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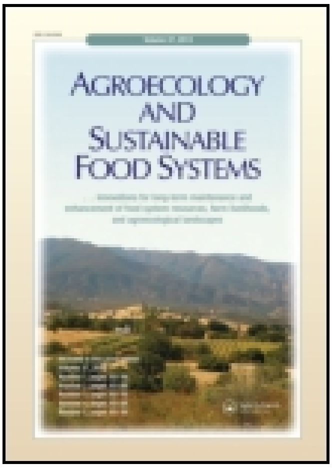

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Understanding Crop Management Decisions for Sustainable Vegetable Crop Protection: A Case Study of Small Tomato Growers in Mayotte Island

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Pests and diseases are one of the limiting factors that farmers have to control to obtain better yields. With a view to gaining a clear understanding of their cultivation practices and technical decisions in order to support farmers in a move toward environment-friendly practices, a two-year survey of tomato farmers was conducted in Mayotte. Thirty five farmers were interviewed several times about their crop management, and field observations were undertaken every two weeks. Results showed that the number of pesticide applications varied greatly (4–23) with a tendency toward over-application, and no relationship was found between the application rate and the health status of the crop. Inefficiency in protecting crop health also reflected a problem of access to pesticide information and a poor control of crop protection methods. Over-application of pesticide has long term impacts on marine health and biodiversity. The planting bed and the individual plant were found to be appropriate units for technical decision making and applying market gardening techniques. However, current agricultural advice does not apply to these units, suggesting that a redefinition of technical advice is needed.

KEYWORDS *crop management, tomato, pesticides, small-scale growers, decision tools, island biodiversity*

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INTRODUCTION

In developing countries, supplying fresh vegetables to growing cities is a major challenge, and pesticide applications have been promoted among farmers as a way to increase productivity (Cooper and Dobson 2007). For instance, in Mayotte Island where the population density is high (about 500 inh./km^2) with an annual growth rate of 3.77% and a large immigrant population, estimated at one third of total population, there is a major increase in demand for fresh vegetables. Indeed, the island imports over half its fresh vegetables, particularly tomatoes. In addition, despite its small land area (374 km^2), Mayotte has a 1,100 km^2 lagoon which is home to a rich marine biodiversity. The lagoon is increasingly threatened by domestic discharges and runoff waters from deforested, agricultural, urban, and industrial zones that empty into the sea. One of the challenges facing many small island developing states (SIDS), including Mayotte, is balancing economic benefits and environmental pressures arising from their agricultural and industrial activities (Koonjul 2004; Van der Velde et al. 2007). In 2008–2009, accidental and isolated cases of pollution were found in surface waters during a search for residues of pesticides against the mosquitoes *Aedes albopictus*, the vector of Chikungunya, a viral human disease (Comité de Bassin de Mayotte 2009), which prompted public authorities to show greater vigilance. If agricultural pollution risks are to be reduced, the first step is characterizing agricultural practices and understanding farmers' reasoning concerning the protection of their crops and where potentially polluting pesticides fit into that reasoning. The characteristics mentioned above are not specific to SIDS, but hold for small-scale growers in developing regions in general.

In Mayotte, most farming households have complex activity systems, and social and religious norms greatly influence farmers' technical choices. The political context generates rapid institutional changes, and agricultural activities are greatly influenced by unclear land tenure, as well as by an unstable immigrant labor force (Burnod and Sourisseau 2007). Similar to Mayotte, many SIDS rely on agriculture for both subsistence and trade, but are vulnerable due to the environmental consequences of using their fragile natural resources for economic development, thus, sustainable development is essential.

If urgently needed technical changes are to be supported in this region where environmental damage of a particularly fragile ecosystem is underway, first, familiarity with current cultivation practices, and an understanding of the range of decision-making processes and the variability in crop performance is needed (Aubry and Michel-Dounias 2006). Much work has been done in recent years on the decision-making processes that determine farmers' practices for the cultivation of annual crops (Aubry et al. 1998; Aubry and Michel-Dounias 2006). These models are beginning to be tested and adapted for short-cycle market garden type of crops in temperate areas (Navarrete and Le Bail 2007; Navarrete 2009), but such work is still rare in the tropics (N'Dienor et al. 2011; Mawois et al. 2011).

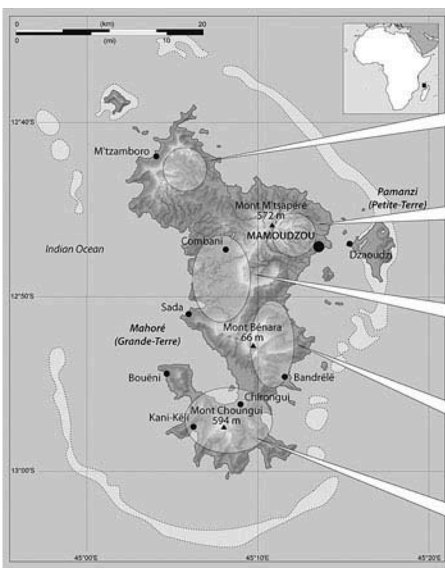
Diagnosis of tomato yield variability in Mayotte revealed that variability partly depended on the health status of the crop (Huat et al. 2013), which, in turn, was linked to two major types of plant management operations: 1) planting density and stem density and 2) pesticide applications of various types and intensities. So there is a need to understand the reasoning behind farmer's cultural operations on this small island with a particularly uncertain production environment.

