WAGENINGEN UNIVERSITY, INRA

Formalizing and simulating spatial biophysical processes for participatory integrated assessment of agricultural systems in the Camargue Delta, Southern France.

Feng Zhu
Supervisors: Jeroen Groot, Sylvestre Delmotte
Registration number: 881117987230
Course code: FSE-80436

Formalizing and simulating spatial biophysical processes for participatory integrated assessment of agricultural systems in the Camargue Delta, Southern France.

Table

1. Introduction

1.1 Environmental spatial analysis and simulation

Nowadays, with the potential threats of pollution, environmental issues are becoming more important to human society. Some of the environmental problems are greatly influenced by the spatial components of the landscapes. For example, the water quality of rivers is known to be improved if grassland strips are maintained between the agricultural fields and the river. The pollution due to agricultural systems are related to the leaching of fertilizers and pesticides in drainage water. The quantity of pollution is however greatly influenced by the location of fields in the landscape; the flow of water in a landscape is determined by the structure of the different landscape elements.

With the increasing awareness of all these aspects of spatial effects on environmental impacts, spatial analysis is growing rapidly in lots of fields. In Fortin and Dale (2005), three factors are presented that determine the popularity of spatial analysis: (1) a growing awareness to include spatial configuration; (2) the rapid change of landscapes requires a dynamic reanalysis according to their spatial differences; and (3) the development of software designed for spatial analyses. Understanding and simulating spatial processes can in some cases reveal critical points and help to make properly informed decisions. In environmental sciences, spatial analysis should be conducted as well.

Spatial analysis and simulation are geostatistical methods to deal with the problem associated with spatial differences. It has already been used in many fields, such as ecology, epidemiology, environmental sciences, resources monitoring, etc. Early spatial analysis research was focused on theoretical and methodological aspects such as methods for spatial processes models, the role of spatial dependence and spatial heterogeneity (Anselin, 1988). Now, with the development of remote sensing, GIS, computer technology and spatial modeling tools, the spatial analysis methods are gaining more strength. Different modeling approaches exist for simulating spatially explicit phenomenon, which are reviewed in the next section.

1.2 Models for spatial analysis

Generally, a spatial model is a simplified description of reality with spatial features. The aim of a model is often to understand, illustrate or forecast how things are working in real world. A spatial model is often called a GIS model. According to Goodchild (2003), modeling in GIS has three important meanings: Data modeling, Static modeling and Dynamic modeling. Data modeling is a kind of conceptual modeling by which structures are built and can be filled with measurement or observation data. Static modeling shows how input data could transform into outputs by using the structures and functions at the same point of time. Dynamic modeling applies the transformations to do predictions at different time intervals.

Some spatial models have already been developed; one type is called Land-use change (LUC) models, which are widely used in different domains, for example:

- Cambardella and Karlen (1999) developed a model for spatial analysis of soil fertility parameters.
- The CLUE-S model was developed by Verburg et al. (2002) to analyze the spatial dynamics of regional land use.
- Lambin (1997) reviewed the approaches to modeling of deforestation and dry land degradation in tropical area.
- Briner et al. (2012) developed a spatial dynamic modeling approach to assess the impacts of economic and climate changes on land-use in mountain regions.

Agent-based model (ABMs), which could also be called individual-based modeling, is another approach which has gained popularity to evaluate nature-society interactions (Ligtenberg et al., 2004). One of the main advantages is that ABMs could show the interaction between different agents while taking into account the land use change. A lot of applications of ABMs have already been made: Railsback et al. (2006) reviewed five ABMs based software tools by implementing example models. Finally, the LandscapeIMAGES model has been developed to simulate different composition and configuration of agricultural landscape for different, sometimes conflicting objectives (Groot et al., 2010). In the next section, we present this modeling approach in more detail.

1.3 The Landscape IMAGES model

Landscape IMAGES is a computer program that can be used to explore the solution space, identify optimal patterns of land-use for user-defined objectives, and finally to identify the trade-offs and synergies among indicators (Groot et al., 2007).

The decision variables are spatially explicit and often integer. The indicators to evaluate the performance of solutions can serve as constraints (with allowed ranges between minimum and maximum values) or objectives (to minimize or maximize). The framework uses a vector-based landscape map in GIS that describes the spatial relations, and allows model results to be visualized for all model solutions (Groot et al., 2010).

Exploration of the trade-offs between objectives in Landscape IMAGES is performed with a multi-objective implementation of the evolutionary strategy algorithm of Differential Evolution (DE, Storn and Price, 1997). DE involves the iterative improvement of a set of solutions or genotypes. The algorithm is initialized by generating a set of solutions with random values for decision variables, only constrained by restrictions imposed on the parameter set. Landscape IMAGES uses Pareto optimality to evaluate the quality of the solutions (Groot et al., 2007). Pareto optimality or Pareto efficiency is widely used in various disciplines, with different definitions. In Landscape IMAGES, any solution in a set of Pareto optimal solutions is not dominated by other solutions (Groot et al., 2007). In other words, on the condition of not deteriorating the performance of one indicator, it is not possible to improve other indicators. Selection of solutions of better ranking results in a pressure normal to the trade-off region, whereas selection of solutions in less crowded parts of the solution space exerts a pressure tangential to the trade-off region, which promotes the spread over the solution space (Khor et al., 2005).

When the use of the territory is heterogeneous, the area can be separated into a lot of discrete spatial units (such as fields) to make each unit with homogeneous activities. The different activities will change the outcome of the multiple indicators. The characteristics of the field can be different, for instance they can be of different soil types. As a consequence, the allocation of the same activity on different fields can also contribute to different results of indicators. So insight into the relationships between the indicator performances in dependence on the allocation of activities to fields, thus this approach offers diverse input choices regarding to the use of the territory.

The input for Landscape IMAGES is implemented in a Microsoft Access database. The file contains input information for modeling and can be adjusted according to the requirement. The other input data are some GIS format file for the map (i.e. ESRI shape files). The output will display into a graph with X- and Y-axis showing different indicators and various dots located in coordinate graphs, each dots represent one solution with relevant decision variables. The indicators of X- and Y-axis can be changed and the minimum, maximum number, major division and minor division can be adjusted to the suitable value. The program uses Pareto optimality to select the solution and display the coordinate graph in green and depends on your scenario you can choose and button some and they will change the color into red. The outcome of the graph could be exported to a MS Excel file, in which quantitative value of input and output could be checked. Then method is that each of the dots have a number and stay the mouse point on the dot shows the number, then according to this number, you can find relevant values in the Excel file. The GIS map could display different selected variables, the different activities or values of the variable will display into different colors.

