

Limiting factors for yields of field tomatoes grown by smallholders in tropical regions

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Title: Diagnosis of limiting factors of field-grown tomato yield in smallholder farms under tropical conditions

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Abstract

Tomatoes are widely cultivated in developing countries and are a major source of income for small-scale farmers. Yields of field-grown tomatoes vary considerably under tropical conditions but the main factors that limit yields remain to be identified. To this end, we conducted an on-farm survey in 22 fields in 2003 and in 28 fields in 2005 in a range of socio-economic settings typical of smallholder farms on the island of Mayotte (Indian Ocean). Data on crop management, fulfillment of water requirements, weed density, nitrogen absorption by the crop and nutrient availability in the soil, as well as the sanitary status of the crop were recorded at two-week intervals throughout the crop cycle. The data were analysed by principal component analysis, and multiple linear regression. Yields varied between years and sites from 0.7 to 45.3 t ha^{-1} in 2003 and from 8.1 to 89.1 t ha^{-1} in 2005. In 2003, the number of

fruits per m², fruit weight, the health status of the crop, and the cation exchange capacity of the soil explained 84.7% of yield variability among fields. In 2005, the number of fruits per m² and the health status of the crop explained 84% of yield variability. In 2003, 61.8% of the variability of the number of fruits per m² was explained by health status and the number of plants per m^2, whereas in 2005, 65.6% of the variability was explained by health status, the number of pesticide applications, and planting density. The results of this study indicate that tomato yield could be increased by improving the health status of the crop by improving the efficiency of crop protection practices and by increasing planting density.

Keywords: tomato; yield variability; pesticides; farmers' fields; tropical area; multiple linear regression.

1. Introduction

Tomatoes (*Lycopersicon esculentum* Mill.) are widely cultivated both in the open field and in greenhouses for fresh consumption and/or for processing. The crop is grown in temperate regions, humid and hot tropical regions, and dry Sahelian regions, which together represent a total area of about 5.22 billion ha and a total estimated production of 129.6 billion tonnes (FAO, 2011). Potential yields can be evaluated by total achievable biomass, biomass distribution between fruits, stems, leaves, roots, and by the dry matter content of fruits (Heuvelink and Dorais, 2005). Yields of field tomatoes usually range between 40 and 100 t ha^{-1} depending on the location, growing season, the cultivar used and crop management practices (Heuvelink and Dorais, 2005). A very wide range of cropping systems exist which vary according to the type of cultivar (determinate or indeterminate growth), mechanized or manual land preparation, weeding, irrigation and harvesting, the irrigation system (furrow, drip irrigation, sprinkle ring, garden hose), fertilization and crop protection (integrated pest management, conventional pest management), and management of the vegetation (with or without staking, pruning, disbudding, deleafing).

The main reasons for differences in yield in greenhouse tomato crops are well known (Heuvelink, 2005; Peet and Welles, 2005). However, fewer studies have focused on field-grown tomato crops for fresh consumption and/or processing, and those that did were mostly conducted in temperate regions in developed countries (Dumas et al., 1998; Clark et al., 1999; Scholberg et al., 2000; Csizinszky, 2005). Few studies have dealt with the factors that affect the production of field-grown tomatoes in tropical areas including water, nitrogen, weeds, and insect pests (Riahi et al., 2009; Asgedom et al., 2011). Special attention needs to be paid to tomato pests and diseases as the climate conditions in tropical areas are favourable for numerous insects including *Helicoverpa armigera, Bemisia tabaci* (vector of Tomato Yellow Leaf Curl Virus), mites *Tetranychus urticae, Tetranychus evansi, Aculops lycopersici*, fungi

63 *Phytophthora infestans*, *Leveillula taurica*, *Fusarium oxysporum* f. sp. *lycopersici, Alternaria*
64 *solani,* bacteria *Ralstonia solanacerum*, *Xanthomonas campestris* pv. *vesicatoria,* nematodes
65 *Meloidogyne incognita, M. arenaria, M. javanica, M. mayaguensis* (Csizinszky et al., 2005).
66 The damage to tomato leaves caused by pests and diseases is known to negatively affect the
67 production of assimilates and filling of the fruits in soilless conditions by decreasing overall
68 plant photosynthetic capacity (Stacey, 1983; Bertin and Heuvelink, 1993), but their real
69 influence on the determination of yield in field conditions remains unclear. In addition, in
70 developing countries, because farmers with limited financial and labour resources often grow
71 several different vegetable crops (tomato, aubergine, onion, hot pepper, carrot, okra, leafy
72 vegetables) over the course of the growing season (N'Dienor et al., 2004; Temple and
73 Moustier, 2004; Huat, 2006), they face different constraints including lack of access to
74 improved seeds, pesticides, organic manure, mineral fertilizers, water, and land, which impact
75 technical crop management and consequently influence the yield.
76 Using a regional diagnosis method that has already been successfully applied on many crops
77 and in a wide range of soil and climate environments, and social and economic conditions
78 (Meynard and David, 1992; Doré et al., 1997; Doré et al., 2008), our aim was to identify the
79 major factors which limit yields of field-grown tomatoes and the main cultivation practices
80 connected with limiting factors in smallholder tropical agriculture.
81
82 **2. Materials and methods**
83 *2.1. Study sites*
84 Our study was carried out in 2003 and in 2005 in Mayotte, a small (374 km²) French island
85 situated in the Indian Ocean (12° 45' S, 45° 05' W) (Fig. 1). Mayotte has a tropical climate
86 with a cool dry season from April to October (average temperature 21 °C) and a hot rainy
87 season from November to March (average temperature 28 °C). Annual average rainfall ranges