Considering the socioeconomic, environmental, and production constraints of such SIDS, the aim of this study was to learn lessons from plant management practices and decisions in tomato crops to encourage farmers to move toward more public health and environmentally-friendly practices. In this paper, we first describe existing crop protection practices and then explain their determinants in the production context in Mayotte. We discuss the current limits of crop protection procedures, and finally make some recommendations in line with the results of the analysis.

MATERIALS AND METHODS

Study Area

The study was carried out from 2003 to 2005 in Mayotte, a small French island located in the Indian Ocean (12°45′ S, 45°05′ W; Figure 1). Mayotte



Region / Year	Farms	Tomato (fields)	Rainfall (mm)	Average temperature (°C)
North				
2003	1	1	1593	27.1
2005	3	5	1501	27.6
North-East				
2003	2	4	1358	27.4
2005	1	1	1194	27.3
Center				
2003	6	8	1571	25.0
2005	8	14	1709	25.3
South-East				
2003	3	5	1430	25.8
2005	6	6	1111	25.9
South				
2003	3	4	1027	27.3
2005	2	2	1114	27.3

FIGURE 1 Location of the smallholder farms and tomato fields surveyed in Mayotte.

has a tropical climate with a cool dry season from April to October (average temperature 21°C) and a hot rainy season from November to March (average temperature 28°C). Annual average rainfall ranges from 1,000 mm on the coast to 2,300 mm inland. Most rain falls in the north and north-western areas, which are directly exposed to the monsoon (Raunet 1992). The soils used for vegetable growing are usually of alluvial origin and clay loam (Raunet 1992), with variable chemical properties, similar to those we measured in the set of farmers' fields we surveyed (pH-H_20: 4.9–6.8, cationic exchange capacity: 2.3–56.1 meq/100 g, organic matter content: 0.9–6.1%, Ntot: 0.6–3.6 g/kg, carbon: 0.6–3.8 g/kg; Huat 2008).

Agriculture in Mayotte is mostly family based, with the hired production labor and collection-resale sector dominated by individuals from neighboring islands in the Comoro archipelago, whose resident status may be illegal, or semi-illegal (Burnod and Sourisseau 2007). Around 30–40% of the population are illegal immigrants who are mainly employed in agriculture and construction. Thus, farmers vary widely in their land tenure and financial resources as well as in their production and marketing strategies, all of which depend greatly on their legal status. Access to agricultural inputs, labor and equipment is also uncertain, with frequent disruptions in the supply of imported fertilizers and pesticides. Agricultural equipment is generally hired out to farmers by local agricultural authorities, but supply often falls short of demand. Finally, there is an unstable work force that operates on verbal work contracts, if any.

Survey of Crop Management and Pesticide Use

Our research method combined on-farm surveys and in-field observations on 15 farms and in 22 fields in 2003, and on 20 farms and in 28 fields in 2005 (Figure 1); six farms were surveyed in both years, to allow us to account for the inter-annual stability of the decision model. The surveys were carried out in the dry season (April–November), which is the best period for vegetable crop production. The farms and fields were selected to represent a wide range of agro-ecological situations (soils and climate) and diversity of farm functioning. The farm types varied mainly in labor resources and in the legal status of the farmers (legal citizen or illegal immigrant), the weight of agricultural activities within the farm, farmer's strategy, and in the farm size, in order to represent the whole range of tomato cropping systems (Table 1; Huat, 2008). Tomato fields ranged in size from 110 m^2 to 2,000 m^2, and the average field size was 360 m^2.

To understand decision making processes in the framework of tomato crop management, we referred to the break management and annual crop management models developed in France for winter wheat (Aubry et al. 1998) and extended to other annual crops in Africa (Dounias et al. 2002). The annual crop management model can be expressed in the form of decision

TABLE 1 Social and technical characteristics of the four types of farmers (n = number of farmers interviewed)

	Type 1 ($n = 10$) Specialized farm	Type 2 ($n = 18$) Unstable farm	Type 3 ($n = 3$) Traditional farm	Type 4 ($n = 4$) Modern Farm
Head of the farm	farmer	farmer	civil servant	farmer
Pluri-activities on farm	no	no	yes	yes
Type of labor used for farming	Family (+ casual laborers)	Family	Laborers (migrants)	Laborers (migrants)
Legal status of the farmer	Legal (French citizen)	Illegal (100%)	Legal (French citizen)	Legal (French citizen)
Farmers' strategy	To increase income through better access to markets; to reduce risk through agricultural diversification	To maximize yields and profits through better access to markets.	To diversify sources of income; to reduce risk through diversification of activities.	To diversify sources of income and reduce risks through diversification of activities; to modernize farms thanks to agricultural grants.
Size of farm (m^2)	2620 (734)[1]	2305 (1222)	1775 (692)	7300 (2336)
Farmer's age (years)	42 (12)[1]	36 (7)	56 (2)	46 (9)
Gender ratio	50% ♀ + 50% ♂	100% ♂	100% ♂	50% ♀ + 50 ♂
Agricultural experience (years)	11 (9)[1]	11 (6)	10 (2)	11 (8)
Number of fields surveyed	13	27	3	7

