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RESEARCH ARTICLE

# Modelling spatial extension of vegetable land use in urban farms

**Marie Mawois · Marianne Le Bail · Mireille Navarrete · Christine Aubry**

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**Abstract** Increasing vegetable production to meet the growing urban demand is essential in developing countries. This article proposes a new model to analyse farm land use for market gardening in tropical urban agriculture and to evaluate the capacity of farmers to increase their vegetable surface area. It is based on a decision model simulating crop sequences and crop location initially validated for temperate arable and vegetable productions. In this study, the leafy vegetables land use model (LYLU) was first adapted to suit the specificities of urban leafy vegetable production: short crop cycles; wide crop diversity; instability of the cultivated area during a season, in our case due to flood recession; manual labour and close relationships with retailers. The output variables of the model were then compared to observations collected on an 11 farms sample. The model estimates the surface area for each leafy vegetable, depending on plant species requirements, farm resources and relations with retailers. This is the first model that simulates the spatial and temporal variation of the farm land and the exploitable surface areas over the cropping season depending on the dynamics of water availability and labour force. In some cases, up to half of the surface remained uncultivated because of slow fields' drainage at the end of the rainy season and/or lack of water in the wells in the dry season. Moreover, the available labour force on farm and the way vegetables were sold greatly affected the intercrop period, which in turn contributed to reducing the cultivated area. Finally the model was used to quantify farmers' room for manoeuvre in order to increase their vegetable cultivation area. Opportunities to overcome them were discussed both at farm and territorial levels. This is an innovative approach that could be useful to face the growing urban demand in developing as well as in Western countries.

**Keywords** Land use · Crop location · Decision model · Farming systems · Leafy vegetables · Urban agriculture · Madagascar

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## 1 Introduction

Vegetables, and among them the leafy vegetables, play an important role worldwide in the populations' diets, filling an essential share of nutritional and medicinal needs (Gockowski et al. 2003; Smith and Eyzaguirre 2007). Except for root vegetables, they are very perishable products. For example, once harvested, leafy vegetables can be preserved <2 days outdoors without deteriorating and fruit-vegetables about 1 week. Therefore, freshness is a major quality criterion and requires harvest staggering to avoid storage (Moustier and Danso 2006), as well as rapid transport to market. In industrialised countries, vegetables are mainly produced in very specialised zones and rapidly transported by refrigerated trucks towards remote consumption areas. This leads to particular technical choices (long shelf-life cultivars, harvests before maturity, etc.), different from those for direct selling (Navarrete 2009). In developing countries, where insufficient means of transport between rural areas and cities rapidly decrease vegetable quality, supplying cities with fresh products (Nguni and Mwila 2007), particularly leafy vegetables (Moustier and Danso 2006), largely relies on urban agriculture. It has recently been found in several contexts that market garden farming systems including leafy vegetables are increasing inside or near cities (De Bon et al. 2010) in response to a growing urban demand. Will it be possible in the future to increase vegetable production as fast as cities develop so as to contribute to their sustainable development (Agbonlahor et al. 2007; Mc Clintock 2010)?

From an agronomic point of view, increasing vegetable production on farms requires either an increase in yields per surface area, within the limit of farmers' technical capacities, and/or an increase in the cultivated surface areas. The latter is an important issue in urban agriculture, which faces potential competition for land from classical urban uses (housing, infrastructure, etc.) (Van Veenhuizen 2006). For example, a recent geographic research has been undertaken in Vietnam by Thapa and Murayama (2008) to evaluate the possibility of extending the surface areas of urban agriculture. These authors proposed a method to classify urban territories according to various criteria (soil, land use, water resources, road network and market access), in order to assess their potential for developing urban agriculture. Economic models have also been built to quantify the evolution of urban horticultural activities and their relationship with material and non-material resources (Parrot et al. 2008). Although all these approaches are very useful for urban planners, they do not take into account farmers' capacities to manage land resources. Therefore, an agronomic question still remains open: To what extent do farmers have the technical and organisational room for manoeuvre to modify their systems at plot and farm level in order to meet the growing urban demand? Assessing farmers' room for manoeuvre, i.e. the capacity to adopt technical changes at a particular level without endangering farm system functioning at another level (Navarrete et al. 2006), requires the identification of the main factors determining the diversity observed in strategic and technical decisions on farms. On this basis, it is then possible to design the decision pattern of land use management. These two points rely on an understanding and modelling of the farmers' decision-making processes in order to simulate and test their room for manoeuvre with regard to technical and farm-management changes.

Such models may vary from simple modules describing the modalities and dates of cultural practices (Jones et al. 2003) to more complex ones formulating a management module as a set of decision rules (Carberry et al. 2002; Keating et al. 2003). We can also represent them as a global decision subsystem that imitates farmers' decision-making processes (Navarrete and Le Bail 2007; Le Gal et al. 2010). Such models refer to management sciences and ergonomic studies applied to farming systems (Sebillotte and Soler 1990; Cerf 1996). For decisions on crop sequences and crop location on farm land, the first conceptual framework concerned arable cropping systems (Aubry et al. 1998; Aubry and Dounias-Michel 2006). This decision model determines key variables as regards crop sequences and crop location on farm land. Its adaptation to market garden crops in France, SaladPlan (Navarrete and Le Bail 2007), also simulates crop sequences and crop location, but in the case of multiple short cycles. Such models have demonstrated their operational value for understanding farming practices as regards farm land-use management (Aubry and Dounias-Michel 2006) and for discussing farmers' room for manoeuvre to cater for the market (Navarrete et al. 2006).

In this study, we analysed how farmers plan crop sequences and crop location for leafy-vegetable production in Mahajanga, a major city of Madagascar where land use for urban agriculture is a key problem (Fig. 1). Leafy vegetables are considered as an emblematic example of market gardening crops, considering their major importance in local diets and the high level of complexity of crop planning. In building the LYLU model we adapted the SaladPlan model to fit the specificities of tropical urban market gardening: high diversity of the leafy vegetables cultivated, instability of the cultivated area on farms during a season, manual labour and strong retailers' influence on technical decisions. The LYLU model affords an understanding of the design of surface areas for each leafy vegetable on farm land in urban tropical conditions.