1.4 Camargue region

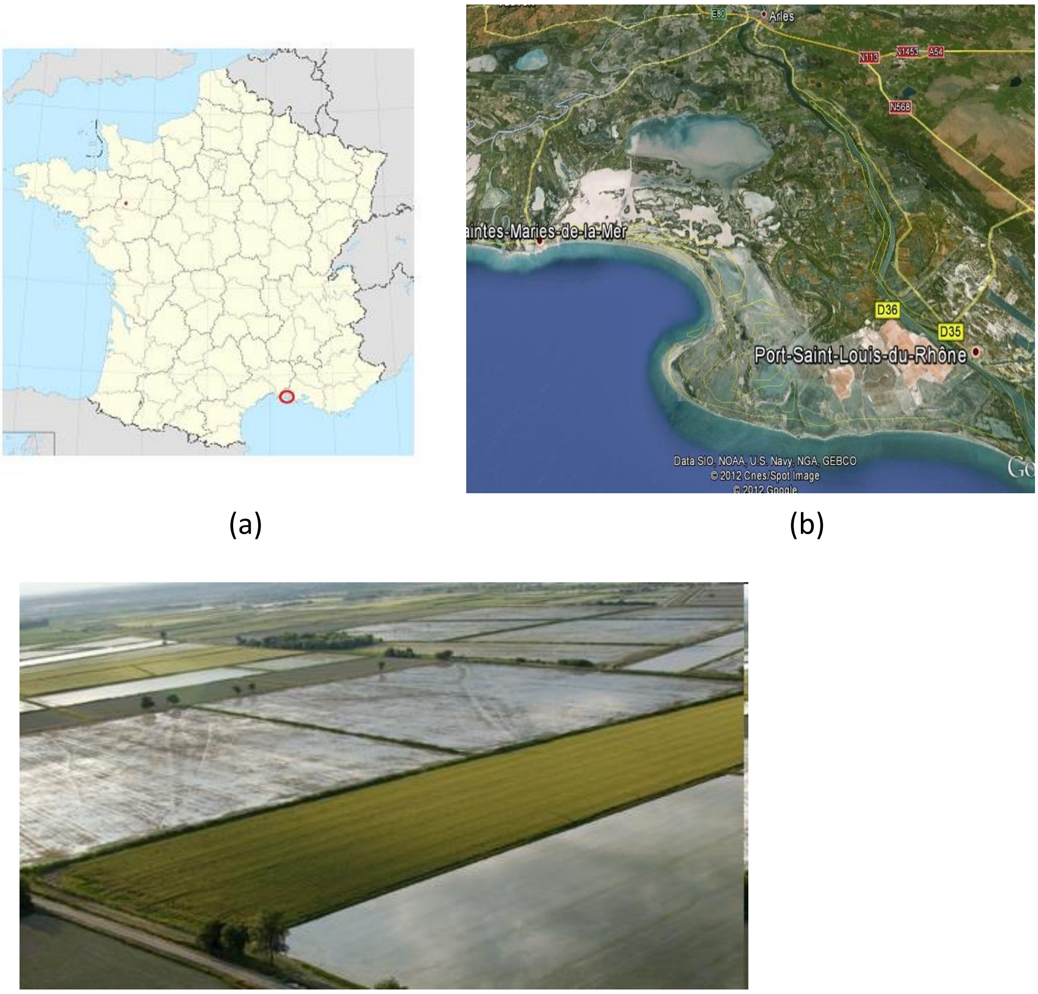
Camargue is a delta in the south of France covering 140,000 hectares (Figure 1a, 1b and c). It is composed of agricultural lands, wetlands, pastures, dunes and salt flats. There is also a Natural Regional Park, a National Reserve and many other publicly and privately owned protected areas.

In the Camargue, around 20,000 ha of land are devoted to rice production. It is the only rice production location in continental France. Rice fields are relatively small (1 to 3 ha), and are carefully leveled and delimited by bunds. The fields are flooded from mid-April or May to September and drained by ditches (Chauvelon, 1998). In a drainage basin called '*Fumemortes*', the water is discharged through the drainage system into the lagoon 'Etang de Vaccares'.

Agriculture in the Camargue therefore has a strong influence on ecological aspects to the region. For example, intensive rice cultivation changed the water flow dynamics and water quality in the Vaccares lagoon. A large amount of irrigation water is pumped from the Rhone River to irrigate the rice fields. Irrigation of rice also plays a key role in desalinating the soils as fresh water from the Rhone River enters the delta. However, continuous rice production uses a lot of agro-chemicals, particularly herbicides that are diffused throughout waterways within the region. Ecologists have called for a reduction in the use of pesticides for a long time (Delmotte et al., 2010).

Nowadays, organic agriculture is gaining popularity, and it is considered as a more sustainable farming approach compared to conventional farming. However, the effect of transforming conventional farming to organic should be assessed in advance to see whether it is promising at different spatial scales. The development of organic farming not only has an important influence in the economy of farmers, but also will impact the economic, social and environmental equilibrium of a region.

In order to evaluate the performance of agricultural systems, quantitative assessment is required to check the different indicators based on multiple criteria such as the quantify of water used, and pesticide and nutrient dynamics. An INRA project is conducted to develop modeling tools for participatory integrated assessment of agricultural systems in Camargue. The local stakeholders of Camargue have shown interest in quantifying indicators related to spatial bio-physical processes, mainly related to water distribution and water quality as affected by nutrients and pesticides. Some of stakeholders have their data and knowledge related to individual indicators, however, they cannot merge these into integrated assessment models.



(a) (b)

(c)

Figure 1. (a) The position of the Camargue region within France (red circle). (b) Google earth satellite image of the Camargue region showing the mosaic of agricultural land and natural areas. (c) Aerial photograph of agricultural fields in Camargue

1.5 Objectives

The research question was **“How can integrated regional assessment be implemented and applied to find multiple reasonable farming systems scenarios considering water, nutrients and pesticides as main indicators in Camargue, France?”**

The purpose of the thesis was to prioritize and improve the spatial distribution of crops in farms to minimize water use, pesticide loss and nitrogen loss to the environment with equal level of economic performance and labor required.

In the Camargue region, the volume of water required to irrigate rice fields differs between irrigation basins. For a single farm, the fields could be located in different irrigation basins. So the allocation of rice fields within each farm influences the total rice area at the irrigation basin level, and thus the total volume of water used. Associated to this, pesticide and nitrogen dynamics could also be influenced by the distribution of rice as well as other crops. To analyze the room for manoeuver related to the spatial allocation of rice, we can use a spatial model. By using a model, it is easier to show the quantitative results to different stakeholders and communicate with them. We can explain the process of how the model works and what would be the outcome for different solutions, and then they know how to achieve their goals.

2. Materials and methods

2.1 General conceptual model

The concept of the LandscapeIMAGES model developed for the Camargue region is to integrate different sub-models in order to quantify individual indicators at different scales, based on GIS maps and other input variables, into one comprehensive model that allows exploring tradeoffs and synergies among indicators.

The analysis of the farming scenarios was performed at multiple levels: field level, farm level, irrigation basin level, and territory level (Figure 2).

<u>Field level:</u> There are a lot of fields in each farm. Each field is cultivated with one crop specie. Field level simulation mainly focuses on the water balance and nutrient and pesticide dynamics.