[1]Mean (standard deviation).

variables, management rules and management units (Aubry and Michel-Dounias 2006). For each farm operation, variables, and rules concern: a) the possible procedures of the technical operation; b) the work site procedures; c) the time structuring; d) the spatial structuring, namely the break into sets; and e) finally prioritizing between fields, or between crops, for competing tasks. The break gathers all the fields under a given crop on a farm in a given year. For each technical operation, the farmer determines temporal positioning and possible modalities, and he determines variables and rules for linking different operations between them (Aubry and Michel-Dounias 2006). In our study, modalities were related to nature and dosage of inputs (pesticides for instance), and to the intensity of vegetation crop management (deleafing, debudding).

Each farmer was interviewed several times during the course of the cropping season: a) before sowing began to find out how he intended to manage the practices in all the tomato fields under his responsibility; b) during the cropping season, to find out which practices were actually applied (dates, procedures, etc.); and c) at the end of the cropping season to analyze with the farmer any divergence from the original schedule and the reasons for that divergence. Given that these in-depth interviews were time consuming, it was impossible for us to interview a large sample of farmers.

Alongside these surveys, and independently of the farmers, observations were made at two week intervals in each field to record the conditions under which agricultural operations were carried out, with a focus on pest and disease control (number and nature of pesticide applications, active ingredients used and application date, pests and pathogens identified), plant management (planting density, staking and pruning, deleafing and debudding), and the health status of the crop. To record the health status, observations were carried out in three 4 m x 3 m plots randomly chosen in each field. We used a visual scale to record the proportion of plants showing symptoms of pest and disease attacks on leaves and fruits, and calculated an index with the following values: M1: <10% of plants attacked; M2: 10–30% of plants attacked; M3: 31–50% of plants attacked; M4: 51–75% of plants attacked; M5: >75% of plants attacked. We calculated the number of days between planting and the M3 stage (P-M3) to assess the effect of pesticide applications on the health status of the crop.

To guarantee the accuracy of the collected data on pesticides management, we observed at several times in the field and for each farmer how the farmers dosed and mixed pesticides with water, and we measured the quantities of pesticides per knapsack, the volume of the knapsack, the number of knapsacks used per tomato field and the area of concerned field.

Previous studies and surveys by agricultural extension agents showed that the main pests and diseases of tomato crops in Mayotte are tomato fruit flies *(Neoceratitis cyanescens*), fruit worms (*Helicoverpa armigera),* white flies *(Bemisia tabaci*), which is the vector of the tomato yellow leaf curl virus, mites *(Aculops lycopersici, Tetranychus* spp.*)*, bacterial wilt *(Ralstonia solanacearum)*, marrow black *(Pseudomonas corrugata)*, bacterial spot *(Xanthomonas campestris*), target spot (*Corynespora cassiicola)*, and nematodes (*Meloidogyna* spp.).

Data were analyzed with ExcelStat 2012.1.02 software for Windows. Differences between means were determined using non-parametric tests, the Kruskal-Wallis test and the Steel–Dwass–Critchlow–Fligner multiple sample comparison test. The relationships between different types of plant management and planting density, on the one hand, and the type of farm, on the other hand, were assessed by the chi-sqaure test. We considered three planting densities: fewer than two plants/m^2, two to three plants/m^2, which is the usual density recommended for field-grown tomatoes, and three to five plants/m^2.

RESULTS

Formalization of Tomato Crop Management

Tomato crop management included no fewer than 15 different technical operations carried out by hand (sowing, hoeing, planting, staking, tying, pruning, deleafing, debudding, weeding, fertilization, organic manure application, irrigation, pesticide spraying, harvesting), excluding land preparation that may be mechanized.

The tomato crop decision model was formulated based on management production practices in the region and was validated with an exemplary farmer (Figure 2) who had been cultivating tomatoes for years, who belonged to type 2 (Table 1), who served as a mentor for young producers, and who commonly cooperated with agricultural development services. Table 2 shows the tomato plant management operations and chemical crop protection operations for the 2003 season. The operations carried out on this farm were comprised of a limited number of procedures which were also done by other farmers (Figure 2): staking, pruning, deleafing, debudding, and chemical crop protection.

Several roles were attached to the deleafing operation: reduce disease development, facilitate the penetration of pesticide products into the vegetation, reduce the volume of pesticides required, and obtain larger fruits. The first deleafing (that we called sanitary deleafing) took place just after planting and consisted in removing any leaves that touched the soil and any leaves with signs of necrosis. The second deleafing aimed at reducing the quantity of senescent leaves and those displaying symptoms of attack (brown spots, galleries, yellowing). The other deleafing operations were carried out at the same time as debudding, and before pesticide application. Chemical protection consisted of nine treatments on average, spread over the cropping cycle. The farmer combined an insecticide (deltamethrin or