88 from 1 000 mm to 2 300 mm, and most rain falls in the north and north-western parts of the
89 island, which are directly exposed to the monsoon (Raunet, 1992). During the growing period
90 in our study (April to December), the monthly average temperature varied slightly across
91 areas and years (Fig. 1). The monthly average rainfall ranged from 0 to 154 mm depending on
92 the location of the farmers' fields. The driest months were July and August. The soils used for
93 the cultivation of vegetables are usually of alluvial origin and are clay loam (Raunet, 1992).
94 Farmers' fields were selected in five major areas covering a wide range of climates, soils and
95 technical management (Fig. 1; Table 1) Sixteen farmers and a total of 22 tomato fields were
96 surveyed in 2003, and 20 farmers and 28 fields in 2005; six of the farmers were surveyed in
97 both years. Data were collected through short in-depth interview with farmers at two-weekly
98 intervals.
99 The size of the tomato fields ranged from 110 m² to 2000 m² (average 360 m²). Except for
100 land preparation, which was sometimes by tractor (19 cases), all the other fields were
101 cultivated by hand. The most variable practices were planting density (11 000 to 54 200 plants
102 ha^{-1} in both years, the amounts of organic manure (0 to 23.3 t ha^{-1}) and NPK fertilizers applied
103 (0 to 2 638 t ha^{-1}), the number of pesticide applications (0 to 23) (Table 1), the variety of
104 tomato, crop rotation and planting date (May 2 to October 6).
105 In 29 cases out of 50, the tomato crop was preceded by a short fallow period. In the other
106 cases, cereals such as maize or rice, root crops such as cassava, and vegetables (cucumber,
107 courgette, melon, tomato, French beans) preceded the tomato crop. The main tomato cultivars
108 used were determinate: Mongal F1 and Calinago F1 because of their tolerance to bacterial
109 wilt (*Ralstonia solanacearum*). In 48 out of 50 cases, the farmers used either NPK chemical
110 fertilizers (15-12-24 or 10-20-20) or organic poultry manure, or both. All the farmers irrigated
111 the plants by hand with a garden hose. At the flowering stage, all farmers except one staked
112 and pruned their plants to maintain two or three vigorous stems, and disbudded the plants

several times before harvest. Sanitary deleafing was practised 8-10 days after planting and consisted in removing all the leaves in contact with the soil. This operation was repeated at each disbudding by removing all leaves with disease symptoms from the whole plant. The number of leaves removed was based on each individual farmer's perception of the damage.

2.2. Measurements

Five representative sub-samples of soil were collected from each field at depths of 0-20 cm and 20-40 cm at the beginning of the cropping season. P-Olsen modified Dabin, total carbon and nitrogen (Dumas), cation exchange capacity (hexamine cobalt chloride), pH (soil: H20 ratio = 1:2.5), water content at pF4.2 and pF2.5 were measured on each sample.

In each field, three plots (4 m x 3 m) were randomly chosen, each including at least 24 plants. Every two weeks, weed infestation was recorded using a visual scale corresponding to the percentage of soil surface covered with weeds. The proportion of plants whose leaves and fruits showed symptoms of attacks by pests or diseases was recorded, and an Mi (i=1 to 5) index calculated at each date; M1: < 10% of plants attacked; M2: 10-30% plants attacked; M3: 31-50% plants attacked; M4: 51-75% plants attacked; M5: > 75% plants attacked. The interval between planting and the M3 stage (P-M3) was calculated in days. Pests and diseases were recorded, along with the number of pesticide applications (NbPA) during the cropping period.

The density of tomato plants per m² was determined by counting the plants 8-10 days after planting and again at the beginning of the harvesting period. Yield components (number of stems, number of trusses, and total number of fruits) were measured at flowering (i.e. when the first truss on the main stem had started flowering on at least 50% of plants per plot) and at harvest and expressed per m². Individual fruit weight was calculated from the total number and total weight of fruits harvested per m².

In 2005 only, three plants were randomly sampled in each plot at four different dates: 8-10 days after planting (P), at flowering (F), two weeks after flowering (F+15), and at the beginning of the harvesting period (Ri). The aerial parts (stems, leaves, and fruits) were separated and dry matter determined after drying at 70 °C for 48 h. Plant total N, P, and K contents were measured on a 1 g sub-sample of dry matter taken separately from each aerial part. We calculated the nitrogen nutrition index (NNI; Lemaire et al., 1997) as the ratio of the N content of the aboveground parts of the plant to critical N content, using the reference values of critical N content for field-grown processing tomato proposed by Tei et al. (2002): $\%N = 4.53DM^{-0.327}$ (DM = dry matter, g).

