the sustainability problem of upland crop production systems, Centre de coopération internationale en recherche agronomique pour le développement (CIRAD, an international governmental organization) and Tafa (an NGO) have developed direct-seeding mulch-based cropping systems (DMC), which not only decrease soil erosion but also increase soil fertility. To understand the mechanisms underlying the performance of upland rice DMC, an experiment was set up in 2003. The yield components of upland rice were studied under high-altitudinal conditions during six rainy seasons from 2003/04 to 2008/09. Treatments compared were two soil management techniques: conventional tillage with removal of most of the crop residues, associated with plowing ('plowing'); and a no-till system with direct seeding under mulch made of crop residues ('no-till'). The rice yields obtained were often better from plowing than from no-till, except in the last season. This difference was due to blast disease, which was significantly lower in no-till with low fertilization (best percentage of full grains and better weight of grain). The differences in yields obtained between no-till and plowing were mainly explained by problems of crop installation. The plant densities and plant growth were lower in no-till. This was particularly linked to slower root development in no-till. Overall, the biomass production of rotations of rice seemed too low in the highland conditions (low temperature) for the no-till system to be successful in the early years (low soil protection and slower restructuring of the soil).

Introduction

In the Madagascar highlands (region of Vakinankaratra), increasing demand for rice combined with increasing land pressure in the lowland areas led to development of upland rice on the hills. In this fragile ecosystem, use of conventional tillage is not sustainable, partly because of erosion compromising both upland rice by washing away of upper soil horizon, and the lowland rice below by silting.

The direct-seeding mulch-based cropping systems (DMC), which have proved their worth (and undergone rapid expansion) in places such as South America, the USA, Canada and Asia (Derpsch and Friedrich, 2009) in providing permanent protection of soil, have opened up new possibilities of sustainability for the upland rice systems.

NGO Tafa and Centre de coopération internationale en recherche agronomique pour le développement (CIRAD) have experimented with DMC for 15 years in Madagascar, particularly in the region of Vakinankaratra, to limit physical and chemical erosion of soil on hills (Michellon *et al.*, 2003). In DMC, the cover plants (live or dead) and the mulches of crop residues fulfill various roles: reducing erosion (Scopel *et al.*, 2005), reducing runoff (Findeling *et al.*, 2003), reducing losses from direct evaporation (Scopel *et al.*, 2005) and levels rates of soil C and N by forming a surface horizon with high humus content with greater biological activity (Azontonde, 2000).

An experimental study was set up by the Unité de recherche en partenariat 'Systèmes de culture et riziculture durables' (URP-Scrid) in 2003 at Andranomanelatra in the highlands of Madagascar, to compare different tillage systems in the cold conditions of this region and to assess the potential performance of systems based on DMC and upland rice.

Materials and methods

The experiment was conducted at Andranomanelatra (19°47' S, 47°06' E, 1642 m elevation) in the Vakinankaratra region of the Madagascar highlands. The climate is tropical altitude with summer rainfall. According to the *World Reference Base* (IUSS Working Group WRB, 2006), the soil is classified as Ferralsol (Razafimbelo *et al.*, 2006). Plots were arranged in a randomized block design with four replications. Treatments compared were two soil management techniques: conventional tillage with removal of most of the crop residues, associated with plowing (treatment 'plowing': PLO); and a no-tillage system with direct seeding under mulch

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made of crop residues (treatment 'no-tillage': DMC). Six to eight rice seeds (cultivar FOFIFA 161) were sown manually in hills at a spacing of 20×20 cm (25 hills per m^2). The rotation was rice (*Oryza sativa*) the first year, followed by common bean (*Phaseolus vulgaris*) the second year. Common bean was associated with (since 2007) or without (before 2007) maize (*Zea mays*). After the harvest of common bean, oat (*Avena sativa*) was sown. Each season, the two crops of the rotation, i.e. rice and common bean, were present in the experimentation. Two fertilizations were used: 'Fu' composed of cattle manure at 5 t/ha, and 'FM' composed of NPK (11% N, 22% P_2O_5 , 16% K_2O) at 300 kg/ha, dolomite ($CaMg(CO_3)_2$) at 500 kg/ha, and cattle manure at 5 t/ha and two top-dressings with urea (46% N) at 50 kg/ha applied after sowing. Weeds were controlled by hand weeding, and insect protection was provided (by imidacloprid [2.5 g Gaucho per kg seed]) at sowing.