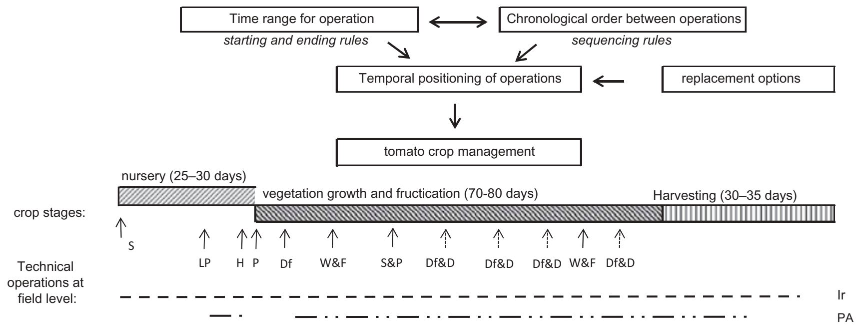


FIGURE 2 Representation of field tomato crop management model by farmers in Mayotte (Legend: So: sowing; LP: land preparation; H: hoeing; Pl: planting; W: weeding; S: stacking; P: pruning; Df: deleafing; D: debudding; F: fertilization; Ir: irrigation; PA: pesticides application).

lambda-cyalothrin) and a fungicide (copper sulphate or mancozeb), except for the last three treatments, which were insecticides only.

These operations were carried out following different types of rules and involved different indicators (Table 2). The start of a given operation was linked either to:

- a date on the farm calendar—for instance, the first chemical treatment and sanitary deleafing took place 8–10 days after planting;
- the occurrence of a climate event—if there was a heavy rainfall less than 3 hours after a treatment, the treatment was repeated on the same day or postponed until the following morning;
- a reference crop stage—pruning began at flowering, and debudding was carried out when the axillary buds measured 5–10 cm.

The scheduled end of operations was also governed by different types of indicators:

- A date on the farm calendar, where, for instance, in the nursery, the last sowing of the season was carried out in August, so that the crop could be harvested in December before the beginning of the rainy season.
- A plant development stage, where the final pesticide application was made before the final harvest.

Crop management practices combined several management units ranging from field to plant, depending on the operation concerned. The basic unit for most operations was a single plant, where staking, planting, pruning, deleafing, debudding, irrigation, fertilization, weeding-hoeing, and harvesting took place. The bed or planting row was the management unit for chemical treatments and manual soil preparation, while the whole field was the management unit when land preparation was mechanized.

TABLE 2 Description of variables and decision rules of crop management model, for an exemplary farmer, applied to plant management and crop protection of tomato cultivated in Mayotte Island

Technical operation	Procedure	Time range for operation	When to be carried out	Must be done before	Replacement options	Management unit	Sequencing rules
Staking	Staking with wooden stakes.	Before flowering to fruit set of first truss	Appearance of the first truss	The plant falls over	Staking spread out over several days, done after flowering due to lack of labor	Bed or individual plants	Sanitary deleafing before staking
Tying	Plants are tied three times: 25–30 cm between ties.	At staking to the first harvest	At staking	The plant falls over	Pruning done after flowering due to lack of labor	plant	Staking before tying
Pruning	Selection of 2 or 3 vigorous stems per plant	Flowering to fruit set of first truss	From staking and flowering of the first trusses	The plant falls over	Staking spread over several days and done after flowering due to lack of labor	plant	Pruning before tying, plant by plant
Sanitary deleafing	Removing senescent and spotted leaves, and those in contact with the soil.	8–10 days after planting to mid-harvesting period	8–10 days after planting, then from pruning	Mid-harvesting period	Leaf removal spread over several days due to lack of labor	plant	Leaf-thinning before pesticide application
Leaf-thinning	Removing all leaves above each truss after fruit setting	Fruit setting to mid-harvesting period	When fruit caliber is around 1–2 cm	Mid-harvesting period	Removing only senescent and spotted leaves	plant	Leaf-thinning and debudding at the same time

Debudding	Removing buds along the stems selected at pruning, at each plant tying, and each week.	Pruning to mid-harvesting period	When buds are 5–10 cm in length	Mid-harvesting period	Keeping buds which bear trusses in flower. Debudding spread over several days due to lack of labor	plant	Tying before debudding. Leaf-thinning and debudding at the same time
Topping	Cutting the apical bud to hasten fruit maturity	During the harvesting period	When fruit turns pink	Fruit colour is slightly red	Topping done only if tomato prices on the markets are increasing	plant	Debudding before topping
Crop protection	Weekly application of insecticide + fungicide with a backpack sprayer	8–10 days after planting till the first harvest	8–10 days after planting	Before the first harvest	Number of pesticide applications and active ingredient rates reduced due to lack of pesticides	Plant	Leaf-thinning + debudding before pesticide spraying

When an operation could not be carried out as originally planned or within the time limit set by the farmer, replacement options were applied (Table 2). We observed that the farmer favored replacement solutions for plant management operations when there was a lack of manpower or a surplus workload on the farm. For instance, three possible alternatives for deleafing and debudding operations were: 1) the job was spread out over several days; 2) deleafing and debudding were more rapid, that is, less time was spent than planned; and 3) as a last resort, the operation was postponed. Constraints linked to the availability of labor could thus result in uneven plants status in the field. For instance, in 2005, the average number of stems per square meter between fields on LP's farm varied from 5.4 to 29.8.