<u>Farm level:</u> There are different situations for the farms in the region: all the fields of

one farm could be located in one irrigation basin, or positioned into two or more irrigation basins. Farms positioned in more than one irrigation basin are more complex to model, so we selected farms with such structure to build the model. The simulation concerns the flow of the water, nutrient and pesticide, labor required and economic aspects of the farm.

Irrigation basin level: It is the level of management of irrigation water. One irrigation basin could include different farms. At this level the volume of water used per area of cultivated rice is determined.

Territorial level: Originally defined by the Fumemorte drainage basin limits, we restricted it for the model development to three irrigation basins and their farms (Figure 3). This small sub-region is composed of three irrigation basin; three farms and 77 fields. Indicators are aggregated at this level by adding values calculated at the irrigation basin level.

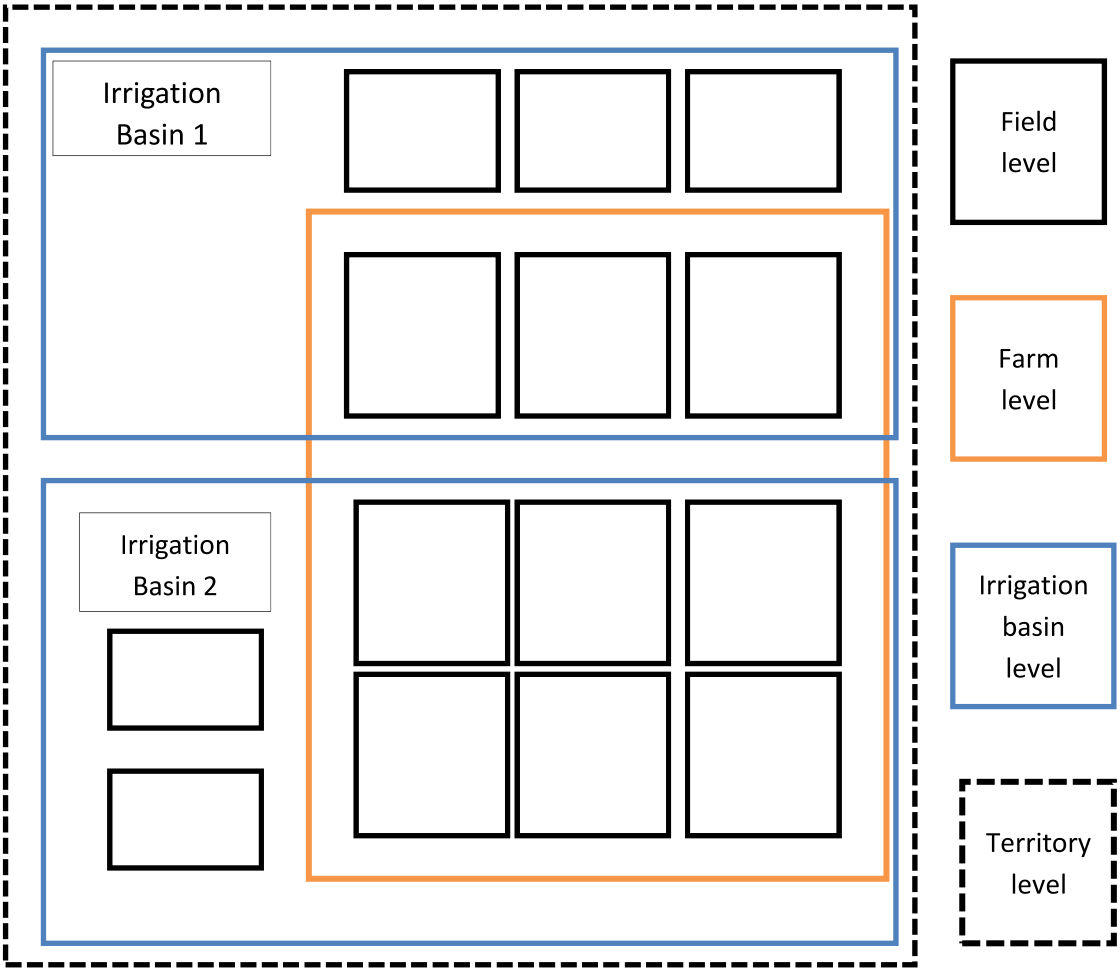


Figure 2. Description of different levels for conceptual spatial model.

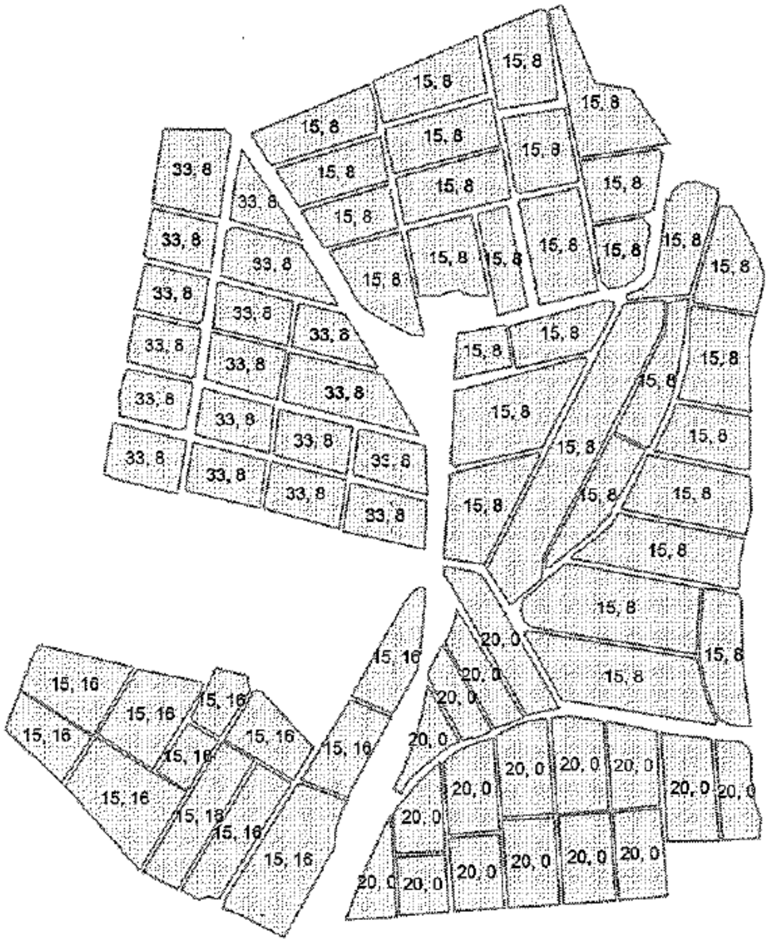


Figure 3. Extent of the case study area. Each polygon represents a field

For each field presented in the figure 3 (that are characterized by an area and a soil type), the model must select an agricultural activity. The agricultural activities are defined, following Delmotte (2011), by the combination of different criteria presented in table 1. In theory, 1600 different activities could be possible, however, some incompatibilities excluded some activities, and the database used in the model has 1283 activities (see(Delmotte, 2011)for more details).