Results

Climatic conditions

Climatic conditions (monthly mean temperature and rainfall) of the six seasons are presented (Fig. 1a and 1b). Temperature restricts upland rice during the crop cycle, in terms of sum of accumulated temperature and crop duration. The average temperatures (daily average over 24 hours) at 1640 m altitude, reach 17°C in October, at the beginning of the sowing period, and are barely above 18°C during the reproductive stage. The amplitude of thermal day/night is high (10–16°). The minimum temperature is below 12°C (below 10°C in October) during

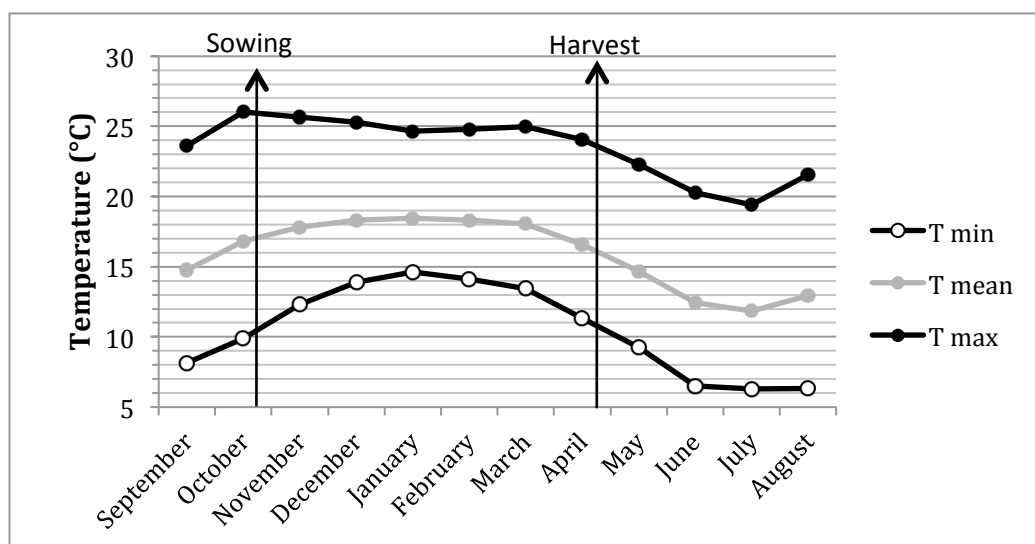


Figure 1a. Maximum (T max), mean (T mean) and minimum (T min) monthly temperatures in six seasons

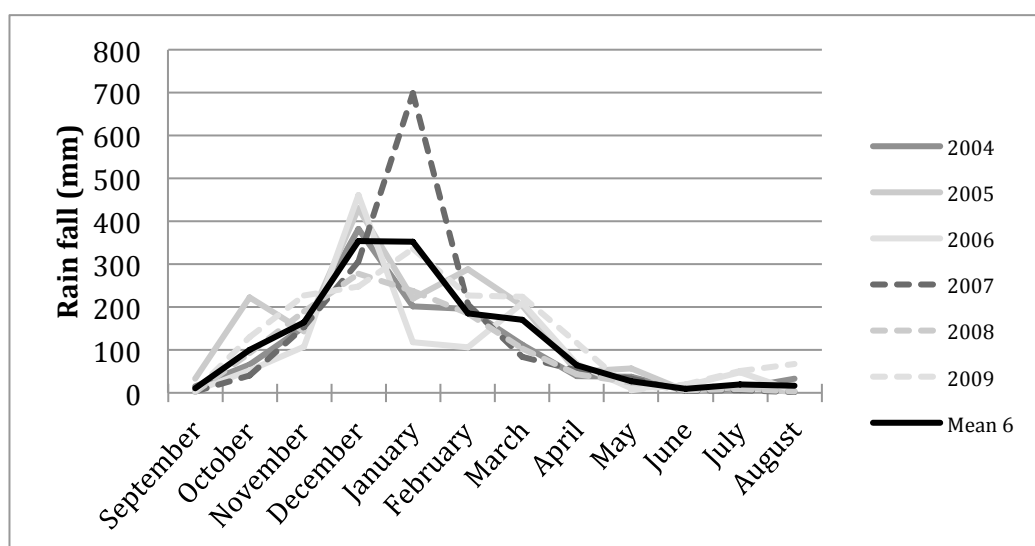


Figure 1b. Monthly precipitation during the crop cycle in six seasons

the early vegetative stages and about 14°C during the reproductive stage and grain filling. Minimum temperature again falls below 12°C in April, inducing low level of grain filling for those varieties that have longer cycle.

The average annual rainfall over the 6 years was 1475 mm. December and January are the rainy months. Despite some variability in rainfall patterns (periods of drought or very rainy periods during cyclones like in January 2007), the rainfall is sufficient to ensure adequate water supply for the rainfed crop during the cycle (October–April). However, the often erratic beginning of the rainy season may prevent early establishment of the crop or at least make it difficult in some years. Hailstorms occur frequently in the highlands and can cause severe losses at harvest time.