This model is a conceptual model parameterised so as (1) to explain a posteriori the variability of surfaces areas cultivated in leafy vegetables on farms and (2) to discuss possibilities of increasing these surfaces based on a

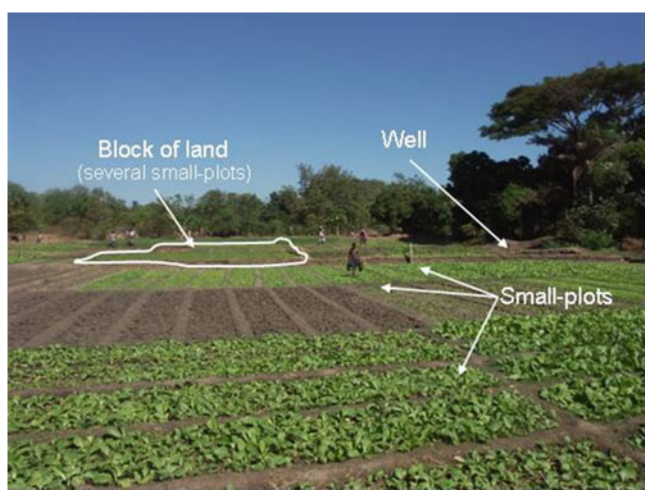


**Fig. 1** Leafy vegetable production in urban area of Mahajanga (Madagascar)

quantification of the gap between the potential variables simulated by the model and the effective variables registered in farms. Therefore, it was not computerised nor developed to predict the levels of the observed variables.

We first present our methodology with (1) the main variables of the previous models, (2) the choice of our study case and the data available on leafy-vegetable production in this context and (3) the choice of the surveyed farm sample and the types of on-farm surveys made. The results then rely on two parts: (1) calibrating the general structure of the LYLU model and (2) evaluating the accuracy of the model to reflect the diversity of producers' land use choices, using data collected with the on-farm survey.

## 2 Materials and methods

### 2.1 The LYLU model

In both previous models, farmers' decisions related to crop sequences and location were represented by four main decision variables for each crop:

1. Cultivable surface area: all the fields on which farmers consider that they can allocate a crop according to the field characteristics (soil texture, soil depth, slope intensity and distance to farmhouse) and crop requirements.
2. Return time: the minimum period before cultivating the same crop again in the same field.
3. Potential preceding crops: all crops which can be cultivated before a given crop. They are classified by farmers in order of interest, according to potential agronomic interactions (positive or negative) between previous and subsequent crops.
4. Size of the field block allocated to a given crop during each crop cycle. It is maximised by the ratio between cultivable surface area (1) and return time (2), but its real value depends on the available resources at farm level (land and labour force) and on exogenous constraints (commercial contract, production quota, etc.).

SaladPlan includes additional variables that take into account short cycles of market gardening crops such as the number of lettuce cycles per plot and per year, the main period for lettuce cultivation on the farm, the length of intercrop periods and the developed surface area under salad throughout the year. This latter enables to take into account in the calculation of the surface area the fact that one plot may host several successive crops per year. The SaladPlan model estimates both developed surface area and harvesting period for each crop, according to (1) the climate, the agronomic requirements of the various crops and the field characteristics and (2) economic and organisational constraints of the farm (labour force and marketing).

### 2.2 Leafy vegetable production in the case study of Mahajanga

Mahajanga is a major city located in the northwest of Madagascar (15 °25 South, 46 °11 East), with an arid, tropical climate (1,400 mm of annual rainfall mostly from December to February). This case was chosen because of (1) its typical urban agriculture situation with high land-use constraints (Mawois et al. 2011), (2) its high population growth rate (more than 3 %/year) leading to a steep increase in the demand for leafy vegetables and (3) the predominance of leafy vegetables in cropping systems. Three main characteristics of the leafy vegetable production were taken into consideration in building the LYLU model.

#### *2.2.1 A wide diversity of leafy vegetables*

Market gardening is mainly practiced during the dry season, from April to the end of November. Three major types of leafy vegetable are grown:

1. Traditional short-cycle leafy vegetables ($LV_{short}$) like Fotsitaho (*Brassica campestris* var. *amplexicaulis* Lour.), Anatsonga (*Brassica Campestris* var. *peruviridis* Lour.) and petsaï (*Brassica pekinensis* Lour.) with a cycle length of about 3 weeks
3. Traditional long-cycle leafy vegetables ($LV_{long}$) like Mafanes (*Spilanthes acmalae* Rich.) and Morelles (*Solanum nigrum* L.) with a cycle length of about 3 months and several harvests over the season
3. Lettuce (Lett, *Lactuca sativa L.*), with a cycle length from 4 to 5 weeks, more demanding in terms of labour, water and fertilisers than $LV_{short}$.

Thus, they vary with regard to the length of the cycle, agronomic requirements and their functions in the farmers' strategy: Lettuce is a high benefit cash crop rather consumed by tourists, while short-cycle leafy vegetables fetch lower prices.

#### *2.2.2 Instability of the cultivated area of farms during the year*

Leafy vegetables in Mahajanga are cultivated in two main types of environment (Mawois et al. 2011):

1. Lowlands, where rice is cropped during the rainy season and leafy vegetables are cropped when the water level gradually drops (following the topography top-down). The upper areas of lowlands (locally called *tanety*) are not flooded during the rainy season and consequently can be planted with market garden crops throughout the year, until wells have dried up. These areas represent a very small proportion of market gardening surfaces.

Soil is mostly sandy-loamy red, with hydromorphism on the lowlands and risks of drought on the *tanety*.

2. Lakesides, under water during the rainy season and progressively cultivated following the retreat of the lake water during the dry season. The soil in these areas is generally more clayey than on the lowlands.

In both types of environment, the start of the rainy season marks the discontinuation (gradual on lakesides) of vegetable crops. Moreover, as land tenure is variable (land either owned, or rented on a long-term basis or rented for the whole season or just a part of the season), some farmers cultivate only during a part of the season.

#### *2.2.3 Entirely manual agriculture leading to specific technical and commercial management units*

The farm land is geographically divided into one or several blocks (called block of land), each block being divided into elementary units called small plots (Fig. 1). The small plot is a rectangular piece of land of variable length (on average 8.8±2.2 m) but relatively stable width (1.5±0.4 m) (Mawois et al. 2011), calculated for the manual watering of half a small plot by a worker walking between plots. The average surface area of a small plot is 13.1 $m^2$ with a standard deviation of 4.8 (average of all the farms over two seasons, i.e. 1,266 small plots). At one date, the number of small plots per block depends on water dynamics that vary during the cultural season (see below). The maximum number per block varied from 3 to 104 with an average of 22 in the sample (standard deviation of 20).

For farmers, a small plot is both a cultivation unit (planting, fertilisation, weeding, watering and pest control) and a commercial unit (negotiation of the harvest date and sale price with retailers). At the beginning of each season, small plots are prepared (delimitated and ploughed) manually, which is highly labour intensive (maximum three small plots per day).

The leafy vegetables are sold on urban markets mostly by female buyers who always ask farmers for a certain diversity of leafy vegetables daily to meet the consumers' demand. These women harvest crops daily and sell the vegetables in the city markets (Mawois et al. 2011). The harvest duration of a small plot is variable, from 1 to 4 days: It depends on the seller's transporting and selling capacity and on the number of farmers she works with.

### 2.3 Data acquisition

Surveys were carried out on 11 farms during two campaigns (2006 and 2007) in order to explain the surface area under leafy vegetables and to compare it with potential values on the farms.