Table 1. Design criteria and the variants for the definition of agricultural activities in Camargue.

Design criterion	Variants
Crop	10 variants: wheat (0), rapeseed (1), lentil (2), alfalfa (3), maize (4), pasture (5), rice (6), soybean (7), sorghum (8), sunflower (9)
Level of input	2 levels: High(0), low(1)
Style	2 levels: Organic(0), Conventional (1)
Preceding crop	10 variants: wheat (0), rapeseed (1), lentil (2), alfalfa (3), maize (4), pasture (5), rice (6), soybean (7), sorghum (8), sunflower (9)
Soil type	4 levels: AB(0), AH(1), SB(2), SH(3)

For each simulation, different objectives can be set up at the different levels. For example, they can be to maximize the profit at the farm level, minimize the labor required at the farm level and to maximize the proportion of rice at landscape level, minimize pesticide drainage, minimize nitrogen drainage and minimize drainage water at the territorial level

There are three reasons for maximizing proportion of rice at landscape level: (i) the requirement from local rice production chain stakeholders as they rely on rice for their work, (ii) consider the environmental aspects, growing flooded crops, like rice, can reduce salinity for some soil type, (iii) besides that Camargue is the only rice production region in France, so for the sake of national strategy, rice should be retained.

Multiple indicators can be used for the analysis, for instance: nitrogen balance, pesticide balance, water balance, and gross margin of the farm and of the whole landscape (table 2).

Table 2. Indicators and their levels in the model

Indicator	Level
Profit	Farm, Territorial
Labor	Farm, Territorial
Rice proportion	Territorial
Pesticide leaching	Territorial
Nitrogen leaching	Territorial
Drainage	Irrigation basin, Territorial

To calculate these indicators and notably the environmental indicators, different sub-models were implemented in the LandscapeIMAGES model. They are presented in the next sections.

2.2 Sub models

2.2.1 Hydrology model

In rice production, hydrology plays an important role. In the Camargue region, large quantities of irrigation water from the Rhone river are pumped in the rice fields from May to September (Chauvelon, 1998). The drainage water could either run to the Vaccares Lake or be pumped back to the Rhone river. The hydrology model was developed first since it influences the nutrient and pesticide balance models.

The main inputs come from irrigation and rainfall, while water outputs are evapotranspiration, drainage and seepage (Figure 4). The other input for the water balance in the field is the subsurface inflow from groundwater, while the other output could go through percolation to lower soil layers.

To simplify the model we do not take into account of subsurface inflow and percolation. This choice was validated by an hydrologist, specialist of the area (Chauvelon, personal communication).

The main equations for the hydrology model are:

Water balance = Water inputs - Water outputs (1a)
Water inputs = Irrigation water + Rainfall (1b)
Water outputs = Evapotranspiration + Drainage + Seepage (1c)

The actual irrigation volumes were calculated from estimated pump flows and related to the distribution of rice area within each irrigation basin. Empirical linear relationships were obtained between rice area and the specific irrigation volume for each irrigation basin monitored (Chauvelon et al., 2001).

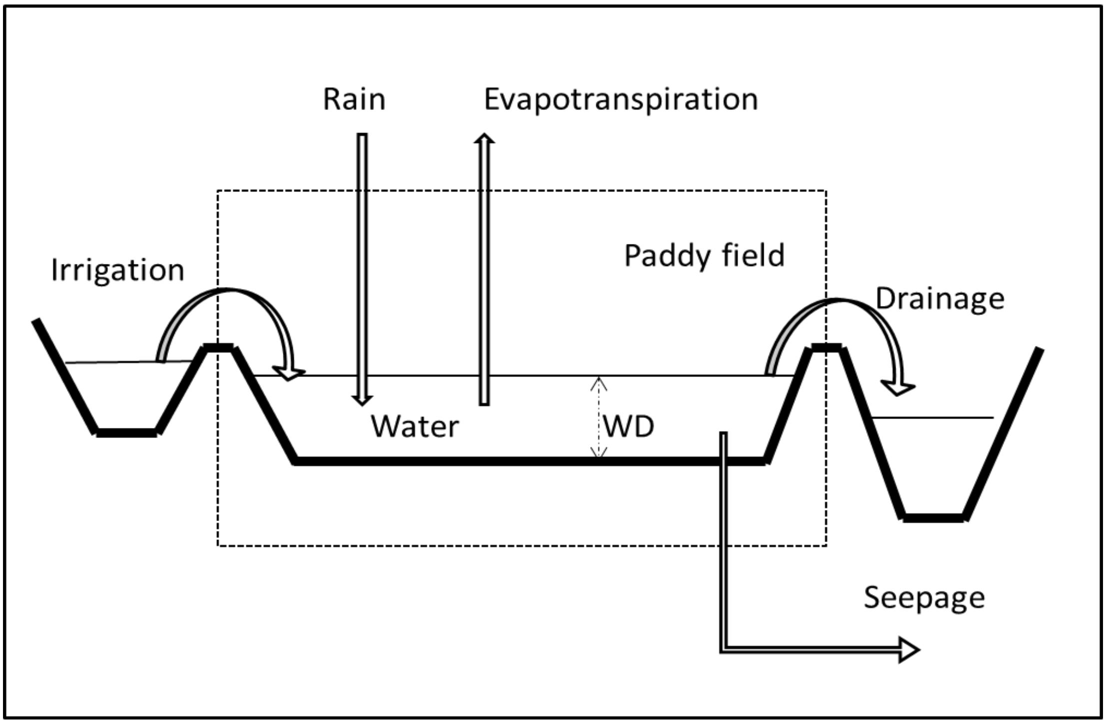


Figure 4. Description of the hydrology sub-model for paddy rice fields. The simulated system is within the dashed rectangle. WD = water depth.

This time scale of the model is the whole growing season of rice. In our model we assume the total growing period for rice is 140 days, which starts from 4th April and ends up at 1st September.

The specific irrigation volume (SIV; $m^3\ ha^{-1}$) is linearly related to the rice area within an irrigation basin. SIV for one irrigation basin could be formulized as:

$$SIV = a \quad \text{if } RiceArea < L \qquad (2a)$$

$$SIV = A * RiceArea + B \quad \text{if } RiceArea >= L \text{ and } RiceArea <= U \qquad (2b)$$

$$SIV = b \quad \text{if } RiceArea > U \qquad (2c)$$

The parameters of A and B as well as the constant value a and b for different irrigation basins can be found in the Appendix 2. So if the rice area within the irrigation basin is known, the relevant irrigation volumes can be calculated. However, in each irrigation basin, there could be more than one farms, so to determine the of area on rice the different farms within the same irrigation basin must be considered. Besides that, the functions have a validity domain related to the area under rice cultivation in the irrigation basin delineated by a lower limit (L) and an upper limit (U), outside of these limits the value of SIV is constant.

Rainfall was collected from local weather data. We averaged the amount of rainfall during the rice growing period in the last 10 years to obtain the total volume of rainfall. The potential ET was computed using the Penman-Monteith method, as proposed by Chauvelon (personal communication).