Runoff and erosion

The advantage of DMC is its effects on reducing erosion and runoff. Data on runoff, in this experiment and other experiments with different slopes, showed much less runoff in DMC than in plowing, and a control of erosion — erosion can be very high with plowing. But, in these highlands conditions (rainfall, low temperature, radiation and evapotranspiration) upland crops can't improve water infiltration into the soil in DMC (Muller *et al.*, 2005). However, the small gains in water consumption in DMC may be useful in a dry year, especially when rooting is limited, or if the crop system is heavily fertilized, and also for the production of catch crops (Muller *et al.* 2005).

Evolution of upland rice yield

Figure 2 shows the evolution of upland rice yields for the six seasons, according to soil management and fertilization; the average yields varied from 0.7 to 4.7 t/ha. The rice yields obtained were consistently better in plowing than in DMC (especially in the 2005/06 season), except for the last season. The effect of fertilization on yield was slight, but the effect of mineral fertilization (FM) on yield was greater in plowing in the first year. The analysis of yield elaboration is done through yield components developed successively during the rice cycle (in reference of studies on wheat by Meynard *et al.*, 1988; Latiri-Souki *et al.*, 1992).¹

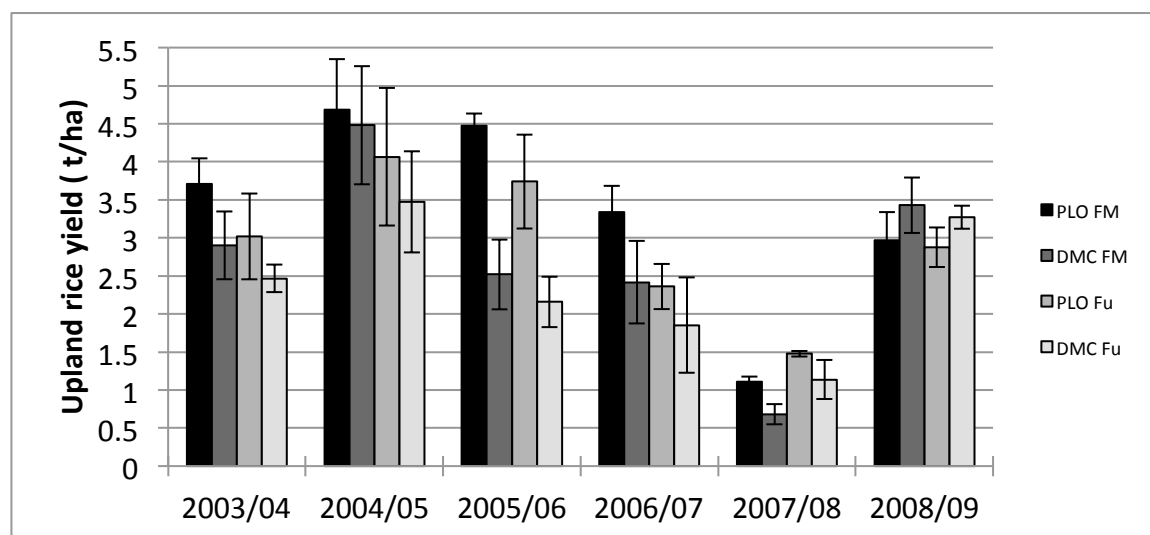


Figure 2. Upland rice yields by soil management (PLO, plowing; DMC, no till) and fertilization (Fu, cattle manure; FM, cattle manure and fertilizer) in six seasons

The yield variations were largely explained by variations in the number of full grains produced per square meter (Fig. 3), which depend on the conditions of growth and development between emergence and flowering, and not by weight (stage of filling) of grains.

Grain sterility

In the absence of constraints, sterility of the variety FOFIFA 161 is about 10%. In the first season, values of about 20% grain sterility were explained by wind occurring during flowering, and, for the two last seasons, high

¹ In other words, yield is the product of its five components: no. plants/m² × no. panicles/plant × no. grains/panicle × grain fertility × grain weight.

grain sterility was explained by the passage of a cyclone at flowering in 2007/08, and the impact of blast disease on early grain filling in 2008/09 (Fig. 4). When it was first released, FOFIFA 161 was considered resistant to blast disease, but its sensitivity apparently increased over the years, and blast pressure is high in the highlands. Epidemiological studies on the incidence and severity of blast were made during 2008/09. These results correlated with the sterility of the grains. A linear relationship was obtained in data from the treatment plowing (R² = 0.7735; Fig. 5). Other epidemiological studies conducted in 2004/05 and 2005/06 on a highly blast-susceptible variety indicated differences between methods of soil management in terms of incidence and severity of the disease. In DMC, the incidence and severity of blast were lower than in plowing, and the dynamics of disease progression were delayed in DMC (Sester *et al.*, 2006).