2.3. Data analysis

For each field, we used the mean values calculated from measurements made in the three plots, and also calculated the standard deviation error and the coefficient of variation for each type of measurement. We identified all the correlated variables by principal component analysis (PCA). Yield was considered as a supplementary variable. The correlated variables (number of stems m^{-2}, number of trusses m^{-2}) were not included in the linear models. The relationships between yield, yield components, crop status and management practices were determined by multiple linear regression analysis with forward stepwise variable selection. The variables selected were the number of fruits per m^2 (NbF m^{-2}), number of plants per m^2 at Ri (DP), mean fruit weight (FW), interval in days from the planting date to the M3 stage (P-M3), number of pesticide applications (NbPA), the quantity of total nitrogen applied (QtotN), cation exchange capacity (CEC) and the nitrogen content of the soil (Nsoil). In 2005, we added two extra variables: the number of trusses per m^2 and the nitrogen nutrition index. The Akaike information criterion (AIC) was chosen to determine the stopping point (i.e. the number of variables included): $AIC = n\log(RSS/n) + 2p$, where n is the number of

observations, RSS is the model residual sum of squares, and *p* is the number of parameters. The minimum AIC is commonly used to identify the parsimonious model that has both a low error rate and few parameters.

All analyses were performed with the software XLSTAT 2012.1. As different fields were sampled in the two years of our survey, we analyzed data from the two years separately. Although we planned to survey the same tomato fields in the two years, this proved to be impossible, because in 2005, several farmers decided to not cultivate tomatoes and also because some farmers were obliged to cultivate different fields than those they had used in 2003.

3. Results and discussion

3.1. Variability in yield and yield components

Measured yield was highly variable, ranging from 0.7 to 45.3 t ha^{-1} in 2003 (mean 19.9 t ha^{-1}), and from 8.1 to 89.1 t ha^{-1} in 2005 (mean 34.2 t ha^{-1}). These average yields were relatively high compared to yields in other developing countries such as Madagascar (8.8 t ha^{-1}), India (18.2 t ha^{-1}), West Africa (7 t ha^{-1}) and Central Africa (7.7 t ha^{-1}) (FAO, 2011) where tomatoes are also mainly cultivated by hand. Planting density, number of fruits, stems, and trusses at harvest were also highly variable (Table 2). The key question is why yields were so low in some fields and high in others.

Results of the PCA showed that around 71.7% of the variability in 2003 (Fig. 2A), and 72.3% in 2005 were expressed by the three first axes (Fig. 2B). The yield components (number of fruits m^{-2} and number of stems m^{-2}) were correlated with the number of trusses m^{-2} and number of plants m^{-2} respectively and expressed by the first axis. In 2005, the NNI and QtotN variables were also linked to axis 1. In 2003, yields were closer to P-M3, FW and NbPA variables and correlated with the second axis, whereas in 2005, this axis expressed the NbPA

188 and FW variables. The third axis mainly expressed QtotN in 2003, and CEC and Nsoil in
189 2005.
190 Given that yield variability was correlated with the number of fruit per m^2, and was close to
191 limiting factors which played a role during the growing and fruit setting period, we focused
192 our investigations on the biotic factors and cultivation practices that could influence the yield
193 components before harvest, and on the final yield.
194
195 *3.2. Characteristic of biotic limiting factors*
196 *3.2.1. Incidence of pests and diseases*
197 The incidence of pest and diseases varied with the growth stage and with the year. In 2003,
198 the index of parasitism was rather low at flowering (59% of fields scored M1, 27% M2, 9%
199 M3, and 5% M4), whereas at the beginning of harvesting period, 64% of the plots already
200 scored M5 and 5% M4. In 2005, at flowering, the health status of the tomato crop had already
201 deteriorated in 46% of the fields: 18% scored M3, 7% M4 and 21% M5. At the beginning of
202 the harvesting period, all the fields expressed the maximum index M5. The difference
203 between 2003 and 2005 in terms of the length of the P-M3 interval (23 to 94 days in 2003 and
204 18 to 67 days in 2005), suggested that disease incidence was higher in 2005, but this may be
205 due either to higher pest pressure or to differences in the major pests, or to the fact that crops
206 were more sensitive to pests in 2005 because of the cultivars or the technical management
207 practices used.
208 In 2003, three fields were severely attacked by bacterial wilt (*Ralstonia solanacearum*), black
209 marrow disease (*Pseudomonas corrugata*), tomato yellow leaf curl virus and nematodes
210 (*Meloidogynous* spp.), and the farmers argued that they had no effective means to control
211 these diseases. The yield components (number of plants and number of fruits m^{-2}) were
212 seriously affected, and the yields of these fields were respectively 2.7, 6.1 and 0.7 t ha^{-1}. Two