2.2.2 Pesticide model

For the assessment of pesticides runoff, a simplified PADDY model (Inao and Kitamura, 1999) developed by Commoretto et al. (Comoretto et al., 2008) was used to model pesticide runoff. The time scale of the model is the day. The required parameter for the PADDY model can be found in Appendix 3. The schematic representation of this model can be found in (Figure 5). The issues encountered for the implementation of this model were to find which factors influence the fractional adsorption rate k_d and desorption rate k_{des}. The equations could be found below:

$$V\frac{\delta C_w}{\delta t} = I - \left(Q_{out} + Q_{seep}\right)C_w - V\left(k_{vol} + k_{deg}\right)C_w - S\,k_{des}\left(k_d C_w - C_s\right) \tag{3a}$$

$$I = Q_{in} C_{w,in} \tag{3b}$$

$$S\frac{\delta C_s}{\delta t} = S\,k_{des}\left(k_d C_w - C_s\right) \tag{3c}$$

Where:
V = water volume for paddy fields (m^3)
Cw = aqueous pesticide concentration (kg m^{-3}).
T = time (day)
I= inflow of pesticide (kg $ha^{-1}d^{-1}$))
Q_{out} = outflow of water ($m^3ha^{-1}d^{-1}$)
Q_{seep}= seepage of water (($m^3ha^{-1}d^{-1}$)
k_{vol} = the volatilization rate for pesticide
k_{deg} = degradation rate of pesticide
k_{des}= soil desorption rate
k_d= soil adsorption rate
S = Soil weight for paddy fiels (m^3)
Cs = concentration of pesticide sorbed to surface soil (kg m^{-3})
Q_{in} = inflow of water ($m^3ha^{-1}d^{-1}$)
$C_{w,in}$ = concentration in the water of paddy field (kg m^{-3})

The input of pesticides for the paddy field comes from pesticides application in the rice field and possibly from inflow of irrigation water. The output of pesticide goes to outflow of drainage, seepage, volatilization and degradation. The outputs of pesticide through water flow divides into outflow and seepage (Figure 5). One thing that has to be noticed is that in this simplified version of the PADDY model, degradation is only occurring in the aqueous phase (Comoretto et al., 2008). Adsorption and desorption between water and surface soil solid occurs. Q_{in}, Q_{out}, Q_{seep} and V and $C_{w,in}$ should be measured or obtained from a database. k_d, k_{vol}, k_{deg} and k_{des} can be estimated on the basis of pesticides properties. Some basic data could be found in (Comoretto et al., 2007).

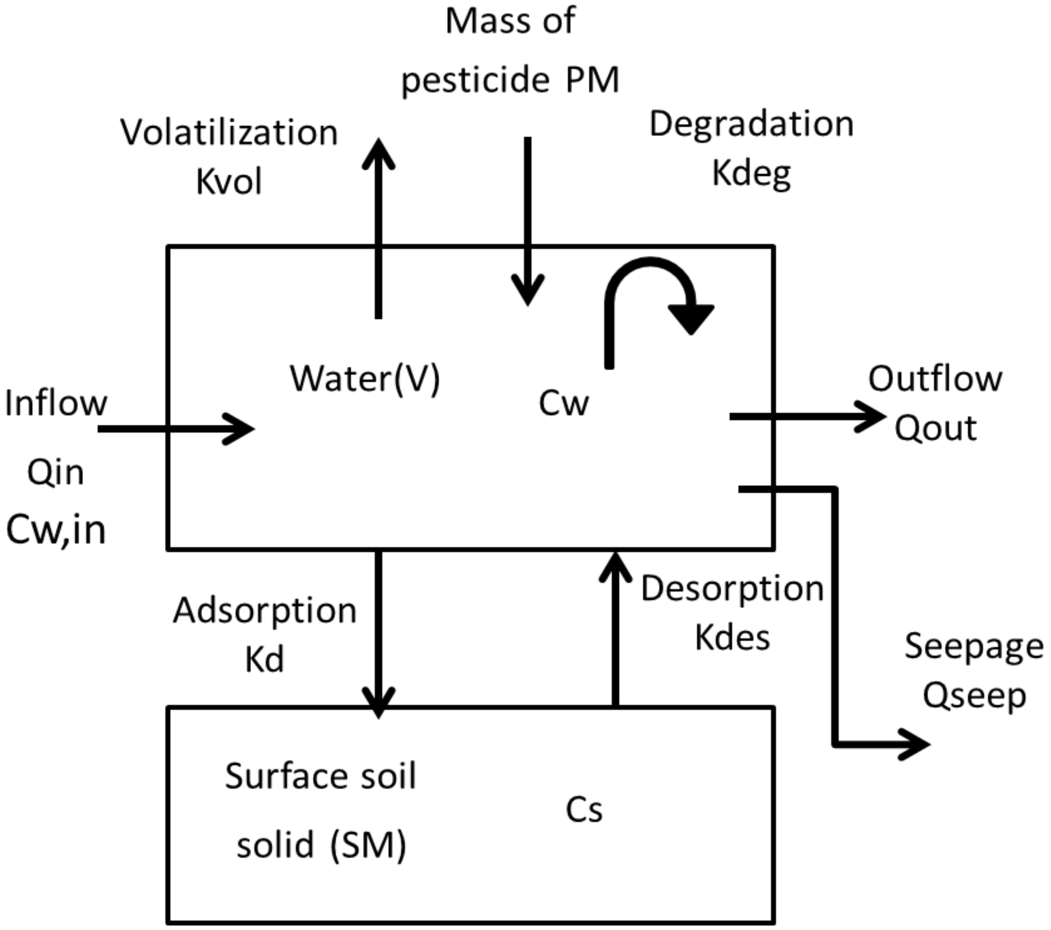


Figure 5: Schematic representation of the pesticide model of a paddy rice field.

Input data

With the help of a specialist of pesticides (Patrick Höhener) and using the functions of Comoretto et al. (Comoretto et al., 2008), we calculated the parameters of pesticides:

$$k_d = f_{om} * k_{om} \qquad (4a)$$

$$\log(k_{om}) = 0.49 * \log(k_{ow}) + 1.05 \quad (4b)$$

$$k_{vol} = \frac{v_{aw}}{WD} \quad (4c)$$

$$k_{deg} = \ln(2) / DT50 \quad (4d)$$

Where:
k_d is soil desorption rate
f_{om} is Organic matter constant
k_{om} is Organic Matter-Water Partition Coefficient
k_{ow} is Octanol-Water Partition Coefficient
v_{aw} is the air-water transfer velocity
WD is the mean depth of water in the fields (m)
DT50 is degradation half life

In order to simplify the calculation of the model we assumed that the WD is constant during the whole rice growing period with the value 0.05 m. The v_{aw} was estimated for each compound as a function of its Henry coefficient using the double boundary layer theory and an average wind speed u_{10} of 5.2m/s at 10 m above ground (Comoretto et al., 2008).