These farms were located on the three production sites in peri-urban areas around Mahajanga. They were chosen on the basis of a preliminary survey aimed at characterising the farming systems on a sample of 91 farms (Mawois 2009). They were selected to cover a wide range in types of land (lowlands and lakesides), the level of available resources (surface area, labour force and water accessibility) and the combination of leafy vegetable crops (Table 1).

The first step of the survey concerned the analysis of the overall farm system management. The second step more specifically addressed the management of leafy-vegetable production. Each block of land and small-plot was pinpointed on the farm land and the farmers' plans for crop sequences and crop location were registered. Based on this field pattern, we analysed how farmers plan the crop sequences and the crop location for leafy vegetable production. These two steps, along with the more global, contextual knowledge described above, provided the data for the input variables of the LYLU model.

Here, all the surfaces areas are expressed in number of small plots because these are the cultivation unit (see above). For model evaluation, on-field observations were made over a period of 2 years (2006 and 2007) to record the number of small plots planted with each leafy vegetable (every 10 days) and the cultural practices of the period. In that survey, the surface areas were calculated for each campaign on each farm. To compare the different surface area variables in the model (see below) over the time and between the farms, we created integrated surface area variables across the cropping season.

Thus, for each variable $V$, $\sum_{t=p}^{q} V_t$ is the integrated surface area variable corresponding to the daily sum of areas $V$ between $t=p$ (beginning of the cultivation season) and $t=q$ (end of the cultivation season). The beginning and end of the cultivation season were estimated, based on weather data (source: http://french.wunderground.com/history/airport/FMNM) and field observations (establishment of small-plots by farmers). During the 2 years of the study, the cultivation season started on 10th April and ended on 30th November. More generally, these dates may vary within a few days from 1 year to another according to the rhythm of rain stop and return.

## 3 Results and discussion

### 3.1 Calibration of the LYLU model

The specific characteristics of the local context presented above led to the following adaptations of the SaladPlan model:

1. The variable expressing the cultivated area on farms varies during a season, depending on water dynamics in lowlands and lakesides.

**Table 1** Main characteristics of the 11 surveyed market gardening farms

| Farm[a] | Total surface areas[b] ($m^2$) | Labour force | | Non-agricultural activity | Marketing strategy[c] | Main crops |
|---|---|---|---|---|---|---|
| | | Permanent | Temporary | | | |
| Ab1 | 970 | 2 | No | No | C | $LV_{short}$, $LV_{long}$ |
| Ab2 | 900 | 2 | No | No | A | $LV_{short}$, $LV_{long}$ |
| Ab3 | 500 | 1 | No | Yes | C | $LV_{short}$, $LV_{long}$ |
| Ad1 | 1,150 | 2 | No | Yes | A | Lett, $LV_{short}$ |
| Ad2 | 310 | 1 | No | Yes | A | Lett, $LV_{short}$ |
| Ad3 | 360 | 1 | No | Wholesaler | B | Lett, $LV_{short}$ |
| Ad4 | 1,670 | 2 | Yes (2007) | No | C | Lett, $LV_{short}$, $LV_{long}$ |
| Ad5 | 610 | 1 | Yes | No | C | Lett, $LV_{short}$ |
| Bk1 | 1,440 | 2 | Yes | No | C | Lett, $LV_{short}$, $LV_{long}$ |
| Bk2 | 950 | 2 | Yes | No | C | $LV_{short}$, $LV_{long}$ |
| Bk3 | 440 | 1 | No | Yes | C | Lett, $LV_{short}$, $LV_{long}$ |

[a] *Adi, Abi* farms on lowland, *Bki* farms on lakeside

[b] For season 2006 (same area in 2007 except Ab3)

[c] *A* farmer who sells directly and through wholesalers, *B* farmer who sells his own and other farms' products on urban markets, *C* farmer who sells only his own products

2. All the surface areas are expressed in number of small plots, which is the technical management unit.
3. Intermediate variables depend on relationships with retailers.
4. Within the wide diversity of leafy vegetables, the six major species were entered in the model as well as the hierarchy of rules between crops.

The calibration step uses the results of surveys.

### *3.1.1 The variables of the model and their combination*

The LYLU model consists of successive steps (Fig. 2) allowing to predict the output variables: (1) the effective developed surface for each vegetable k ($S\_dev_k$,) and (2) crop sequences on farm land. The input variables (in italics in Fig. 2) are organised on three levels: (1) the crops' requirements (water and fertiliser) and the environment (soils and climate), (2) the productive resources on the farm (mainly land, labour and water) and (3) the retailers' requirements (species, quantity and harvest period). Intermediate variables (framed in Fig. 2) consist of temporal or spatial variables. The model progressively estimates:

- The effective exploitable surface area (box A)
- The cultivable surface area devoted to each vegetable (box B)
- The effective period suitable for each vegetable (box C)
- The blocks and periods for each crop (box D)
- The maximum developed surface per block (box E)
- The effective number of cycles per block (box F).

The combination of these variables allows to estimate the developed surface area for each vegetable on the farms and to identify crop sequences on each plot. We shall now examine how these variables are calculated from input and intermediate variables.

*Evolution of the effective exploitable surface area (box A in Fig. 2)* The effective exploitable surface area (S_eff) is the set of surface areas where small plots have been set up for market gardening on the farm. It varies in space and time due to the water dynamics on the farm land and to the labour force needed to establish small plots before transplanting each crop. It depends on the calculation of an intermediate variable, i.e. the maximum exploitable surface S_max.

1. Calculation of the maximum exploitable surface area depending on water dynamics (S_max)

   The maximum exploitable surface area (S_max) of the farm changes with time. It is the set of surface areas sufficiently dried out at a time *t*, for small plots to be set up and potentially irrigated (which depends on the proximity of functional wells). The decision rules are summarised in Table 2 (a): They depend on practical indicators to estimate the drying out of small-plots and on the distance to the well. The maximal exploitable surface area is limited by the total surface area (S_tot), i.e. the surface area managed by the farmer for the market gardening season. There is a gradual increase of S_max over the rainy season due to the retreat of water to reach a maximum corresponding most frequently to S_tot.