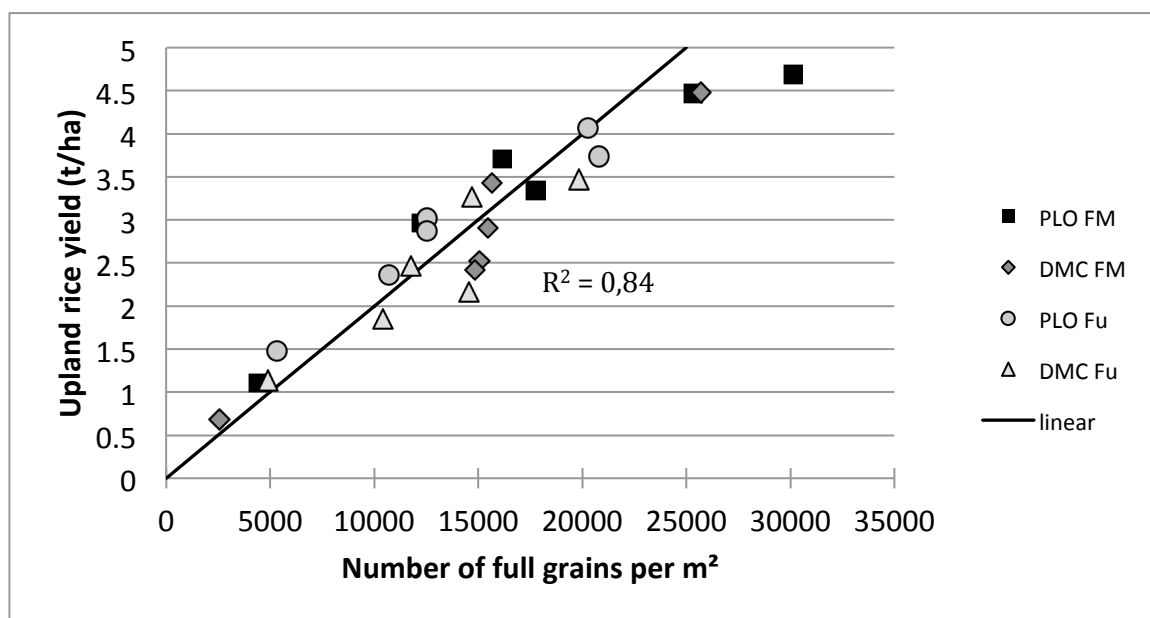


Figure 3. Relation between yield and number of full grains per m² at harvest, for all seasons and treatments

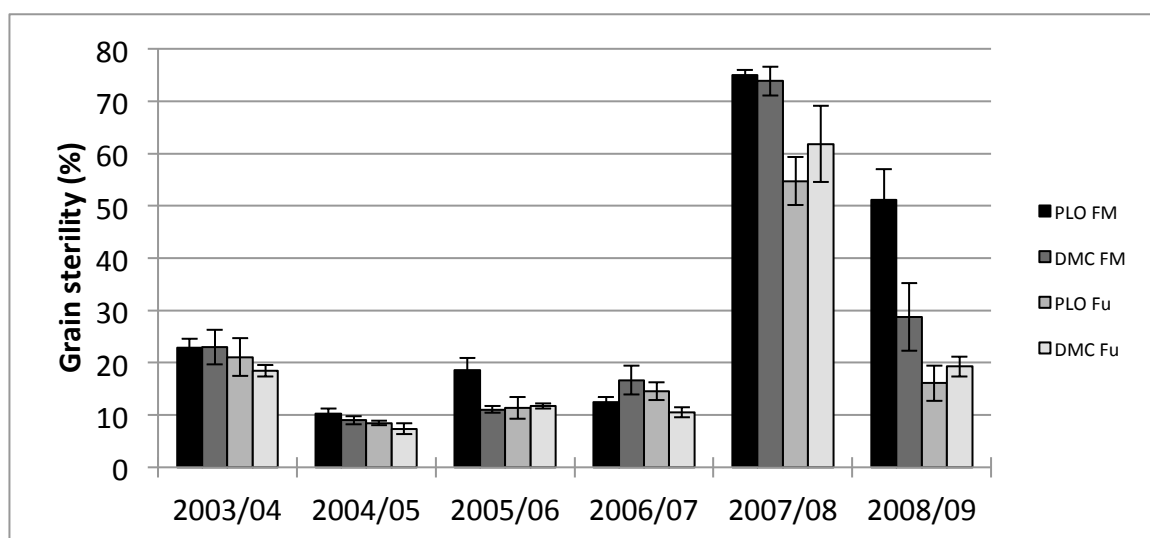


Figure 4. Grain sterility (%) by soil management (PLO, plowing; DMC, no till) and fertilization (Fu, cattle manure; FM, cattle manure and fertilizer) in six seasons

Stage from emergence to heading of rice crop

Looking specifically at the stage from emergence to heading (Fig. 6), the effect of fertilization was marked on the production of panicles per m². There was better production of panicles independent of soil management,

most clearly in the first and the last seasons. There was no effect of organic-matter fertilizer in DMC in 2004/05, 2005/06 and 2007/08 seasons, when plowing FM gave the most panicles per m². For the 2006/07 season, there is a weak effect of fertilization. Differences in yields for this season (2006/07), higher in plowing FM, were explained by a greater production of spikelets per panicle in plowing (data not shown).