Input data for this submodel were, for each of the 7 possible pesticides, their dates and doses of application, and information about each soil types, such as their organic matter content. Each rice activity was assigned with a list of pesticide used, leading to 3 categories (from one pesticide application to 4).

2.2.3 Nitrogen model

Flooded soils are generally characterized by the absence of oxygen when compared to upland soils. In most rice fields, the dissolved oxygen content of the overlying water column remains relatively high due to a low density of oxygen consuming organisms and photosynthetic oxygen production by algae. In contrast, in the underlying soil, oxygen is slowly renewed and the demand is usually high, especially in those soils with high organic matter content. The greater potential consumption rates of oxygen at the soil-water interface compared to the renewal rate through the floodwater results in the development of two distinct soil layers: an oxidized or aerobic top layer and an underlying reduced or anaerobic layer. The thickness of the aerobic zone can vary considerably Reddy (1982).

Nitrogen exists in soils and water in many forms and constantly changes from one form to another. Nitrogen is found in both inorganic and organic forms. The two major inorganic forms of nitrogen are ammonium (NH_4^+) and nitrate (NO_3^-).

The nitrogen processes in the rice fields mainly include: urea hydrolysis, ammonification, NH_3 volatilization, nitrification, denitrification, mineralization and immobilization. When urea is broadcast on flooded soil, it is hydrolyzed to NH_4^+ and HCO_3^- ions. During volatilization, part of the ammonium produced during urea hydrolysis is converted to gaseous ammonia.

In my nitrogen model I simplified the nitrogen balance model from (Antonopoulos, 2008). The model simulates the dynamics of NH_4^+, and NO_3^-. The following equations are used (Figure 6):

$$\frac{\mathrm{d(V\,C}_{NH4})}{\mathrm{dT}} = \mathrm{QinCNH4} - \mathrm{QoutCNH4} - \mathrm{QseepCNH4} - \mathrm{Nvol} - \mathrm{Nnit} - \mathrm{Nupt} \qquad (5a)$$

$$\frac{\mathrm{d(VNO3)}}{\mathrm{dT}} == \mathrm{QinCNO3} - \mathrm{QoutNO3} - \mathrm{QseepNH4} + \mathrm{Nnit} - \mathrm{Nden} - \mathrm{Nupt} \qquad (5b)$$

The process of volatilization is assumed to follow first-order kinetics. The process of Volatilization, nitrification and denitrification could be described by:

$$\mathrm{Nvol} = \mathrm{CNH4}(1 - \exp(-\mathrm{kvol\,t})) \qquad (5c)$$

$$\mathrm{Nnit} = \mathrm{CNH4}(1 - \exp(-\mathrm{knit\,t})) \qquad (5d)$$

$$\mathrm{Nden} = \mathrm{CNO3}(1 - \exp(-\mathrm{kden\,t}) \qquad (5e)$$

Input data for this submodel are: nitrogen application amount and date, ammonia and nitrate concentration in irrigation water. The first two information were added to the database that describe the agricultural activities in the model, while the other two last were determined using values found in (Chauvelon et al., 2003).

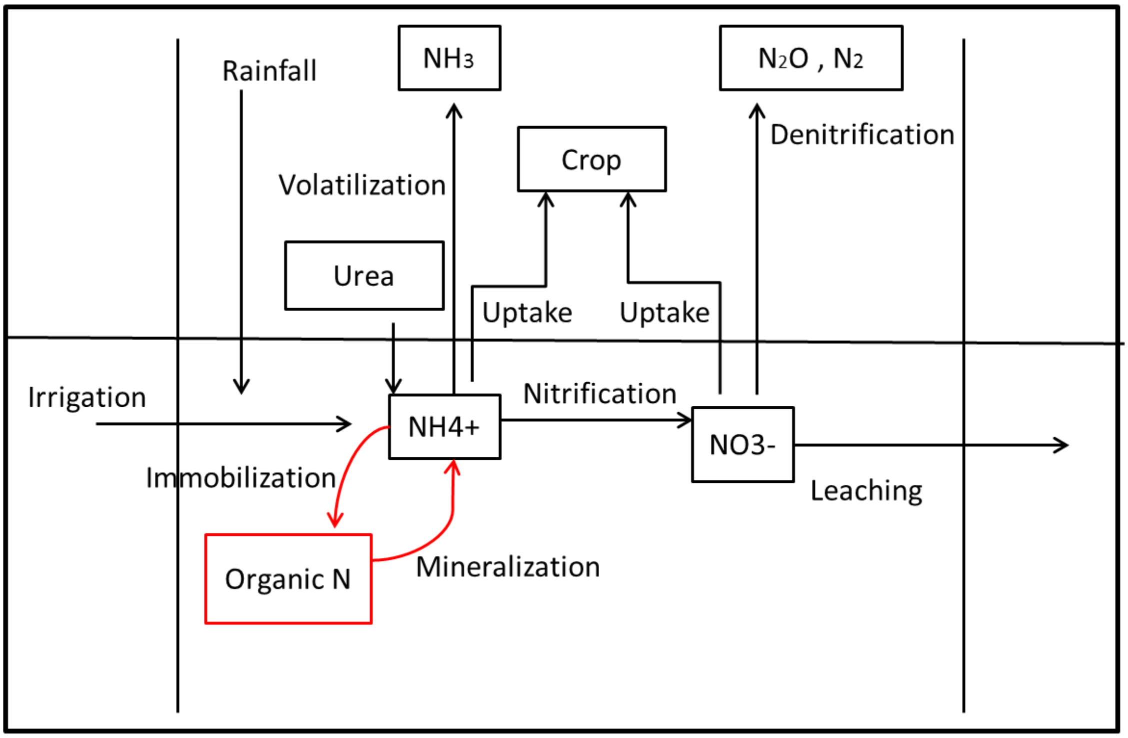


Figure 6. Schematic representation of the nitrogen model of a paddy rice field.

2.3 Testing the model

The model was first developed in MS Excel, then programmed into Landscape IMAGES. The consistency was checked between the MS Excel model and the LandscapeIMAGES implementation by comparing the values of the indicators at the farm level and landscape level (see table 3). This consistency check allowed identifying errors in both the Excel and LandscapeIMAGES implementations of the model.

Table 3. Comparisons of the indicators of Excel model and Landscape IMAGES.

Farm 33	LandscapeIMAGES	Excel
Total area	23.1	23.11
Production Costs	605	605.34
Margin	159	159.02
Subsidy	700	700
Profit	859	859.04
Total Value	764	
Labour	8.04	8.04

Other comparisons for the detailed calculation of irrigation and drainage water volumes, pesticides and nitrogen runoffs were done successfully. We therefore considered that the LI model was coherent compared to the conceptual model presented above, and used it for simulating different scenarios.

2.4 Scenarios definition

Six scenarios were defined with few different objectives according to different concerns. These scenarios were used to test the Landscape Image model.