213 other fields suffered serious fruit losses due to blossom end rot and late attacks by cut worms
214 (*Helicoverpa armigera*) during the harvesting period, which resulted in low yields (4.0 t ha^{-1}
215 and 11.7 t ha^{-1}) despite a relatively long P-M3 interval (72 and 60 days, respectively).
216 In 2005, Tephritidae *Neoceratitis cyanescens* and the plant pathogen *Corynespora cassiicola*
217 were the cause of the main problems observed in the fields.
218
219 *3.2.2. Nitrogen nutrition*
220 In 2005, NNI measured at four crop stages varied considerably among fields, ranging from
221 0.41 to 1.26 at 8-10 days after planting, from 1.43 to 3.24 at flowering, from 2.00 to 3.68 two
222 weeks after flowering, and from 1.59 to 3.27 at the beginning of the harvest period. An
223 increasing NNI trend over the cropping cycle revealed an improvement in nitrogen nutrition,
224 perhaps the result of improved availability of N in the soil due to N-mineral fertilization and
225 the mineralization of organic matter. At planting, the mean mineral N content of the network
226 of fields and the mean organic matter content at a depth of 0-20 cm were respectively 2.02 g
227 kg^{-1} and 3.08% in 2003, and 2.43 g kg^{-1} and 4.2% in 2005, revealing satisfactory nitrogen
228 content and soil organic matter content with respect to the standard values of Latrille (1981)
229 and Odet (1989).
230 A total of 80% of the fields received from 3.3 to 23.8 t ha^{-1} of organic poultry manure at
231 planting, corresponding to 24.7 to 178.5 kg ha^{-1} of nitrogen according to the standard values
232 developed by Chabalier et al. (2006). Consequently, most of the fields appeared to receive
233 correct amounts of N with respect to tomato N requirements.
234 In 2005, the variation in the nitrogen nutrition index (NNI) was weakly correlated with the
235 increasing doses of nitrogen fertilizers supplied to the crop (data not shown). The farmers
236 usually irrigate their tomato plants once or twice a day, so nitrogen leaching probably caused

237 a variation in N uptake in the field network, and consequently a variation in NNI for a given
238 quantity of nitrogen applied.
239
240 *3.2.3. Climatic conditions over the two years and at the different sites*
241 We observed that the best yields (56 to 89 t ha^{-1}) were obtained in the central part of the island
242 where the average temperature for the whole study period (24.2 °C) was 0.5 °C to 2.9 °C
243 lower than in the other areas. Yields of more than 40 t ha^{-1} were obtained in the southern,
244 south-eastern, and central zones, suggesting a beneficial effect of cooler temperatures on
245 yield. However, as the surveys were conducted separately in 2003 and 2005, and spanned
246 only two years, we cannot conclude if the best yields were due to the effect of climatic
247 conditions at regional scale.
248
249 *3.3. Limiting factors of yield components and yield*
250 We performed several stepwise regression analyses to investigate the factors that might
251 negatively affect yield throughout the crop cycle. Theoretically, yield can be broken down
252 into the following components: yield = number of plants per m^2 x number of stems per plant x
253 number of trusses per stem x number of fruits per truss x mean fruit weight.
254 For 2003, forward linear regression selected a model with four variables and with an
255 explanatory power of 84.7% of yield variability (Table 3A). In this model, the number of
256 fruits per m^2 (NbF m^{-2}), fruit weight (FW), P-M3, and CEC variables were deemed to be
257 positively correlated with yield. The health status of the crop (P-M3) explained 55% of the
258 yield. In 2005, only two variables were selected for the regression model (Table 3B), with P-
259 M3 and NbF m^{-2} explaining 84% of yield variability. All the variables exhibited similar
260 effects with greater effect of NbF m^{-2} in 2003 and of P-M3 in 2005.

Consequently, we performed a stepwise regression analysis of the number of fruits per m² which appeared to be the main yield component correlated with yield. For 2003, forward linear regression selected a model with two variables (DP and P-M3) and with an explanatory power of 61.8% of the variability of number of fruits per m^2 (Table 4A). In 2005, three variables were selected for the regression model (Table 4B) and P-M3, the number of pesticide applications and DP explained 65.6% of NbF m^{-2} variability. All the variables had similar effects with a high contribution of P-M3 to NbF m^{-2} variability in both years.

3.4. Effect of crop management on limiting factors

As the health status of the crop (expressed by P-M3) and the number of plants per m^2 appeared to be the main factors involved in yield variability, we investigated the effects of tomato crop management on these limiting factors.

3.4.1. Pest and disease management

The P-M3 interval (in days) was weakly correlated with the number of pesticide applications ($r^2 = 0.29$ in 2003; $P < 0.05$; no effect in 2005) which calls into question the use and efficiency of such applications. Moreover, under the cropping conditions studied here, we found no significant relationship between the sanitary index (Mi) and the number of pesticide applications (data not shown), either at the flowering stage, or later, at the beginning of the harvesting period. However, none of the farmers used the pesticides correctly, as both too small and too large doses of pesticide were applied in both years (Table 5). Overuse of insecticides and fungicides was less marked in 2003 than in 2005, and major differences among farmers were observed. Farmers undertook an average of 9 pesticide applications (± 4.3) in 2003 and 9.5 (± 3.5) in 2005. They usually used a knapsack sprayer, and wore no protective clothing even though they were aware of pesticide hazards. In 2003, the doses of