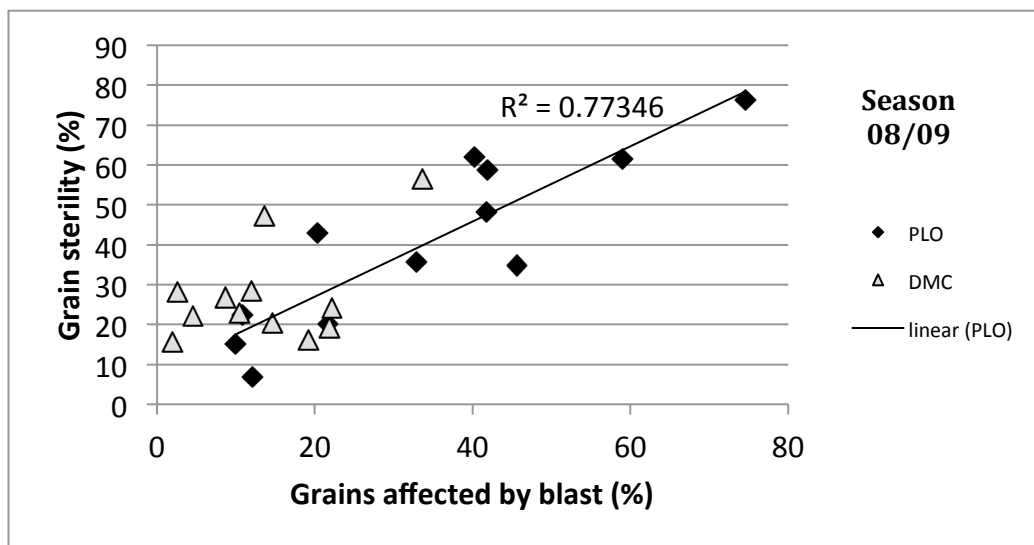


Figure 5. Relation between percentage of grains affected by blast and percentage of grain sterility in the 2008/09 season

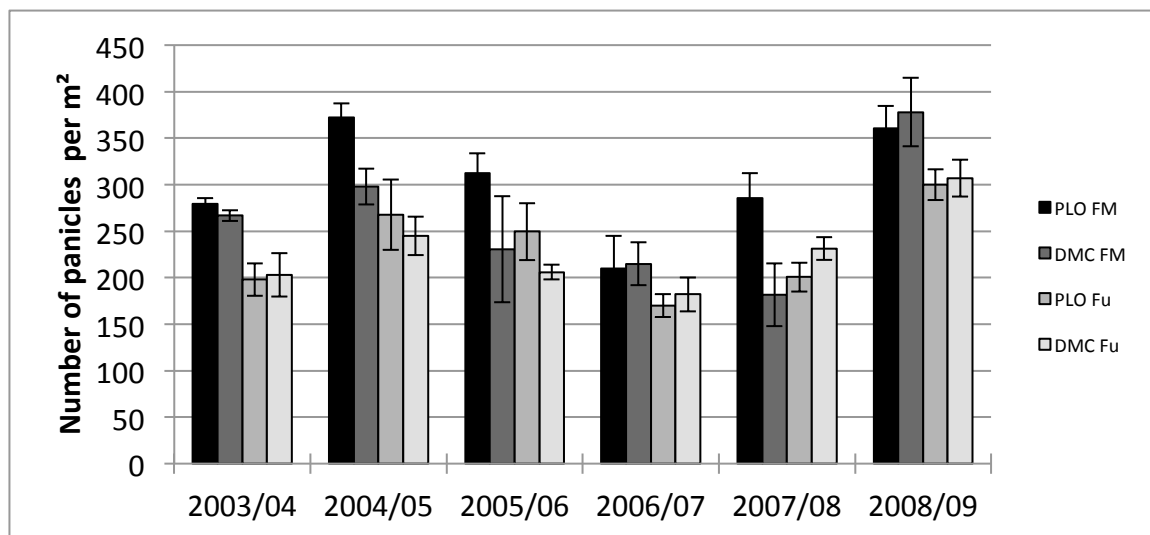


Figure 6. Number of panicles per m² by soil management (PLO, plowing; DMC, no till) and fertilization (Fu, cattle manure; FM, cattle manure and fertilizer) in six seasons

Making the connection between the two first components of yield (number of panicles per m², and number of plants per m²), we can see the effects of treatments on the development of the number of grains, and obtain information on this stage from emergence to heading. A linear relationship (Fig. 7) was found between these two components, followed by a plateau. For all points on this relationship (especially 2004/05 FM and 2005/06), variations in the number of panicles per m² were explained by variations in the number of plants per m². In 2008/09, density of plants did not induce more panicles, as the number of panicles produced per plant was reduced by competition between plants. The effect of fertilization was marked: fewer panicles per plant, for similar densities of plants, were observed in Fu treatments (particularly in 2003/04, 2004/05, 2006/07 and 2008/09).