2.4.1 Scenario 1: Business as usual

This scenario is based on the current situation and all the activities in the database. Three objectives were used: to maximize the profit at farm level, to minimize labour required at farm level and to maximize the proportion of rice cultivated (irrigated area) at landscape level. This scenario was used as reference scenario, and the outcome compared with the other scenarios.

2. 4.2 Scenario 2: Green is beautiful

In this scenario, we only allow allocation of production activities under organic farming management, whereas the objectives are identical to the ones of scenario 1. By comparing the outcomes of this scenario with the outcomes of scenario 1, we analyzed the potential changes that could be caused by organic farming.

2.4.3 Scenario 3: Healthy fish

In this scenario, we will focus on the indicators of pesticide run off, in order to protect the health of the fishes of the Vaccares Lagoon of Camargue. Thus, in the model, we added the objectives of minimizing pesticide run off at the landscape level while at the same time keeping the economic objectives at the farm level of scenario 1.

2.4.4 Scenario 4: Cyanophycee devil

The large amount of nitrogen and phosphorus in drainage water running into Vaccares causes eutrophication. In this scenario, we added to the economic objectives at the farm level the objective to minimize nitrogen leaching at landscape scale.

2.4.5 Scenario 5: Empty Vaccares

Intensive rice cultivation radically changed the hydrological regime of the Camargue (Chauvelon, 1998). As a consequence, the water level in Vaccares is quite high what endangers the functioning of the lagoon. In order to reduce it, we set the minimization of the volume of drainage water as an objective at the landscape level, still in addition to the objectives of scenario 1.

2.4.6 Scenario 6: Let’s dream

This last scenario combines all the environmental indicators: related to thehydrology and to pesticide and nitrogen losses at the landscape level, as well as economic indicators to choose the best solutions for the region.

3. Results

The results are displayed from different levels. First, potential agricultural activities are compared. Then at field level, the dynamic of pesticide and nitrogen will be analyzed. At landscape level, two comparisons have been made: the comparison among different scenarios and the comparison among different solutions. After that, “Let’s dream” scenario has been further analyzed. Finally multi scale analyze has been done to “Let’s dream” scenario.

3.1 Comparison of potential agricultural activities

In this section, we compare solutions obtained for the scenario 6, in order to analyze the range of variations of the land use and of the different indicators observed for different solutions for a single scenario. In Tables 4 and Table 5, six chosen solutions are presented, it concerns the three are lowest profit solutions and the three are highest profit solutions.

First, crop frequencies are analyzed to see the different crop patterns between low profit solution and high profit solution. According to Table 4, the low profit solutions achieve about 740 euro per ha, only half amount compared to high profit solutions (more than 1460 euro per ha). The percentage of rapeseed, lentil and prairie in low profit solutions are much higher than in high profit solutions. The other crops keeps at low percentage in low profit solutions, while in high profit solutions, Rice is main crop species (solutions 64 and 179) or one of the main crop species (solution 64), besides rice, maize and soybean grow at a high percentage.

Then the frequencies of input level and farming style are counted, from Table 5, we can see higher input level give high profit return, while the relationship between farming style and profit is not clear.

Table 4. Crop frequency statistics of Comparison between low profit solution and high profit solution

solution	Profit (euro/ha)	Wheat	rapeseed	Lentil	Lucerne	Maize	Prairie	Rice	Soybean	Sorghum	Sunflower
371	721	7[a]	10	18	8	3	17	4	4	5	2
18	737	7	16	14	6	4	14	5	4	6	2
156	740	5	19	14	5	4	16	6	4	3	2
179	1465	1	0	1	6	12	4	37	12	2	3
64	1468	1	0	2	4	11	5	35	16	2	2
225	1492	3	6	0	3	16	4	17	21	5	3

[a] the number means the number of fields that grow the specific crops

Table 5. Input level and cropping style frequency statistics of low profit solution and high profit solution

Solution	Profit (euro/ha)	Input level		Style	
		0[a]	1	0[b]	1
371	721	32	46	44	34
18	737	33	45	40	38
156	740	33	45	38	40
179	1465	46	32	58	20
64	1468	45	33	58	20
225	1492	42	36	38	40

[a] 0 stands for low input level while 1 means high input level

[b] 0 stands for organic farming and 1 means conventional farming

From Table 6 we can see for highest labor cost we need approximately 7.2 hours per ha, while for lowest solution we only need about 2.8 hours per ha (All 6 solutions are chosen from scenario 6, 3 are lowest labor cost solutions and 3 are highest labor cost solutions). The rice is significantly higher in high labor group (average 50 compared to 3 in lower labor cost); while more rapeseed, lentil and prairie are grow in lower labor cost group. The frequencies of other crops are similar in two brackets. From Table 7, we can conclude that high input level require more labor while there is no significant relationship between farming style and labor cost.

Table 6. Comparison between low labor cost solution and high labor cost solution

Solution	Labor(h/ha)	Wheat	rapeseed	Lentil	Lucerne	Maize	Prairie	Rice	Soybean	Sorghum	Sunflower
147	2.78	5	15	18	6	7	8	3	4	6	6
315	2.81	5	9	21	8	5	11	3	4	5	7
198	2.90	6	7	21	8	4	9	4	6	6	7
295	7.18	1	2	1	5	6	3	51	7	1	1
325	7.21	3	1	2	3	7	5	49	6	1	1
267	7.22	1	0	2	4	6	3	52	9	0	1

Table 7. Input level and cropping style frequency statistics of low labor cost solution and high labor cost solution

Solution	Profit (euro/ha)	Input level		Style	
		0[a]	1	0[b]	1
147	2.78	35	43	38	40
315	2.81	32	46	43	35
198	2.90	36	42	43	35
295	7.18	42	36	38	40
325	7.21	40	38	36	42
267	7.22	40	38	39	39

[a] 0 stands for low input level while 1 means high input level

[b] 0 stands for organic farming and 1 means conventional farming

3.2 Pesticides and nitrogen dynamics at the field level

The different sub models for pesticide and nitrogen were used to simulate their dynamics in the water of paddy fields during the 140 days growing season. Figures 7a-c, show, correspond to the concentration of quantity of the different pesticides used simulated for a field with a sandy soil situated in the irrigation basin 8.
The quantity of pesticides in water is almost nil before the application, on the day of application, the quantity reaches a maximum and progressively decrease through volatilization, degradation, soil absorption and lost in drainage water. The three pesticide application strategies presented here (in figure 7 a-c with a IFT (Index Frequency treatment) of 2, 3 and 4, meaning 2, 3 or 4 application per season) corresponds to different pesticides used, different application dates and doses. Accordingly, the peaks of quantity and the dynamics of disappearance of pesticides in water are same among strategies.

Figures 7a and 7b present the dynamic of nitrogen concentration in water. There is nitrogen in water before the fertilizer applications, as there is a little concentration of nitrogen in irrigation water. For organic farming system (Figure 8a), there is only an application and one peak, while for conventional farming (Figure 8b) the fertilization is split in 2 applications. The first peak of conventional farming is similar to the peak of organic, while the second peak of is much higher. As the decreasing rate is high for both farming style, during most of the rice growing season, the nitrogen concentration keeps at a low value (around 0.02 kg/ha).