Variability of Plant Management Models and Chemical Treatments

The comparison of the model crop management plan (Figure 2) with the other farmers' practices revealed that some decision rules were common to all the farmers, be it in the procedures or in the positioning and sequencing of operations (Table 3). Plant management, including staking, pruning, deleafing and debudding, was applied by all, as was preventive chemical control. The priority given by farmers to chemical treatments over other operations in the case of a heavy workload on the farm reflected the importance of controlling pest attacks at all costs.

The main differences were linked to the modalities of the decision variables (Table 3). For example, the sanitary deleafing before flowering

TABLE 3 Technical operation for tomato plant management and crop protection by farmers*

Technical operation	Modality	Number of farmers	%
Staking and pruning		35	100
Leaf thinning to reduce pests			
Before flowering	1	7	21
Throughout the crop cycle	2	28	79
Leaf thinning for improving fruit size			
Maintaining green and healthy leaves	0	5	14
Removing leaves under fruit set trusses	1	30	86
Debudding			
Only once at staking and pruning	1	2	6
Soft debudding (3–4 during the cycle)	2	19	54
Hard debudding (each week)	3	14	40
Pesticide application			
Use of fungicide and insecticide		34	97
Use of insecticide only		1	3
Mixture of fungicide + insecticide		33	94
No application during harvesting period		12	34
Application during harvesting period		23	66

*Farmers were interviewed in 2003 and 2005.

(modality 1) was only done by 21% of the farmers, as opposed to 79% who deleafed several times during the cropping cycle (modality 2). Deleafing to increase productivity took two forms: the first consisted in keeping all the green and healthy leaves above a set truss when the fruits measured 1–2 cm, and the second consisted in removing all the leaves under the truss with its set fruits (86% of cases). Debudding took three forms: 1) once at the same time as staking + pruning; 2) 3–4 times during the cycle, that is, each time the plant was tied to its stake, and 3) 7–9 times during the whole cycle, that is, once a week on average.

Of the nature of pesticides that were used, only one farmer used insecticides alone; all the others farmers used insecticides and fungicides, and 97% of these farmers used a mixture of pesticides. Dithane M45 and Bordeaux Mixture were the main fungicides used by 91% and 56% of the farmers, respectively, and Decis E25 and Karate Xpress were the main insecticides used by 62% and 71% of the farmers, respectively (Table 4). No herbicide was used by any of the farmers. The 14 commercial formulations that were inventoried included 13 active ingredients belonging to 10 different chemical families (Table 4).

The number of pesticide applications per field varied from 4 to 23 depending on the farmer, and could not be linked to the time lapse between planting and the appearance of stage M3 (Figure 3), nor to total amount of active ingredients applied (Figure 4). Although many pesticides

TABLE 4 Commercial formulation, active ingredients, and chemical groups of pesticides, and number of tomato farmers* who used pesticides

Commercial formulation	Active ingredients	Chemical groups	Number of farmers (% of total)
Fungicides			
Topsin	Thiophanate methyl	Benzimidazoles	1 (3%)
Dithane M45	Mancozeb	Dithio-carbamates	31 (91%)
Bordeaux mixture	Copper sulphate		19 (56%)
Norsineflo	Manèbe + Thiophanate methyl	Benzimidazoles	9 (26%)
Daconil	Chlorothalonil	Chloronitriles	6 (18%)
Score	Difenoconazole	Triazole	2 (6%)
Aviso DF	Cymoxamil + metiram zinc	Acetamides + Dithiocarbamates	1 (3%)
Insecticides			
Decis E25	Deltamethrin	Pyrethroid	24 (71%)
Karate Xpress	Lambda-cyalothrin	Pyrethroid	21 (62%)
Klartan	Tau-Fluvanilate	Pyrethroid	6 (18%)
Callifol	Dicofol	Carbinol	6 (18%)
Trigard	Cyromazine	Triazine	5 (15%)
Vertimec	Abamectin	Avermectines	4 (12%)
Endor	Endosulfan	Organo-halogens	4 (12%)

*Data for 2003 and 2005.

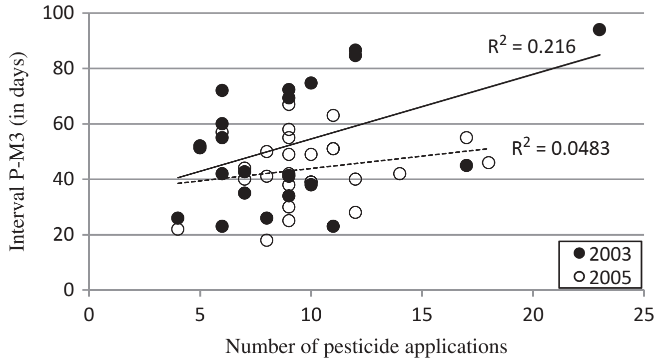


FIGURE 3 Relationship between the interval (in days) from the planting date to the M3 pest and disease infestation stage (31–50% of tomato plants attacked) and the number of pesticide applications.