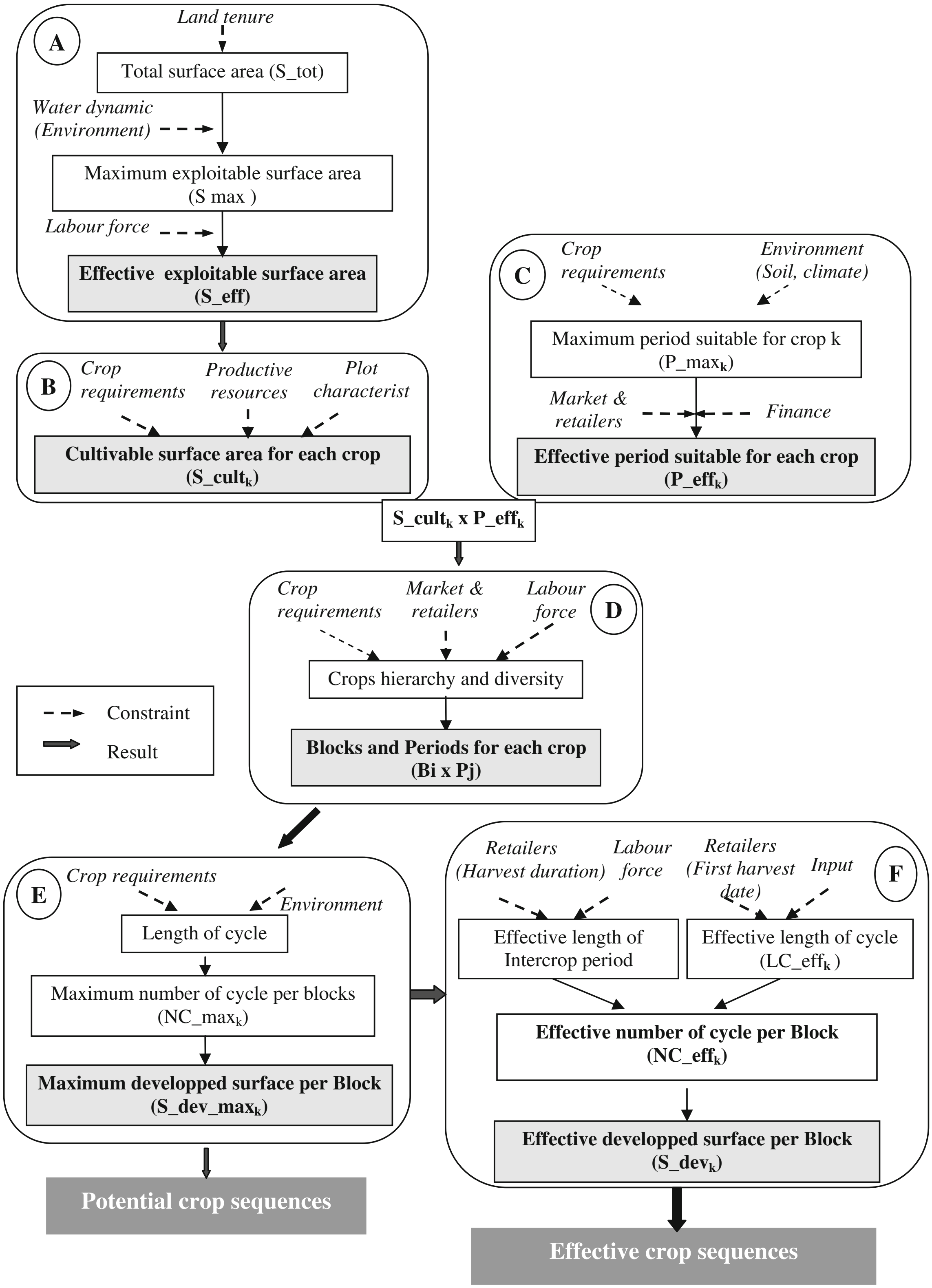


**Fig. 2** The LYLU conceptual model. The six boxes represent the successive steps for predicting the output variable, S_dev$_k$, the effective developped surface per block for each crop k. The A, B, E, and F boxes are spatial data (in number of small plots), and the C box is temporal data (in number of days)

At the end of the season, the return of the rains gradually precludes market gardening, first in the lower areas and gradually on the higher ground as well. The abandonment of small plots depends on the beginning of the rainy season and the intensity of the rains. The higher areas of the lowlands (*tanety*) are cultivated during the rainy season and quickly abandoned during the dry season because they rapidly dry out and are often far from water points.Thus, $\sum_{t=p}^{q} \mathrm{S\_max} = \sum_{t=p}^{q} \mathrm{S\_tot} - \left( \sum_{t=p}^{q} \text{S not dried out} + \sum_{t=p}^{q} \text{S far from a functional well} \right)$ with $p$ = beginning of the season and $q$=end of the season.

2. Calculation of the effective exploitable surface area (S_eff) depending on labour

   The maximum exploitable surface area (S_max) is not always cultivated due to the lack of labour to perform three essential manual operations before planting: (1) creation or renovation of wells, (2) creation of plant nurseries and (3) establishment of small plots. A surface area is effectively exploitable (S_eff) only once these three operations have been carried out.

   Therefore, in the model, the effective exploitable surface area (S_eff) is deducted from S_max, depending on the surface/labour force ratio when the water retreats (Table 2, b).

   Thus, there is a lag between the drying out of the soil and the setting up of small plots (Fig. 3a) that can reach up to 2 months for certain areas of land.

   Thus $\sum_{t=p}^{q} \mathbf{S\_eff} = \sum_{t=p}^{q} \mathrm{S\_max_t} - \sum_{t=p}^{q} \text{S not established with small} - \text{plots}$, with $p$=beginning of the season and $q$=end of the season.

*The effect of the specific features of each crop type on the calculation of the cultivable surface area (box B in Fig. 2) and of the effective suitable period (box C in Fig. 2)* The above variables concern the establishment of the global surface area of usable land for crops on a farm. Regarding decisions on the setting-up and location of each crop type, two other variables have to be determined: the cultivable surface area per crop ($\mathrm{S\_cult_k}$) and the effective period suitable for the crop $\mathrm{P\_eff_k}$.

1. Calculation of the cultivable surface area for each crop ($\mathrm{S\_cult_k}$)

   The cultivable surface area for each crop type ($\mathrm{S\_cult_k}$) is the set of fields suitable for a given crop, determined according to field characteristics (soil, localisation, available water, etc.) and crop requirements. A small plot may belong to the cultivable area of two or more crops.

   As lettuce requires highly fertile soil and large amounts of water, its cultivable area ($\mathrm{S\_cult_{lett}}$) is systematically smaller than the effective exploitable surface area (S_eff). For other traditional leafy vegetables ($\mathrm{LV_{short}}$ and $\mathrm{LV_{long}}$), the cultivable area generally corresponds to the effective exploitable surface area (S_eff).