286 Deltamethrin used by all the farmers ranged between 43% and 267% and of Lambda-
287 cyhalothrin between 87% and 533% of the recommended doses, and in 2005, doses of
288 Deltamethrin ranged between 22% and 360% and those of Lambda-cyhalothrin between
289 113% and 480% of the recommended doses (Table 5), evidence for the absence of appropriate
290 pesticide management.
291 The positive relationship between the P-M3 interval (in days) and yield revealed a major
292 impact of pest and diseases and the need to prevent their attacks at the beginning of the crop
293 cycle to avoid high yield losses. However, the chemical control measures implemented by the
294 farmers had very limited effects on pests. Although all the farmers used pesticides, all their
295 fields were nevertheless subject to severe attacks at the beginning of the harvesting period.
296 The Lepidoptera *Helicoverpa armigera*, the Tephritidae *Neoceratitis cyanescens* and the
297 foliar disease *Corynespora cassiicola* were the main problems recorded in the fields. In a field
298 trial with processing tomatoes at UC Davis, California, Wilson et al. (1983) reported that
299 fruits less than 2.5 cm in diameter abort when fed on by *Helicoverpa zea,* and Brevault and
300 Quilici (2009) observed in field-grown tomatoes in Reunion Island that *N. cyanescens*
301 attacked small developing fruits 2-3.5 cm in diameter, primarily from 10 to 20 days post-
302 flowering. These fruits are completely damaged when they ripen and may drop off the plant.
303 In the absence of insecticide application during the fruiting period, these authors observed that
304 40% of a given generation of fruits were damaged by the tomato fruit fly. In islands in the
305 Indian Ocean and particularly in Mayotte, *N. cyanescens* is a major constraint for tomato
306 production (Bordat, 2008) and the efficacy of chemical control has been neither validated nor
307 demonstrated in the field (Ryckewaert et al., 2010).
308 The absence of a relationship between the number of pesticide applications and the crop
309 sanitary index Mi at the beginning of the harvesting period could be explained by under
310 dosing of pesticide in some of the fields (Table 5) or the inefficacy of the insecticides

311 (Deltamethrin and Lambda-cyhalothrin) used by the farmers to control the major insect pests
312 *H. armigera* and *N. cyanescens* during the post flowering period. These insects were probably
313 involved in the variation in the number of fruits per truss per m^2, and in the number of fruits
314 per m^2 in both years, as fruits that aborted or dropped prematurely were not recorded. The
315 inefficacy of the pesticides may also be explained by under and overuse, or the use of
316 inappropriate pesticides, as already observed in other rural, urban and peri-urban vegetable
317 cropping systems in developing countries (Kanda et al., 2009; De Bon et al., 2010; Lund et
318 al., 2010). Our survey showed that the famers did not have a thorough understanding of the
319 different types of pests and of appropriate control measures, and highlighted the problems that
320 can arise from inappropriate use of pesticides by farmers and the risk of environmental
321 degradation as well as sanitary risks for the users. There is thus an urgent need to increase
322 farmers' understanding and use of safe plant protection practices (Barman, 2007; Snelder et
323 al., 2008).
324 In addition to applying pesticides, 25 farmers out of 26 practiced different degrees of sanitary
325 deleafing several times during the post-flowering period. Their objective was to decrease the
326 propagation of pests in the field, to reduce the number of applications of chemicals, and to
327 facilitate the penetration of the chemical products within the vegetation. However, no
328 measurement was made to assess the effectiveness of this practice for pest and disease
329 control.
330
331 *3.4.2. Planting and stem density*
332 The number of fruits m^{-2} was influenced by the number of plants m^{-2}, but there was no effect
333 of the number of stems $plant^{-1}$ (data not shown). This result could be linked to the practice of
334 pruning and disbudding which consisted in keeping two to three fruit-bearing stems per plant
335 from flowering to harvesting. The survey confirmed that farmers based their control of the

vegetation on the individual plant unit and not on the unit area, and by choosing the same number of stems per plant whatever the planting density. We could argue that manual pruning and disbudding also influenced the variation in the number of stems m^{-2} and therefore the number of fruits m^{-2}. These practices also reduced the influence of the variety on the number of fruits per m^2, consequently the varietal diversity in the field network was not a constraint for carrying out the agronomic diagnosis. Figure 3 shows links as a function of plant density, and the highest points suggest that the only limiting factor was density. As pest attacks increase with plant density (at least fungi under tropical conditions), there is probably an optimal threshold beyond which yield will decrease. These results indicate that yields of field-grown tomatoes could be increased by increasing the planting density.

An on-station trial implemented in Mayotte in 2005, two treatments with pruning and one without (Huat, 2008), confirmed the positive relationship between the number of fruits m^{-2} and increasing the number of stems m^{-2}. The same relationship was observed by Ece and Darakci (2007) with indeterminate field-grown tomato varieties in Turkey.

In 2003, the average density of tomato plants in the farmers' fields was lower than the densities usually recommended (2.5 to 3.0 plants m^{-2}) for determinate varieties in tropical areas and managed without pruning and disbudding (Messiaen, 1998). Although small-scale farmers in Mayotte Island considered that pruning and disbudding make it possible to obtain better marketable yields and to limit pest infestations in the crop, (which has not been demonstrated), most small scale farmers in Africa are reluctant to apply these operations because they are very demanding in terms of labour and associated costs (Asgedom et al., 2011). As the number of fruits appears to be the main determinant of the dry mass partitioning between fruits and the vegetative parts of tomato plants (Heuvelink and Dorais, 2005), a certain number of fruits can be removed to obtain the desired average fruit weight. Individual fruit mass increases with a decrease in the number of fruits per plant, as competition between