Comparing plowing and DMC in FM treatment closely (Fig. 8), we see that the differences between soil management for 2004/05 and 2005/06 were as a result of differences in plant densities, with lower values than

in the relationship for 2007/08 (i.e. we can see a difference in plant densities between plowing and DMC, on the same relationship for 2004/05 and 2005/06, but below the relationship for 2007/08; Fig. 8).

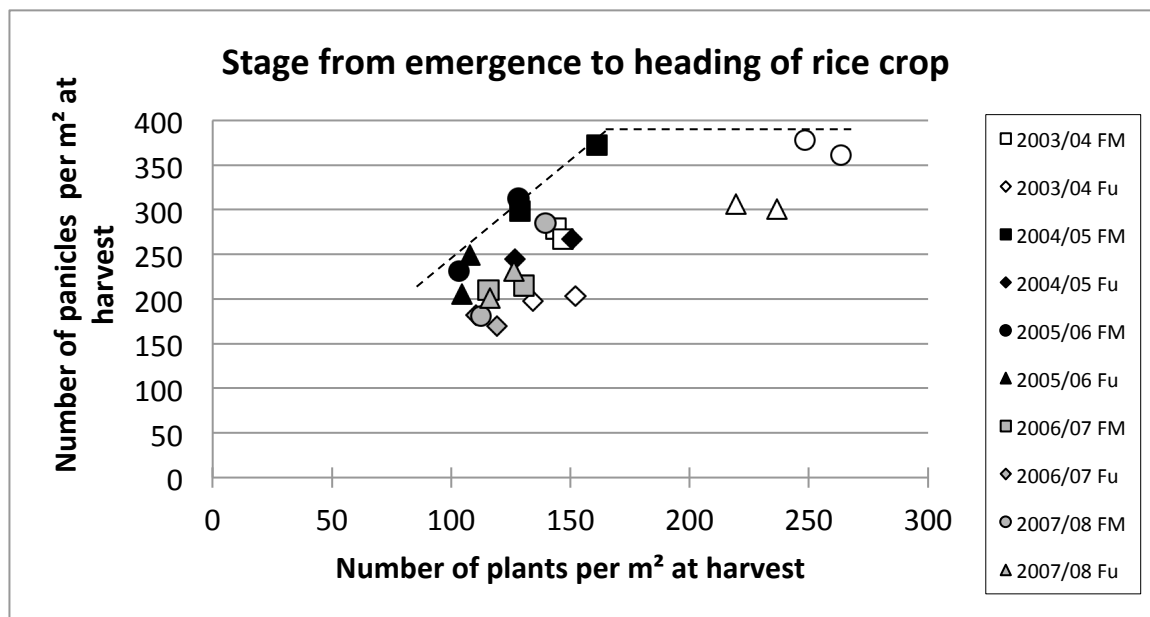


Figure 7. Relationship between number of panicles per m² and number of plants per m² at harvest for all seasons and fertilizations, independent of soil management (There are two data points per treatment as plowing and DMC are not specifically differentiated.)