   Due to water dynamics and to the evolution of the crops' water requirements during the season, $\mathrm{S\_cult_k}$ varies during the cultivation season (Fig. 3b): This is a salient characteristic of these environmental conditions. For example, the presence of a functional well no fur-

**Table 2** Agronomic rules determining the maximum and effective surface area suitable for vegetable cultivation

| |
|---|
| (a) Maximum surface area suitable for vegetable cultivation (S_max) |
| $\mathrm{Sp}_i \in$ S_max IF the soil and water conditions described below are met on $\mathrm{Sp}_i$, with $\mathrm{Sp}_i$=small plot $i$ and $i$=number of small plot |
| 1. Soil sufficiently dried out (according to visual and tactile indicators): |
| (i) On lakesides, the depth of the lake water is more than knee high (>40 cm) |
| (ii) On lowlands, the surface is dry and can be walked on without sinking into mud |
| AND |
| 2. Surface potentially irrigated with a functional well close by |
| (i) Well located <65 m from $\mathrm{Sp}_i$ |
| (ii) Well not dried out |
| AND |
| 3. At the beginning of the rainy season, small-plots are abandoned |
| (b) Effective surface area suitable for vegetable cultivation (S_eff) |
| $\mathrm{Sp}_i \in$ S_eff IF $\mathrm{Sp}_i$ is set up at time $t$ (requires availability of labour force), with $\mathrm{Sp}_i$=small plot $i$ and $i$=number of small plot |
| For $p$=beginning of the dry season and $q$=end of the land drying out: |
| IF $\sum_{t=p}^{q} (\mathrm{S\_max} - \mathrm{S\_eff})1/\sum_{t=p}^{q} \text{Labour force} \ll 3, \text{then S\_eff} \ll \mathrm{S\_max}$ |
| (once blocks of land have dried farmers cannot carry out the work to set up more than 3 small − plots per day) |
| IF $\sum_{t=p}^{q} (\mathrm{S\_max} - \mathrm{S\_eff})/\sum_{t=p}^{q} \text{Labour force} \geq 3, \text{ then S\_eff} = \mathrm{S\_max}$(S_max is considered workable as soon as the blocks of land have dried out) |

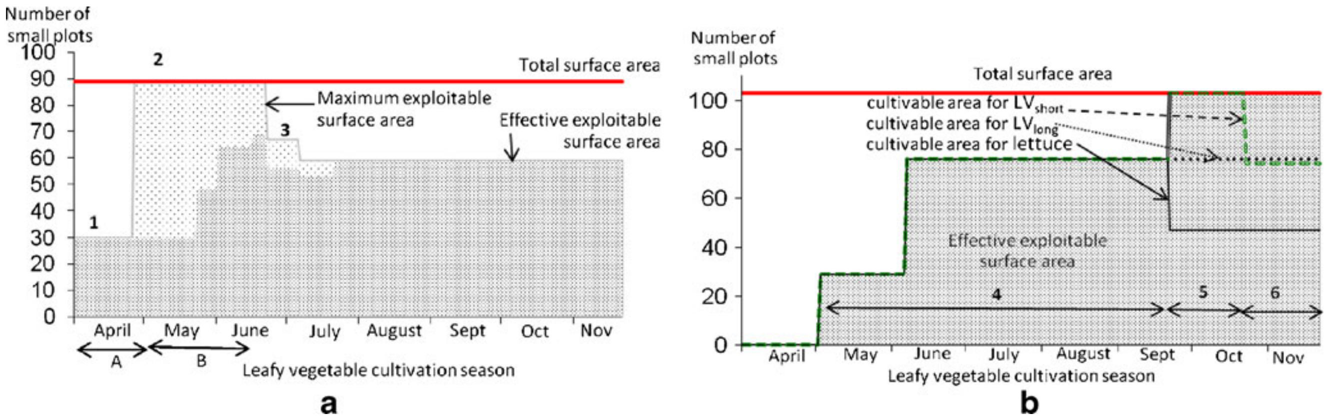


**Fig. 3** Typical case of the evolution of the maximum exploitable surface area (S_max) and the effective exploitable surface area (S_eff) (**a** in lowland) and the cultivable surface area of different leafy vegetables (S_cult$_k$) (**b** in lakeside). S_max evolution: (1) only the upper areas of lowlands (*tanety*) are dried out; (2) drying out of lowlands; (3) progressive abandonment of tanety due to the drying out of wells during the season. S_eff evolution: **a** tanety are established very soon in the season; **b** small plots are only established gradually as the labour force is progressively free from the tanety. Cultivable areas of leafy vegetables: (4) as long as the low-lying land has not dried out, there is no preferential localisation for lettuce or LV$_{short}$. The cultivable surface area of each vegetable (S_cult$_k$) is the set of small plots (or S_eff); (5) once the low-lying land has dried out, the labour force available for irrigation is limited. The highest small plots are no longer planted with lettuce because they are too far from wells. (6) At the end of the crop season, the higher land only receives LV$_{long}$ because the soil is very dry and more difficult to work; these crops remain planted for longer before harvesting (which means less tilling) and require less water (fewer irrigation trips). Thus, during this period, lettuce is planted only on medium-lying land while LV$_{short}$ is cultivated on medium- and low-lying land

ther than about 50 m is a necessary condition for a small-plot to belong to the lettuce cultivable area because of the rhythm of watering. When a well is drying, small-plots close to it come out of S_cult$_{lett}$.

2. Calculation of the effective period suitable for each crop type (P_eff$_k$)

   The maximum period suitable for each crop (P_max$_k$), from first planting to last harvest, depends on crop requirements and climate. For example, the decision rule for lettuce limits its production period from the beginning of May to the beginning of November (Table 3a). The effective period (P_eff$_k$) is then calculated, taking into account consumer demands, relationships with retailers and price variations (Table 3b).

*From cultivable areas and effective period suitable for each crop type to temporal crop sequences and crop location on farm land (boxes D–F in Fig. 2)* The space and time devoted to each crop on farm land can be restricted due to the combination of these periods (P_eff$_k$) with the cultivable surface areas (S_cult$_k$).

1. Setting up of blocks and periods (box D)

   To model the decisions related to the crop sequences and the rotations, it is necessary to take into account the hierarchy between the crops and their diversity. The crops hierarchy and diversity evolves over time and space during the cropping season; it depends on economical, organisational and agronomical criteria:

   - *The characteristics of the small plots*: within its cultivable area, a crop may have priority on certain small-plots and be secondary for others (further away from the well…).
   - *The market prices and relationships with retailers*: a diversity of crops is sought by retailers throughout the season to meet consumer demand. In addition, the proportion for each crop type varies during the season due to market conditions. Thus the farmer adjusts the areas cropped under one crop in coordination with his retailers according to the period of the year.
   - *The labour force available during the cropping season for crop maintenance*: the most labour demanding crops may not be priority when labour force is limiting. Farmers will cultivate first less labour demanding crops.

To estimate the respective weight of each crop at a given time, and thus the crop sequences, LYLU estimates:

(a) The blocks of crops (Bi), which are a set of small plots having the same decision rules as regards crop location and crop sequences and the same field characteristics (for example access to wells)
(b) The periods ($T_j$), during which S_cult, P_eff, diversity and crop hierarchy are stable.