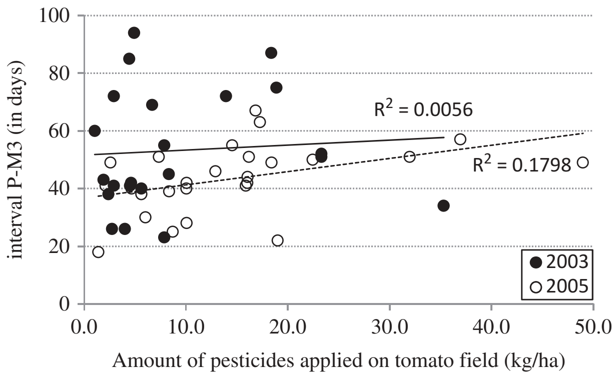


FIGURE 4 Relationship between the interval (in days) from the planting date to the M3 pest and disease infestation stage (31–50% of tomato plants attacked) and the amount of total pesticides applied on tomato fields (in kg/ha).

were used, they appeared to have only a very limited effect, and in addition, the effect was highly variable. The average number of applications per type of farm ranged from 8.9 to 9.5 per tomato field with no difference between the types of farm (Table 5). However, the average number of fungicide applications was significantly higher ($P < 0.05$) among type 2 farms (8.3 ± 1.9) compared to type 1 (4.3 ± 3.9), which were the two types of farm for whom agricultural activities were the main source of income. No statistical difference was found between farm types concerning the number of active ingredients used.

There was a tendency to over apply both the main insecticides and fungicides used in both years. The average dose applied compared to the pesticide manufacturers' recommendations was 112%, 208%, 129%, and 99% in 2003, and 184%, 194%, 260%, and 112% in 2005 for deltamethrin,

TABLE 5 Pesticide management by the four types of farmers (n = number of farmers surveyed) in Mayotte

	Type b1 ($n = 10$)	Type b2 ($n = 18$)	Type b3 ($n = 3$)	Type C ($n = 4$)
Number of fields surveyed	13	27	3	7
Number of pesticide applications	9.5 (5.4)[1]	9.5 (2.4)	9.3 (2.3)	8.9 (4.7)
Fungicides	*4.4 (3.9)[2]a*	*8.3 (1.9)b*	*5.3 (4.6)ab*	*8.0 (5.1)ab*
Insecticides	*6.1 (3.8)*	*8.7 (3.1)*	*9.3 (2.3)*	*6.4 (4.1)*
Number of active ingredients				
Fungicides	*2.0 (0.7)*	*2.7 (1.6)*	*1.0 (0)*	*2.7 (1.6)*
Insecticides	*2.2 (0.6)*	*2.5 (1.5)*	*1.7 (0.6)*	*2.0 (0.9)*
Quantities of active ingredients applied				
Fungicides	17.5 kg/ha	18.2 kg/ka	3.9 kg/ha	18.8 kg/ha
Insecticides	2.0 l/ha	5.5 l/ha	1.5 l/ha	1.7 l/ha

[1]Mean (standard deviation).

[2]Means with no letter in common were significantly different (0.05 level). Differences between means in farmer groups were tested with a non-parametric test for k independent samples.

TABLE 6 Percentage of the average dosage applied by farmers in 2003 and 2005 compared to the recommended dosage on the pesticide packaging for (A) insecticides and (B) fungicides

		2003		2005	
Active ingredient	Dosages on the packages	Mean (SD) %	Range %	Mean (SD) %	Range %
A–Insecticides					
Deltamethrin	0.5 l/ha	112 (62)	43–267	184 (86)	22–360
Lamda-cyhalothrin	0.25 l/ha	208 (104)	87–533	194 (117)	82–480
Tau-Fluvalinate		251 (148)	100–404	317 (104)	200–400
Dicofol	1 l/ha	115 (68)	44–180	146 (143)	70–431
Cyromazine	0.4 kg/ha	141		82 (27)	42–113
Abamectin	0.5 l/ha			112 (19)	96–141
Endosulfan	1.75 l/ha			42 (1)	41–43
B–Fungicides					
Mancozeb	2 kg/ha	129 (64)	14–267	260 (206)	75–805
Copper Sulphate	6.25 kg/ha	99 (102)	5–288	112 (88)	32–314
Maneb + Thiophanate-methyl	5 l/ha	91 (79)	17–200	104 (63)	62–226
Chlorothalonil	3 l/ha	19 (2)	18–21	92 (20)	50–109
Difenoconazole	0.5 l/ha			258 (230)	95–420
Cymoxanil + metiram-zinc	2,5 kg/ha	153 (5)	149–156		

lambda-cyalothrin, mancozeb, and copper sulphate, respectively (Table 6). However, the minimum and maximum values recorded revealed cases of much higher over-application, up to 533% for lambda-cyalothrin, as well as some cases of under-application too (e.g., 5% and 32% in 2003 and 2005 for copper sulphate; Table 6).

Of the farmers included in this study, 34% did not apply pesticides during the harvesting period, whereas 66% did (Table 3). Of those farmers who applied pesticides during harvest, none respected the pre-harvest interval for application.

Changes in Practices Between 2003 and 2005

The comparison of practices in the two years revealed the stability of the crop management model. Few changes in practices were observed and most were in situ adaptation to off-farm constraints involving access to inputs and equipment. For example, in 2005, the exemplary farmer decided to treat earlier after planting and to diversify the range of pesticides used for better pest control. Another farmer decided to no longer debud after pruning due to a high work load on the farm, and to see whether this technique led to higher yields or better fruits. However, he was unable to reach any conclusions as to the merits of debudding after pruning. This approach led to a personal learning process where the information acquired was subsequently used to enrich a range of replacement solutions that could be applied when he was faced with outside constraints. Most of the farmers believed that staking and pruning, like large applications of fertilizer and manure, were required to achieve high yields, and did not wish to take the risk of abandoning those techniques, even when faced with severe labor constraints.