361 fruits for assimilates is reduced. Nevertheless, determinate cultivars need light pruning: only
362 the first or two three axillary shoots should be removed, because heavier pruning reduces
363 marketable yields (Csizinszky, 2005).
364 Yield could be increased by increasing planting density and pruning the plants down to 2-3
365 stems, or by increasing the number of stems per plant (i.e. the number of trusses and fruits per
366 plant) by not pruning the plants. One practical solution would be to measure the effect of
367 several medium and high plant densities combined with different modes of pruning and
368 disbudding on yield, and in other cropping conditions, to help small-scale farmers improve
369 their yield based on their own cropping system.
370
371 *3.4.3. Limitations of the study*
372 The fraction of the variability of the number of fruits per m^2 not explained by the linear model
373 (around 38% in 2003 and 34% in 2005) can be attributed to several factors. At the beginning
374 of the study, we planned to survey the same tomato fields in 2003 and 2005, but this proved to
375 be impossible, firstly because several farmers decided to not cultivate tomatoes in 2005, and
376 secondly because some farmers used different fields than those they had used in 2003. This
377 was because most tomato producers in Mayotte are illegal immigrants who do not enjoy
378 secure land tenure. Every year, they have to renegotiate with a land owner to obtain a piece of
379 land to cultivate. Their situation is unstable, and their objective is thus to obtain high yields to
380 increase their income.
381 We collected management variables during surveys of farmers, and errors may have resulted
382 from the farmer failing to remember exactly what practices he applied in a particular field.
383 These errors were not quantified in this study, as doing so would require independent sources
384 of management information. Errors in the model may also reflect the absence of relevant
385 explanatory variables that were not measured in the survey (e.g. differences in pest

386 population, spatial variations in weather conditions, water consumption). We chose to
387 perform our agronomic diagnosis using easy-to-use indicators such as the curve of critical
388 dilution of nitrogen, and visual indicators of plant health such as sanitary status Mi and P-M3
389 which appeared to be appropriate in our study. The critical nitrogen curve of Tei et al. (2002)
390 based on the processing tomato cultivar PS1296 and tested in central Italy needs to be
391 validated under tropical conditions using different tomato genotypes.
392 The sanitary status of the crop was evaluated independently of the date of deleafing.
393 Depending on whether the observation was made before or after deleafing, the Mi value could
394 differ, which could partly explain the variability of Mi, independently of the number of
395 pesticide applications. Our difficulty in identifying significant relationships between these two
396 variables may also be due to strong interactions between variables and/or omission of major
397 variables affecting yields that we were not able capture in our survey.
398
399 **4. Conclusion**
400 Yield varied considerably among farmers, ranging from 0.7 to 45.3 t ha^{-1} in 2003 (mean 19.9 t
401 ha^{-1}), and from 8.1 to 89.1 t ha^{-1} in 2005 (mean 34.2 t ha^{-1}). By using a stepwise regression
402 procedure, we were able to explain around 80% of yield variability in the two years with a
403 few variables, and roughly 65% of the variability of the yield component number of fruits per
404 m^2. The health status of the crop expressed by the P-M3 indicator drove the majority of
405 variability of the number of fruits per m^2 in the network of fields. The period between
406 flowering and the beginning of harvesting appears to be decisive for the elaboration of the
407 yield component number of fruits per m^2. To our knowledge, to date, there has been no
408 diagnosis of yield-limiting factors of field-grown tomatoes in smallholder farms under
409 tropical conditions using this method.

From a practical point of view, our results showed that it should be possible to increase the tomato yield in two ways: (i) increasing the number of stems per m^2, either by limiting the number of disbudding operations to one at pruning, or by increasing planting density; (ii) improving farmers' knowledge of safe and efficient plant protection practices. Increasing plant density under severe pruning rather than stem density favours the use of soil resources (fertilizers, water), but has higher planting costs (seeds, labour) and mean fruit weight. Increasing stem density by keeping all stems or removing only two or three fruit stems at the flowering stage will favor the number of fruits per m^2 and increase humidity within the canopy, but will reduce mean fruit weight and favour the development of pathogens under tropical conditions. Nevertheless, tomato yield variability was not attributable solely to pest abundance or pesticide use. Further studies are needed to interpret the effects of interactions between planting density and health status on tomato productivity under various conditions, and to identify other management practices to improve regional production and reduce the environmental impacts of pesticide use.

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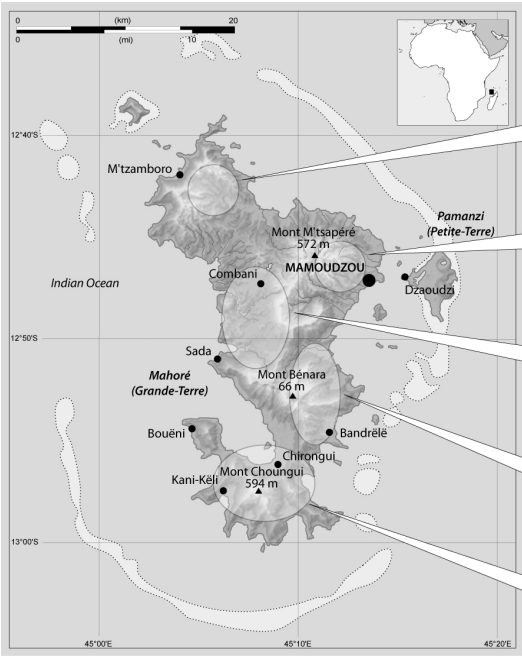
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518