The combination between Bi and $T_j$ allows for potential crop sequences to be identified. It depends on trade-offs and

**Table 3** Rules determining maximum and effective periods suitable for each crop type k

| |
|---|
| (a) Maximum period for each crop cultivation (P_max) |
| $P\_max_k$=(first $date_k$ for planting−last $date_k$ for harvesting) |
| IF k=lettuce or petsaï THEN $P\_max_k$=(beginning of May−beginning of November) |
| IF k=$LV_{short}$ or $LV_{long}$ THEN $P\_max_k$=(beginning of the dry season−end of the dry season) |
| (b) Effective period for each crop cultivation (P_eff) |
| $P\_eff_k$=(effective first $date_k$ for planting−effective last $date_k$ for harvesting) |
| IF k=lettuce AND farmer sells all his products through retailers THEN $P\_eff_k$ is restricted to the tourist season (July–August) where prices are high |
| IF k=lettuce AND farmer sells at least a part of his lettuces to retailers having a bigger selling capacity THEN $P\_eff_k$=$P\_max_k$ |
| IF k=lettuce AND farmer does direct selling THEN $P\_eff_k$=$P\_max_k$ |
| IF k=petsaï THEN farmer waits to harvest a first $LV_{short}$ cycle to set up petsaï (liquidity requirements) $P\_eff_k$=After harvest of the first cycle of $LV_{short}$ |
| IF k==$LV_{short}$ or $LV_{long}$ THEN $P\_eff_k$=$P\_max_k$ |

on hierarchies' rules between crops (according to the income level expected by the farmer, the labour force available and input requirements), as well as on the crop diversity required for selling. For example, even if the lettuce price is highest in July and August, traditional leafy vegetables are also cropped to fulfil retailers' demands.

2. Potential crop sequences and maximal developed surface area (box E)

   In each block of crop (Bi) the length of the cycle for each crop type ($LC_k$) and the minimum length of intercrop periods (IC_min) determine the number of cycles (NC) suitable for cultivation, and as a consequence crop sequences.

   The length of a cycle of a given crop k depends on crop requirements and environment; in our study a preliminary survey (Dumont, 2006) was used to estimate it because of the lack of scientific data for traditional leafy vegetables.

   The minimum length of the intercrop period (IC_min) is the time available between the harvest of the preceding crop and the planting of the next one. If there are no restrictions, a plot harvested on 1 day may be tilled and planted on the same day (IC_min<1).

   The maximum number of cycles (NC_max) can thus be estimated according to the mean values of the length of cycles: $NC\_max_k$=$P\_eff_k$/($LC_k$+IC_min)

   Finally, with the combination of the number of cycles and of hierarchy and diversity, the LYLU model allows to identify potential crop sequences, which in turn allows to calculate the maximum developed surface areas ($S\_dev\_max_k$) per block.

3. Effective crop sequences and effective developed surface per block (box F)

   The maximum number of cycles (NC_max), and as a consequence the maximum developed surface area (S_dev_max), is not always attained, for two main reasons:

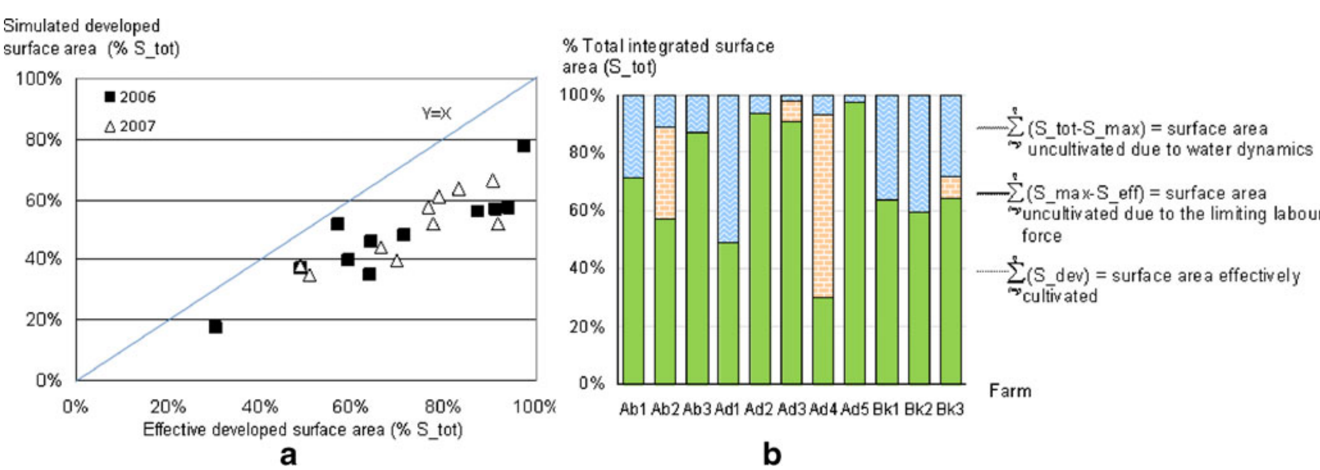


**Fig. 4** Gap between the surface areas calculated with the model and the surface areas registered on farms (in 2006), all crops taken together. The different variables are given as a percentage of the total integrated surface area (S_tot). The identification of farms refers to Table 1

– The first harvest date and the harvest duration depend on the relationships with retailers
– The length of the intercrop period depends on the labour force available to till and plant a plot once it has been harvested.

These two determinants influence the effective length of the intercrop period (IC_eff) and/or the effective length of the cycle (LC_k), and thus reduce the effective number of cycles (NC_eff) and the effective developed surface area (S_dev).

To conclude, the LYLU model progressively estimates the crop sequences (Fig. 2), depending on farm characteristics (especially water status of land and labour force), agronomic crop requirements (especially as regards water) and market requirements (especially as regards the harvest capacity).

## 3.2 LYLU validation and use of the model for understanding how to increase vegetables areas

### *3.2.1 Analysing the gap between developed surface area simulated by the model and surface area registered in farms*

We compare, all crops taken together, the developed surface area simulated by the model (S_eff obtained with box A) to the effective developed surface area registered on the 11 farms over two successive years (S_dev). The LYLU model enables us to understand 63 to 94 % of the effective developed surface area in 2006 and 60 to 89 % in 2007 depending on farms (Fig. 4a). The model systematically underestimated the developed surface area.

Two types of reasons explain the gaps: (a) the difficulty to parameterise the influence of the effective intercrop period and (b) some particular determinants not taken into account by the model. They are analysed below.

*The influence of the effective intercrop period* The following part analyses whether taking into account the length of the intercrop period improves the quality of the simulation by the model.

As already indicated if no restrictions are present, the minimum intercrop period (IC_min) is <1 day. However, there is a high variability of the effective intercrop period (IC_eff) registered on farms, from less than 1 day up to 85 days.

Two main determinants explaining the variability of IC_eff. were analysed in the survey.