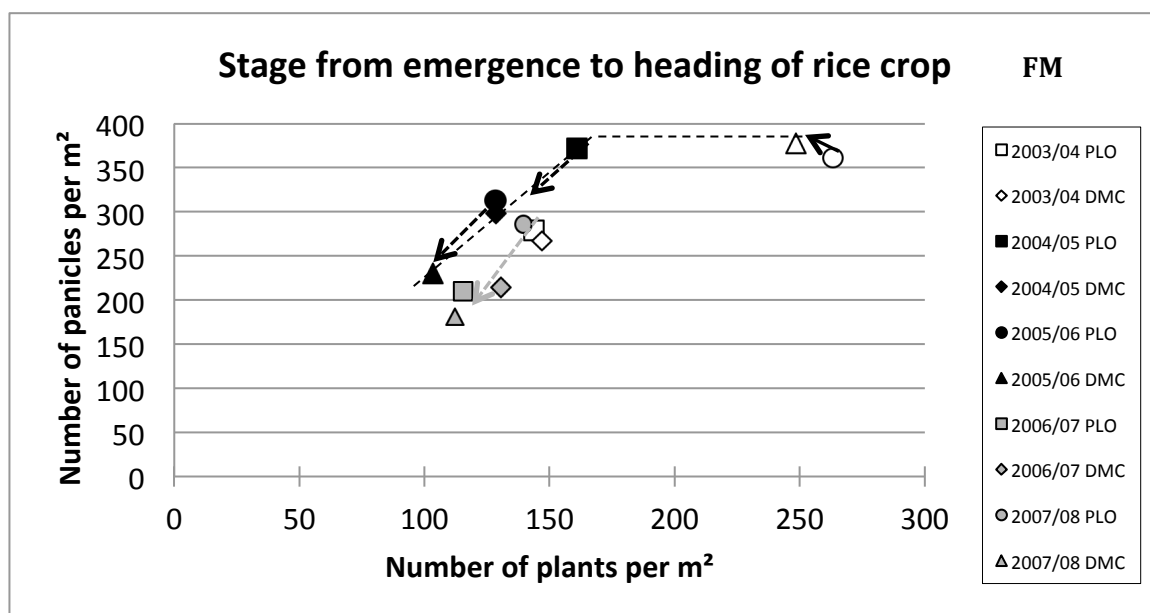


Figure 8. Relationship between number of panicles per m² and number of plants by m² at harvest for all seasons by soil management in fertilization FM

Establishment of the crop is more difficult in DMC: no tillage slows root development, and more difficult weed control in DMC (especially in early years) can explain these differences.

However in 2008/09, the sixth year of cropping, a positive effect was observed in DMC on this stage of crop cycle compared to plowing.

First results in a separate root experiment (data not shown), showed greater and faster root development with soil plowing. Measurement at early flowering stage on other cropping systems (upland rice in rotation with intercropping of maize comparing plowing and DMC; upland rice in rotation with intercropping of maize and

Brachiaria in DMC) showed greatest number of root impacts in plowing in the first 10 cm of soil, and greatest number of root impacts in DMC from 25 cm depth of soil (although differences were not statistically significant) (Dusserre *et al.*, 2008). A method for characterization of root system of upland rice has been developed (Dusserre *et al.*, 2009b) and experimentation is underway to compare root development in plowing and DMC.

The main hypothesis is slower rice development under DMC than under plowing.

Confirming this hypothesis, durations between sowing and flowering were longer in DMC than in plowing in 2004/05 and especially 2005/06 (Fig. 9). The FM treatment in plowing always had the shortest duration. Thus, fertilization stimulates the establishment of the crop.

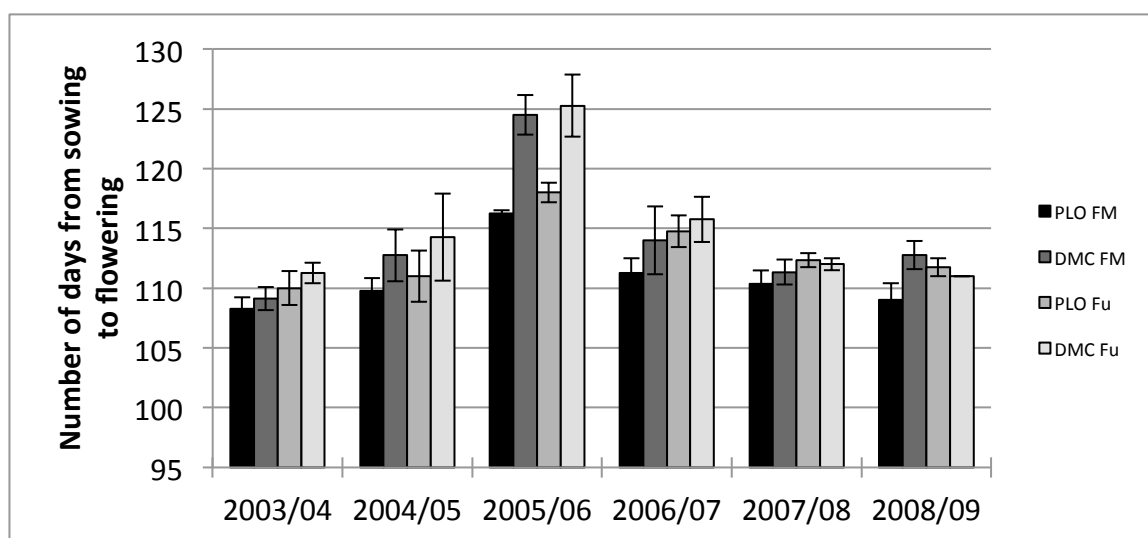


Figure 9. Number of days from sowing to flowering by soil management (PLO, plowing; DMC, no till) and fertilization (Fu, cattle manure; FM, cattle manure and fertilizer) in six seasons

Soil insects like scarab beetle larvae (white grub) cause reduction of number of plants/m², and can significantly damage upland rice. In this cropping system (upland rice in rotation with bean followed by oat), ratings of attack indicated no reduction in attacks in DMC over time, unlike other cropping systems observed (e.g. as rice in rotation with succession of oat, bean and ryegrass in DMC, where there is no need to treat the seeds after 4 years of cropping); in fact, attacks are greater under DMC (Ratnadass *et al.*, 2008).