519 **Fig. 1.** Location of the tomato fields surveyed in smallholder farms in the five major areas of Mayotte Island
520 (Indian Ocean) in 2003 and 2005.
521



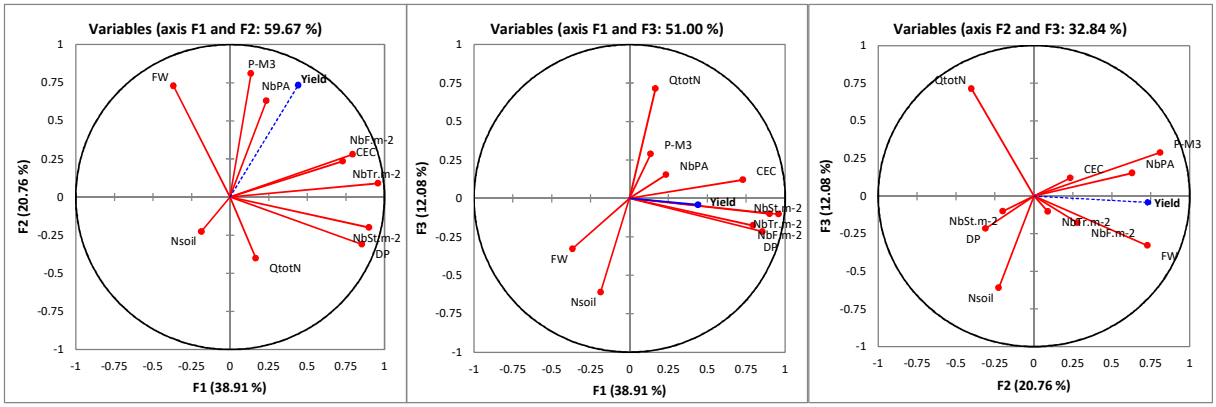
North	Tomato (fields)	Rainfall (mm)	Average temperature (°C)
2003	1	1593	27.1
2005	5	1501	27.6
North-East			
2003	4	1358	27.4
2005	1	1194	27.3
Center			
2003	8	1571	25.0
2005	14	1709	25.3
South-East			
2003	5	1430	25.8
2005	6	1111	25.9
South			
2003	4	1027	27.3
2005	2	1114	27.3

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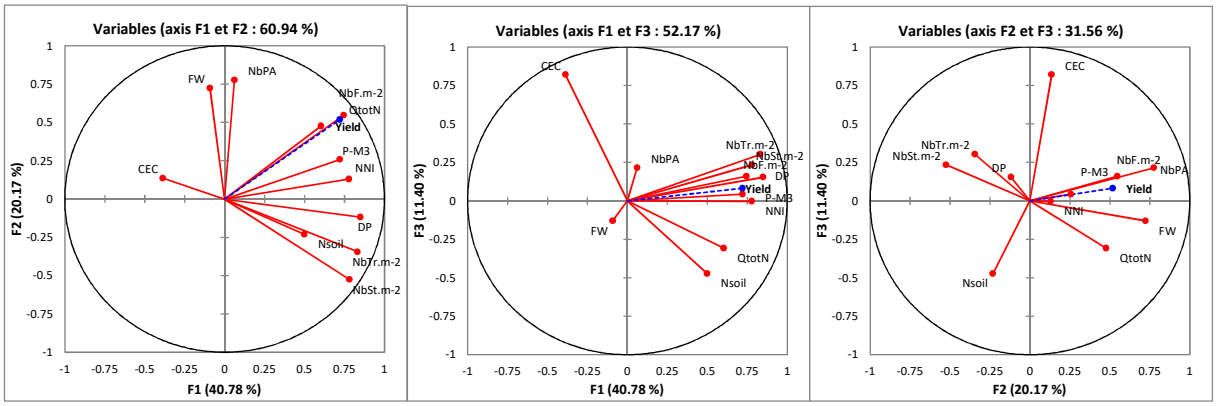
Fig. 2. Principal components analysis with yield component variables, crop and soil status variables and cultivation practice variables: (A) for 2003, (B) for 2005. Yield (dashed line) was projected as a supplementary variable.

NbF m^{-2}: number of fruits m^{-2}; NbTr m^{-2}; number of trusses m^{-2}; NbSt m^{-2}: number of stems m^{-2}; DP: number of plants m^{-2}; FW: fruit weight (g); QtotN: Quantity of total N applied ($kg.ha^{-1}$); NbPA: number of pesticide applications; P-M3: Period in days between planting and M3 sanitary index; NNI: Nitrogen nutrition index of the crop; Nsoil: N content of soil ($g.kg^{-1}$) at a depth of 0-20 cm; CEC: Cation exchange capacity of soil ($meq.100g^{-1}$) at a depth of 0-20 cm.