- *The harvest duration linked to the marketing strategy*: depending on the farmers' marketing strategy, harvest duration may vary. A farmer who sells directly to consumers (strategies A and B in Table 1) often harvests each small-plot over a longer period (from 1 to 7 days) than a farmer selling to retailers (from 1 to 3 days) because of its limited selling capacity.
- *The delays in tilling and planting the following crop* once the small plot has been harvested linked to the productive resources available on the farm. The most limiting resource is the labour force to till and plant at the heart of the season (July–August), which explains all intercrop periods above 10 days. This is the case for farmers who have a non-agricultural activity in the city during the cropping season (case of Ad3 in 2006, Table 1), as well farmers faced with personal time-consuming events during the season: wedding, death, etc. (case of Ad2: the surface area not cultivated because of IC_eff changed from 15 % in 2006 to 8 % in 2007). On the contrary, when the labour force increases from 1 year to the next, intercrop periods decrease (unshown data).

The combination of these two determinants explains variations of effective intercrop periods (IC_eff) which, in turn, reduce the exploitable surface area from 2 to 15 % depending on farms and years. To determine the respective part of these elements, specific in-depth surveys with farmers and retailers would be necessary.

*The other reasons of the gap between simulated and registered surfaces area* Two other reasons explained the discrepancy between the model and reality.

First of all, lack of precision in the calculation of the model variables explained part of the gaps. For example, even if, in the model, the drying out and the establishment of small plots is modelled gradually, in the calculation of S_max and S_eff, we used the beginning dates by block as a simplification. Thus, we maximised S_max and S_eff, implying an overvaluation of the gap between S_dev and S_eff.

However, the major difference between calculated and observed variables comes from the farmers' practices (highlighted in the survey) that were not modelled in LYLU:

– The occupation of some surfaces by plant nurseries or seed production, either throughout the cropping season or between two crop cycles. Thus, the number of cycles on these plots, and the cultivated surface areas were reduced on some farms. Nevertheless, the small plots used for seed production are generally of small size.
– At the beginning of the season, planting was delayed on some farms after small-plot establishment because of a growth delay in plant nurseries or the unavailability of crop inputs like organic matter.
– When crops were harvested a few weeks before the end of the season, some farmers did not re-plant the small plot because the crop could not end its cycle.

– Furthermore, on some farms, at some stages in the cultivation season, some crops were abandoned before harvesting because of the large surfaces under cultivation and a limited labour force (irrigation having priority over harvesting).

Such phenomena are very frequent on farms but remain difficult to quantify because they mainly relate to the day-to-day management of the system. They are thus not easy to represent in decision models like LYLU, which aim to have a generic structure and therefore focus on planning management (leading in the case of LYLU to estimations of potential surfaces and potential crop sequences).

Differences between the potential simulated by the model and the reality are therefore frequent. Although the various uncertainties and adaptations of farmers are not directly included in the simulation process, their identification *a posteriori* helps to understand the variability of gaps between simulated variables and registered ones.

### *3.2.2 Decomposition of the effective surface areas to understand how to reach the potential surface area*

We now evaluate the land use intensity, a crucial issue in urban agriculture as indicated above, i.e. the extent to which the total surface area available on a farm is completely cropped with leafy vegetables. To this end, we compare the variables S_tot, S_max and S_eff (estimated by LYLU, using the characteristics of each farm as input variables) to the effective developed surface area registered on farms (S_dev) during the survey. It enabled to assess the gaps between real and potential surfaces and therefore to understand how to reach the potential surface area.

As indicated on Fig. 4b, 22–83 % of the total surface area was not cultivated during the season 2006 (34–65 % in 2007, data unshown):

– The gap between the integrated total surface area (S_tot) and the maximum exploitable surface area (S_max) variables corresponds to the daily sum of surface areas mainly uncultivated because of water dynamics. Thus, at the temporal scale of the season, 2–51 % in 2006 (Fig. 4b) and 3–49 % in 2007 of the total integrated surface areas of farms (S_tot) could not be cultivated. Water dynamics are also an important constraint: The maximum surface area (S_max) usable by farmers was strongly dependant on drainage at the beginning of the season. Therefore, farmers had no room for manoeuvre to extend S_max.
– The gap between the maximum exploitable surface area (S_max) and the effective exploitable surface area (S_eff) corresponds to the daily sum of surfaces uncultivated essentially because of the lack of labour needed to create small-plots at the beginning of the season. In the survey, 0 % (labour force not limited) to 63 % of the total integrated surface areas (S_tot) were not cultivated (Fig. 4b). A majority of farmers cultivated during the season all or nearly all the surface they could use taking into account the water dynamics (seven farms). The four cases where there is a gap between S_eff and S_max are all due to restrictions encountered by the farmers in available labour resources. An illustrative example is presented by farm Ad4 in 2007: one person arrived in 2007 to work with the farmer, both could dig a new well and then use a new part of the farm land which was not used before. By overcoming his labour force problem, this farmer managed to increase his effective exploitable surface area by more than 30 % as compared to 2006.

As a conclusion, taking into account the intermediate variables S_max, S_eff and IC_eff partially explained the gap between the total surface area and the surface registered on the farms. The majority of the farmers surveyed used the land as intensively as they could, according to their resources. Their room for manoeuvre to increase the values of the variables often depended on their access to additional task force (inside the family or thanks to temporary workers), water management (particularly at the end of the growing cycle) and their relationships with retailers (speeding up the harvest). These limiting factors highlight the overall question of the availability of territorial resources of land, water and labour force. We investigated this question by analysing whether additional resources could be useable for vegetable production (Mawois et al. 2011). The results show that the possibility to extend areas used for cultivating vegetables depends mainly—but with the exception of decisions made by the farmer (cash flow management and investment capacity)—on drivers relating to the urban environment. Indeed, in other periurban vegetable growing contexts, it has been shown that urban and agricultural uses may compete for the labour force, land and sometimes water (Midmore and Jansen 2003; Aubry et al. 2012). Moreover, while distance to markets drives the spatial location of vegetable growing, as indicated by other authors (see Thapa and Murayama 2008 for example), the direct influence of buyers on the organisation of leafy vegetable cycles during the growing season has not yet been studied.

### 3.3 Extrapolation: use of the LYLU model in various conditions

As indicated above, the LYLU model explained 63–99 % of the effective developed surface area (S_dev) in the sample. Therefore, the diversity of farmers' decisions was reflected quite well in a generic model, and it allowed us to quantify the gap between the effective surface area for each vegetable registered on farms and the potential surface area calculated with the model, and thus to discuss farmer's room for manoeuvre (Mawois et al. 2011).

### 3.3.1 A generic conceptual model

This study on market gardening in tropical conditions confirms that despite necessary adaptations, the general decision framework first built on arable crops (Aubry and Dounias-Michel 2006; Joannon et al. 2006) and then on market gardening (Navarrete et al. 2006) in temperate French conditions is quite generic. The progressive calculation of areas based on maximum (potential) areas then effective areas (taking into account constraints) appears once again an efficient framework.

### 3.3.2 An improved decision model

We now discuss how our study enriched the previous decision models, and in which environment it could be re-used.