Biomass production of crop rotation

Quantification of biomass produced on the rotations of rice (without grain) were measured for the first (oat straw) and the two last seasons (maize straw, bean residue and oat straw) (Fig. 10). To improve the total production of biomass, we added maize into the rotation in 2007/08. Non-grain biomass ranged from 5 to 6 t/ha in FM treatment. For comparison, on studies conducted in farmers' plots in a different ecology in Madagascar (altitude 700 m) where DMC is adopted, the biomass produced is in the order of 6.5–7.5 t/ha (Naudin, personal communication). The increase in biomass production of rice rotation could be a good way to improve DMC. More aerial biomass could contribute to better protection of the soil and more subterranean biomass could speed up improvement of and maintain good soil porosity through the biological activity of roots and soil organisms.

Conclusions

Long-term experimentation (six seasons: 2003/04 to 2008/09) allowed analyses of the performance of upland rice cropping systems.

The temperature conditions are very restrictive for the cultivation of upland rice in the highlands. The water conditions are not limiting in terms of amount available for the crop, but can have adverse effects (waterlogging, leaching) (not analyzed in this study).

The rice yield obtained was often better in plowing compared to DMC, except in the last season. The reversal in 2008/09 was due to blast disease at early grain-filling stage, which was higher in plowing than in DMC.

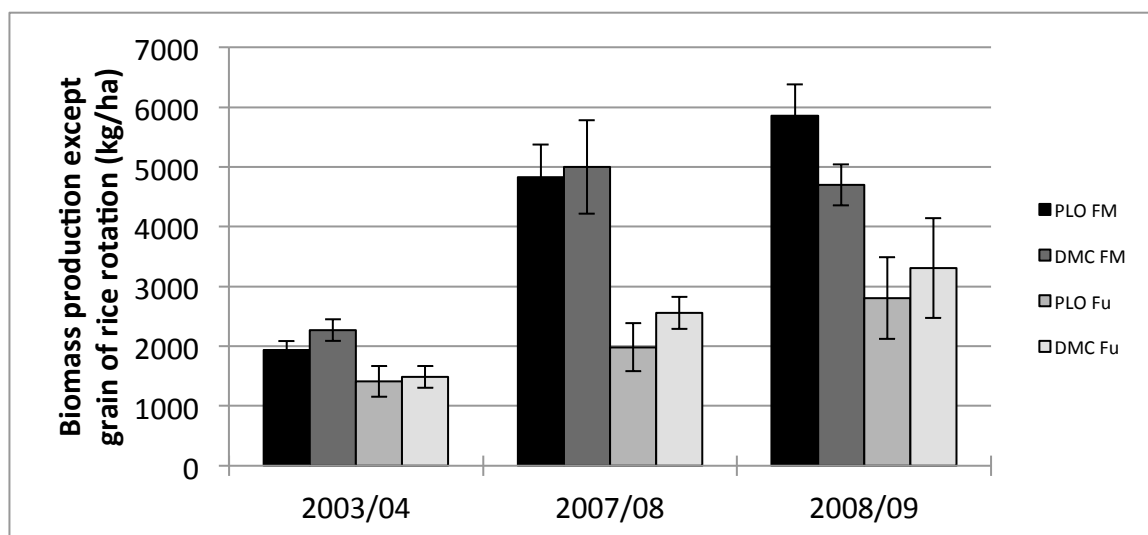


Figure 10. Biomass production except grain of rice rotation (kg/ha) by soil management (PLO, plowing; DMC, no till) and fertilization (Fu, cattle manure; FM, cattle manure and fertilizer) in three seasons

The differences in yields obtained between DMC and plowing were mainly explained by problems during crop establishment. Plant density and plant growth were lower in DMC. This was particularly linked to slower root development in DMC.

Overall, the biomass production in crop rotation of rice seemed too low under the highland conditions (low temperature) for DMC to be successful in the early years (low soil protection and slower natural restructuration of the soil).

Diversified crop rotations or intercropping with plants with more efficient root systems are being tested. These plants may show other advantages such as being fodder plants (pigeon pea, finger millet, *Stylosanthes*, vetch, lupin) and/or having repellent properties against soil insects (forage radish, rattlepod *Crotalaria* sp.) (Dusserre *et al.*, 2009a). However, these systems require more technical expertise for their implementation and may be inaccessible to farmers.

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