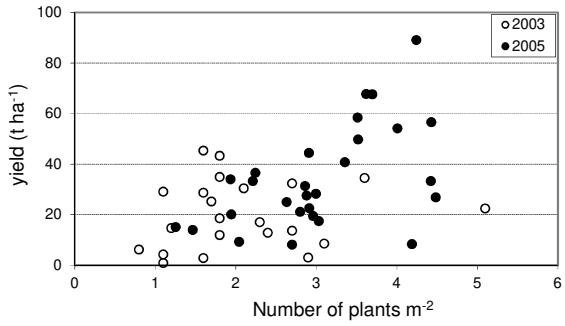
A- 2003



B- 2005



541
542 **Fig. 3.** Relationship between yields and planting density.



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547
548 **Table 1**
549 Main tomato cropping practices used.
550

	2003		2005	
Practices	Mean±SD	Range	Mean±SD	Range
Planting density (plants ha^{-1})	23918±9882	11000-54200	32180±8669	14680-48690
NPK fertilizers (kg ha^{-1})	196±243	0-890	858±655	0-2638
Organic manure (t ha^{-1})	7.2±3.6	0-14.8	7.3±6.8	0-23.3
Number of pesticide applications	9.0±4.3	4-23	9.5±3.5	0-18

551

552

553

554 **Table 2**
555 Variability of tomato yield and yield components.
556

	2003		2005	
Measured variables	Mean±SD	Range	Mean±SD	Range
Yield (t ha^{-1})	19.9±13.4	0.7-45.3	34.2±20.3	8.1-89.1
Number of plants m^{-2}	2.1±0.9	0.8-5.1	3.0±0.9	1.3-4.5
Number of stems m^{-2}	5.3±3.2	1.9-16.3	14.0±5.6	4.8-29.7
Number of trusses m^{-2}	10.3±5.6	3.1-24.5	42.1±16.0	15.9-87.1
Number of fruits m^{-2}	24.0±11.9	3.6-45.6	87.2±54.3	18.3-243.1
Mean fruit weight (g)	89.0±26.0	54.6-157.2	65.7±17.9	23.5-94.7

557

558

559 **Table 3**
560 Regression statistics for yield, with variables listed in order of selection using a step forward procedure.
561
562 **A-** 2003
563

Significant variables*	Estimate	Standard error	t	P > |t|	Cumulative r^2	AIC
Constant	-24.765	4.917	-5.037	0.000	-	-
P-M3	0.227	0.067	3.387	0.004	0.550	98.645
NbF m^{-2}	0.465	0.128	3.643	0.002	0.709	89.961
FW	0.176	0.050	3.536	0.003	0.790	83.622
CEC	0.239	0.086	2.770	0.013	0.847	77.425

564 ***** P-M3: interval in days from the planting date to M3 stage; NbF m^{-2}: number of fruits per m^2;
565 FW: mean fruit weight; CEC: cation exchange capacity.
566
567 **B-** 2005
568

Significant variables*	Estimate	Standard error	t	P > |t|	Cumulative r^2	AIC
Constant	-9.338	6.446	-1.449	0.160	-	-
NbF m^{-2}	0.267	0.040	6.654	< 0.0001	0.800	126.564
P-M3	0.461	0.182	2.533	0.018	0.840	122.166

569 * NbF m^{-2}: number of fruits per m^2; P-M3: interval in days from the planting date to M3 stage.

570

571

Table 4

Regression statistics for number of fruits per m^2, with variables listed in order of selection using a step forward procedure.

A- 2003

Significant variables*	Estimate	Standard error	t	P > |t|	Cumulative r^2	AIC
Constant	-9.442	5.859	-1.612	0.124	-	-
DP	8.128	1.651	4.923	< 0.0001	0.296	103.211
P-M3	0.317	0.075	4.223	0.000	0.618	90.650

* DP: number of plants per m^2; P-M3: interval in days from the planting date to M3 stage.

B- 2005

Significant variables*	Estimate	Standard error	t	P > |t|	cumulative r^2	AIC
Constant	-128.283	29.858	-4.296	0.000	-	-
P-M3	2.158	0.567	3.808	0.001	0.423	210.188
NbPA	5.891	1.786	3.297	0.003	0.558	203.624
DP	21.299	7.493	2.842	0.009	0.656	197.499

* P-M3: interval in days from the planting date to M3 stage; DP: number of plants per m^2; NbPA: number of pesticide applications.

585
586 **Table 5**
587 Average application rates of pesticides used by farmers in 2003 and 2005 calculated as a percentage of the dose
588 recommended by pesticide manufacturers in *Index Phytosanitaire Acta* (Acta, 2005).
589

	2003		2005	
Pesticide	Mean±SD	Range	Mean±SD	Range
Deltamethrin	112±62	43-267	180±95	22-360
Lambda-cyhalothrin	208±104	87-533	218±124	113-480
Tau-Fluvalinate	251±148	100-404	317±104	200-400
Dicofol	115±68	44-180	293±195	155-431
Cyromazine	141	-	82±27	42-113
Abamectin	-*	-	136±8	130-141
Mancozeb	129±64	14-267	294±212	75-805
Copper sulphate	99±102	5-288	134±89	44-314
Maneb + Thiophanate-methyl	91±79	17-200	128±79	62-226
Chlorothalonil	19±2	18-21	84±31	50-109
Difenoconazole	-	-	420	-
Cymoxanil + zinc metirame	-	-	153±5	149-156

590 *-: no measurement

591

592