One major improvement was to consider the exploitable surface areas for market-gardening as variable over the cropping season, which led us to create three additional surface variables: S_tot, S_max and S_dev_max. The temporal variability of surface area has already been studied in other conditions, such as pioneering issues, flood recession crops or rice farming on lowlands (van Duivenbooden et al. 1996). All these studies underlined complex territorial dynamics and crop land uses on large scales, such as a village territory and over annual or supra-annual time periods. Other works gave a deeper analysis of spatial organisation of the farm land in flood recession situations on a seasonal scale (Mathieu 2005), but only for arable crops. Consequently, there are few works linking the spatial and temporal dynamics of territories with cropping decisions and it has never been modelled on an agronomical point of view. Nevertheless, understanding and modelling this evolution is crucial to evaluate farmers' room for manoeuvre to increase cultivated surface areas, particularly in the case of short-cycle crops with a succession of several cycles in a season.

Another improvement consisted in modelling the dynamics of the cultivable surface area of a crop, whereas in previous models, it was considered as stable over the year. Moreover, the relative weights of the variables are shown to be different between temperate developed countries and tropical developing ones. The cultivable surface area variable plays a very important role in LYLU, mainly for the location of the most demanding crops such as lettuce, whereas this variable had a very low weight for the same species in temperate conditions (Navarrete and Le Bail 2007). This difference is probably due to the importance of manual labour in determining the surface area useable in developing countries where hardly any work is mechanised.

Some variables, although already modelled in previous models, did not have the same importance. On one hand, the crop return time and the potential preceding crops, which are quite important variables in models built for arable crops (Aubry and Dounias-Michel 2006), do not significantly affect farmers' decisions in the LYLU model, as the same species is repeatedly planted on the same plot several times during the same season. This could be related to the fact that during the wet season, the lake filling up or the rice irrigation totally changes the biophysical conditions of soil, hence reducing huge soil-borne pest problems on the following market gardening crops, but preceding effects may one day become more important and necessitate further adaptations of the model. On the other hand, in the urban agriculture conditions of Mahajanga, characterised by local marketing supply chains, the diversity of crops and their relative importance appeared to be a crucial element. This evolves over time, strongly affecting land use and crop sequences on farm land, probably more than in temperate conditions where long channels largely complement local supplies (Navarrete et al. 2006).

In previous models, marketing requirements were considered as external constraints. The LYLU model provides a better understanding of the relationships between short marketing channels and farming practices. Indeed, we identified more precisely which variables were mainly affected by the relationships with retailers: the number of cycles and the harvest duration. A similar partitioning of technical decisions between farmers and retailers has also been found in vegetable production in other developing countries (Dossa et al. 2011).

The LYLU model could therefore be re-used in such situations, and even in Europe, because of the increasing weight of short supply chains associated with market gardening cropping systems (Morgan et al. 2006; Smith and Mc Kinnon 2007) and where having large crop diversity on the farm is crucial (Aubry et al. 2011; Navarrete 2009).

### 3.3.3 A model for discussing farmers' room for manoeuvre

The LYLU model enabled to identify more precisely which surface areas could be increased depending on each farm and which were the limiting factors of this extension. In our case, they mainly came from the uncertainties on instantaneous resources availability (water, labour force, land, market, etc.). Such phenomena remain significant in the environment of tropical market gardening but also in temperate contexts (Petit et al. 2010).

To improve such use of the model, it could be useful to describe more precisely the evolution in space and time of the exploitable surface area and the cultivable surface area. In the actual version, the surface area variables were integrated on the whole cropping season and farm land. These variables combined space and time. It is useful to compare farms with crops of different cycle length. However, to assess innovations in view of improving land use, it would be necessary to distinguish the solutions lengthening the duration of cropping and those improving the spatial extension of crops. A second improvement would be to give more consideration to the diversity and hierarchy between crops and the influence of retailers, as indicated above. However, these variables are difficult to quantify because of the prevalence of steering over planning in these decisions.

One question is whether improving the accuracy of a decision model is relevant or not, considering that it will substantially increase its complexity. Several authors have demonstrated that using a rough but simplified model in a participative debate could be very useful. Such participatory modelling processes have been developed extensively recently and have demonstrated their operational value for identifying and clarifying the impacts of solutions to a given problem, usually related to supporting decision making, policy, regulation and management (Voinov and Bousquet 2010). In our case, such methods could have two objectives: (1) increasing and sharing knowledge on leafy vegetable land use among farmers (for example regarding crop hierarchy and diversity) and (2) introducing a debate between stakeholders concerning land use in an urban territory and how to increase vegetable production. A simple model even not computerised could therefore illustrate the various constraints and the room for manoeuvre of various types of farm to develop market garden production.

Finally, LYLU could be improved with the dual aim of (1) better describing farmers' decisions and quantifying their room for manoeuvre and (2) preparing the building of a computerised model to simulate alternative land uses on these farms. A proxy representation of farmers' decisions allows to overcome the limitations of expert-based frameworks (Zhu et al. 2007) and may complete the understanding of regional agricultural landscapes (Castellazzi et al. 2007; Leenhardt et al. 2009). However, it requires a high level of complexity in the modelling language and structure, which is perhaps not yet attainable in our case. The elaboration of a computerised model to simulate alternative land uses in farms is only in its infancy for arable farming systems and still needs to better represent decisional adjustments. Therefore, exploring this way for market gardeners' management decisions would be even more difficult because of the spatial and temporal complexity of decisions. We would first need to clarify its potential uses to adjust the complexity of the model (Le Gal et al. 2010).

## 4 Conclusion

The LYLU model furthers understanding of the constitution of the cultivated surface areas at farmland level in a tropical urban area. A large part of the diversity in cultivated surface areas was explained by the model. The gaps between model and reality were explained by imprecise variables and unmodelled determinants. These results extend and enrich the decision model regarding crop location on farmland, which was built for arable crops in temperate climates and later adapted for lettuce cultivation, also in temperate climates.

LYLU could be used to estimate the possible increase of the cultivated surface areas under leafy vegetables when increasing resources of the farms, especially accessible irrigated water and labour, which are the two main limiting resources identified. Both are possibly influenced by the proximity of the city and dependent on economic and political choices regarding urban development. The model gives the opportunity to take into account the dynamics of land use by farmers, which is poorly described and integrated in the urban development policies of most countries. As in urban areas, short-cycle leafy vegetables are widespread and productive resources (land, labour and water) are often rare, particularly in tropical zones, LYLU could be used not only in other tropical zones but also in other urban contexts. Its major interest is to help to (1) identify the factors limiting the potential increase of cultivated surface area and to (2) discuss and quantify the rooms for manoeuvre at farm and territory levels to raise these limiting factors (Mawois et al. 2011). This can be useful tool to define local public policies, which proved to be a determining factor for the promotion of the urban agriculture in other contexts.

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