Some other practices also changed on certain farms, such as changing varieties, a switch from motorized tillage to manual tillage, due to lack of inputs and equipment at the beginning of the season.

Diversity of Management Methods and Uncertainty of Access to Productive Resources

The wide range of technical management methods also partly reflected some structural characteristic of the farms, notably access to land, or belonging to a particular farm type. Type 2 farmers (illegal immigrants) mostly planted at high densities (>3 plants/m^2), as shown by the χ^2 analysis between the four types of farmers and the three density classes ($P < 0.05$). On the other hand, no relation was found between those four farm types and the two forms of deleafing ($P = 0.17$), or the three forms of pruning/debudding ($P = 0.23$), or between the forms of pruning/debudding and planting density ($P = 0.33$). All farmers managed plants and pruned irrespective of planting density.

Type 2 farmers mostly (10 out of 18) planted at the highest densities and treated most with fungicides. These farmers were all concerned by uncertain land tenure, and were applying an intensification logic despite restricted access to productive resources. This behavior was indicative of seeking to make the most of the current cropping season, as the next one was in no way guaranteed. Type 4 farmers, who were in a stable situation as far as land tenure was concerned (like type 1 and type 3), and who had the greatest financial capacity and access to technical information, did not apply more pesticides and did not manage the vegetation differently from type 2 farmers, which could be explained by the fact that they used illegal laborers who had often learned to farm with their peers (type 2 farmers) and took some management decisions.

In general, farmers appeared to use the solutions available at hand, that is, as far as possible they tried to cope without using resources from outside the farm, and to count only on their own work force. In this type of highly manual family-based agriculture, we estimated that an average of 900–1,000 m^2 of land under tomato production could be farmed by a single person. Thus, any disruption of the system that affected labor availability forced the farmer to find alternative solutions. An illustration was the series of replacement solutions applied by one farmer when he had no back-up labor for pruning/deleafing operations: a) spread the work over several days; b) reduce the work load per plant in order to complete operations on the scheduled day; c) postpone the whole operation with no guarantee that he would be able do it later; and d) abandon the operation.

But, whatever the plant management system applied, or the chemical crop protection methods used, or the planting density, the farmers were obliged to cope with pest management. All the fields in the study had the maximum infestation score (M5) at the start of harvesting, based on the symptoms of attack by target spot, bacterial canker, tomato fruit flies, and tomato fruit worms, and pest incidence varied from field to field.

The variability among farmers in the number, rates and mixtures of pesticide applications partly reflected a problem of access to pesticide resources in terms of pesticides availability in market throughout the year, exacerbated by the reticence of type 2 farmers to go into town for supplies, and partly a poor control of chemical protection techniques, notably because the recommendations given by the technical extension services had not been adapted. The sanitary deleafing carried out by all the farmers, and its intensity, was in response to the lack of available pesticide products and the severity of parasite attacks, even though its lack of effectiveness in controlling pests had been demonstrated. Although, according to the farmers, deleafing helped limit the spread of diseases, according to our observations on field, it was not effective in reducing tomato fruit flies (*Neoceratitis cyanescens*), one of the main pests, or in limiting fruit losses.

DISCUSSION

Our representation of the management of a short-cycle crop, such as field-grown tomatoes, complied with the model used in its general structure (planning/management, decision variables, decision rules and indicators, management unit), and in the categorization and formalization of decision rules (with sequencing, triggering/ending, and arbitration rules for technical management). The use of the crop management model in a smallholder farming context, in which the work is mainly manual, with diversified short-cycle crops such as market garden crops, was a source of enrichment for the model. For instance, the formalization of crop management at the field scale showed that the smallest management units, such as the planting beds, planting line or row, or even a single plant, were also significant units for making technical decisions and applying techniques, as also shown by Mawois et al. (2011) in Madagascar.

These smallholder management units may not be compatible with current agricultural advice, as shown in the case of chemical treatments where the recommendations given by agricultural advisors are based on treatments per hectare, as in large-scale crops under temperate conditions, whereas the farmers in Mayotte calculated their protection based on beds or the number of plants, and using their basic tool, the knapsack sprayer. This resulted in major discrepancies between the advice given and the farmers' practices concerning pesticide dosage and volume applied. This finding at the field scale, validated on all the farms, argues in favor of the redefinition of the technical advice given concerning chemical treatments. The fact that under- and over-application was observed on the same farm, and among farmers, reinforces this recommendation. Such mismatches are frequently observed among family-based market gardens in Sub-Saharan and tropical regions, as reported (Ntow et al. 2006; Kanda et al. 2009; Asgedom et al. 2011; N'Dienor 2011; Pedlowski et al. 2012; Huat et al. 2013).

The ineffectiveness of pesticide applications in terms of failing to reduce the impact of pests on the crop, when the active ingredients of the fungicides and insecticides used are potentially polluting and harmful for humans and for aquatic environments (Agbohessi et al. 2012; Ahouangninou et al. 2012; Kafilzadeh et al. 2012), was one of the most important findings of this study, as were the complementary strategies, or even substitutions, between plant management and chemical treatments used to cope with the plant health statuses encountered. This ineffectiveness was evaluated by the importance and the duration of symptoms attack on a field more than isolated impact of yield that was very difficult to identify in our study.

There was a lack of appropriate technical information to guide farmers on the merits and opportunities of these combinations of operations. As regards pruning, a particularly time-consuming operation, a trial we conducted in 2005 (Huat 2008) showed that tomato yield can be increased, without affecting fruit size, by growing the crop without pruning. The merits of the other non-chemical operations carried out partially for sanitary reasons need to be more systematically tested. In particular, deleafing is a routine technique in greenhouse tomato growing, to regulate production (Scholberg 2000; Gaytan-Mascorro et al. 2008) or to reduce parasite pressure in certain cases (Bonato and Ridray 2007), but which is relatively rare in field-grown tomatoes. Although deleafing does have some advantages, if it is too severe it may jeopardize the biological control of a pest by its natural predators, because the eggs and larvae of predators are removed along with the leaves (Bonato and Ridray 2007).

The uncertain access to productive resources of different origin (unstable supply of inputs, insufficient equipment, insufficient manpower, legal status), affected cultivation operations and their variability among farms and between years, and proved to be particularly high. This compounds the difficulty involved in designing appropriate technical advice, particularly for crop protection, that is adapted to the needs and preferences of farmers, with appropriate training geared to conventional methods of control and toward alternative cost-effective methods of pest control (Ntow et al. 2006; Snelder et al. 2008).

The uncertainty of access to a given resource was not perceived in the same way by all the farmers. Their perception depended on the individual farmer's access to information and on the alternative solutions available in order to cope with a constraint, and on the consequences of a given technical choice for crop performance. This result is in accordance with findings of others authors (Hashemi and Damalas 2011; Probst et al. 2012). The farmer's perception of risk might thus be an incentive or a deterrent to seeking alternative solutions. For example, a small group of farmers in this study were ready to eliminate staking and pruning their crop, whereas the majority of farmers could not envisage growing tomatoes without pruning or staking. In fact, this group of farmers wanted to avoid the risk of failure. Most of the farmers needed reassuring that any new technique could be applied without any greater constraints than they used to cultivate. In Mayotte, plant management operations (staking, pruning, deleafing) are the result of a learning process between farmers, so far without any major intervention from research and development agents.

In the farmers' decision-making model, their perception of uncertainty and risk must be accounted for, and also the learning process which helps farmers extend their range of possible solutions to face unforeseen situations; such a learning process could occur thanks to the farmer's own experience, or the exchanges of ideas with other social groups of farmers (Darnhofer et al. 2010). But these solutions are not always effective. The way farmers see the merits of a given practice is therefore a source of invention and discussion for agricultural researchers, with a view to testing the relevance of certain farming practices compared to the objectives the farmers have in mind when applying the practices in a given context.

Together, the high level of pests, widespread incorrect use of pesticides, the general intensification of agriculture and the increase in demographic pressure, are responsible for the increasing pressure on the environment. Although all farmers said they were aware of the negative impact of poor pesticide use on the environment, most did not take any precautions to protect themselves and the environment: For instance, they did not wear protective clothing, and mixed sprays and washed spraying equipment close to the water supply. This situation is made even more complex and political in that a large proportion of local products are produced by farmers and agricultural workers who are illegal immigrants, and their main objective is to achieve high tomato yields by increasing agrichemical inputs (fertilizers, pesticides), regardless of their impact on the environment.

The majority of the population relies heavily on agriculture for both subsistence and commercial purposes. Although our analysis focused on the island of Mayotte, the situation is similar in other small island developing states (Van der Velde et al. 2007; Saffache 2008). The development of local crop production should be done while maintaining the rich marine and terrestrial ecosystems (Myers et al. 2000). These islands are very dependent on the preservation of their natural resources, and alternative and sustainable agricultural practices need to be encouraged and supported by institutional measures or obligations.

CONCLUSION

The analysis of technical management methods helped shed light on the great variability in tomato growing practices in Mayotte, and increased our understanding of the main determinants. The uncertainty of access to resources and the lack of simple technical information on the use of plant protection products largely explain the variability in practices and their inefficiency, notably in terms of crop protection.

A compromise is needed between crop management that involve cultural plant management techniques (pruning, staking, deleafing) for pest control. If marine resources are under threat due to risky and inefficient agricultural practices, more research is needed to find better ways of optimizing plant/stem density for yield and pest management purposes, and to develop agro-ecological pest management methods which are labor and costs effective.

According to the United Nations Environmental Programme (2004), the time it takes for environmental pressures to become severe and possibly irreversible is much shorter on small developing islands due to the high vulnerability of their fragile ecosystem to pollution. Governance solutions have to be found to ensure that Mayotte and other similar SIDS will continue to benefit from their natural resources while regulating the pressures on the environment, notably to ensure local agricultural production continues to increase without the risk of environmental pollution. Agricultural extension services should help farmers implement alternative methods of pest management like IPM that use fewer toxic pesticides.

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