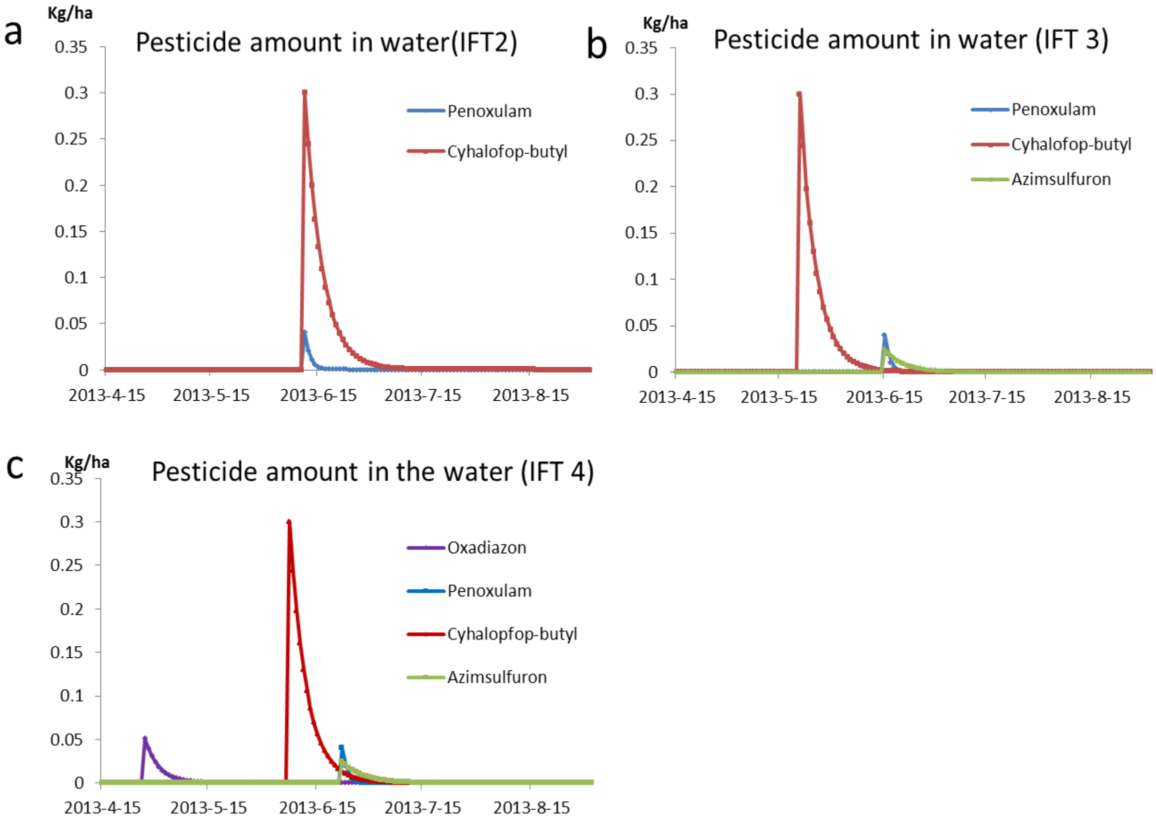


Figure 7. Dynamics of pesticide amount in the water of paddy field for different pesticide application strategies (a) IFT 2, (b) IFT 3, (c) IFT 4.

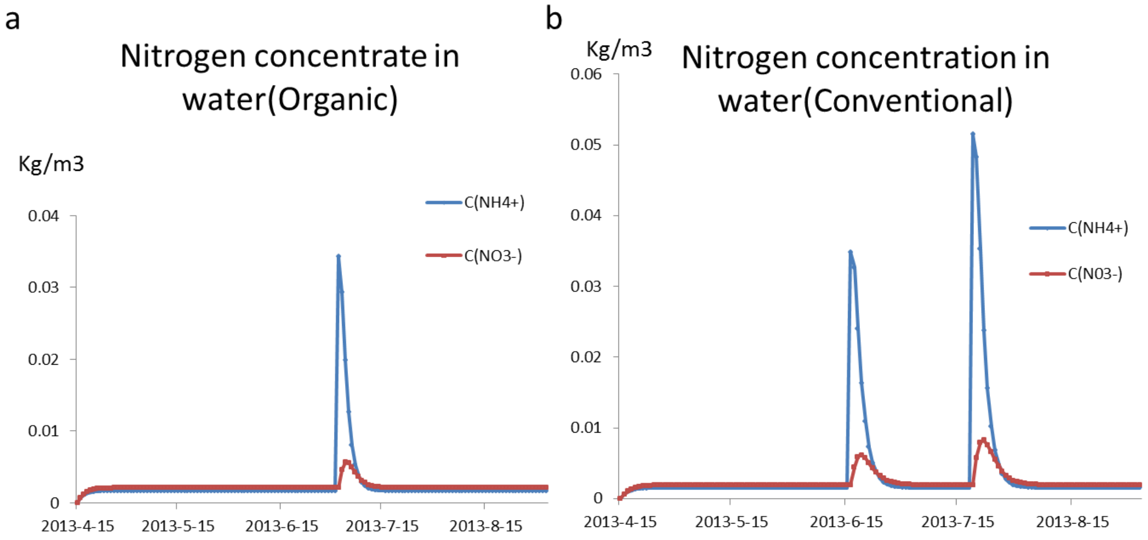


Figure 8. Dynamics of nitrogen concentration in the water of rice paddy fields, (a) for organic farming, (b) for conventional farming.

3.3 Comparison of the different scenarios at the landscape level

The LandscapeIMAGES model produces a set of solutions that, compared to the initial situation, show improvement for at least one of the objectives that were defined for the scenario. The results presented in this section are at the landscape level. Regarding the indicators used (notably profit, labor requirement and proportion of rice cultivated), the solution sets largely tended to overlap between the different scenarios assessed. However, compared to the 'Business as usual' scenario (Sc. 1), the scenario with organic farming (Sc. 2; 'Green is beautiful') resulted in higher profits and lower labor requirements for the same proportion of rice (Figures 9a and 9b). As a consequence, for the same labor input, a considerably higher profit could be reached with organic farming (Figure 9c).

'Healthy fish' (Sc. 3), 'Cyanophycee devil' (Sc. 4) and 'Empty Vaccares' (Sc. 5) overlapped, meaning that it is possible to decrease the values each of the three environmental indicators (pesticide run off, nitrogen leaching, or drainage water) while maintaining the other three objectives (profit, labor requirement and proportion of rice cultivated).

The 'Let's dream' scenario (Sc. 6) demanded more labor input for the same level of profitability and proportion of rice (Figures 9b and 9c). Compared with scenario 1, at the same rice proportion, higher labor is required and lower profit is achieved (Figures 9a and 9b). There is a trade-off between the three environmental indicators (pesticide run off, nitrogen leaching, and drainage water) and the other three objectives (profit, labor requirement and proportion of rice cultivated).

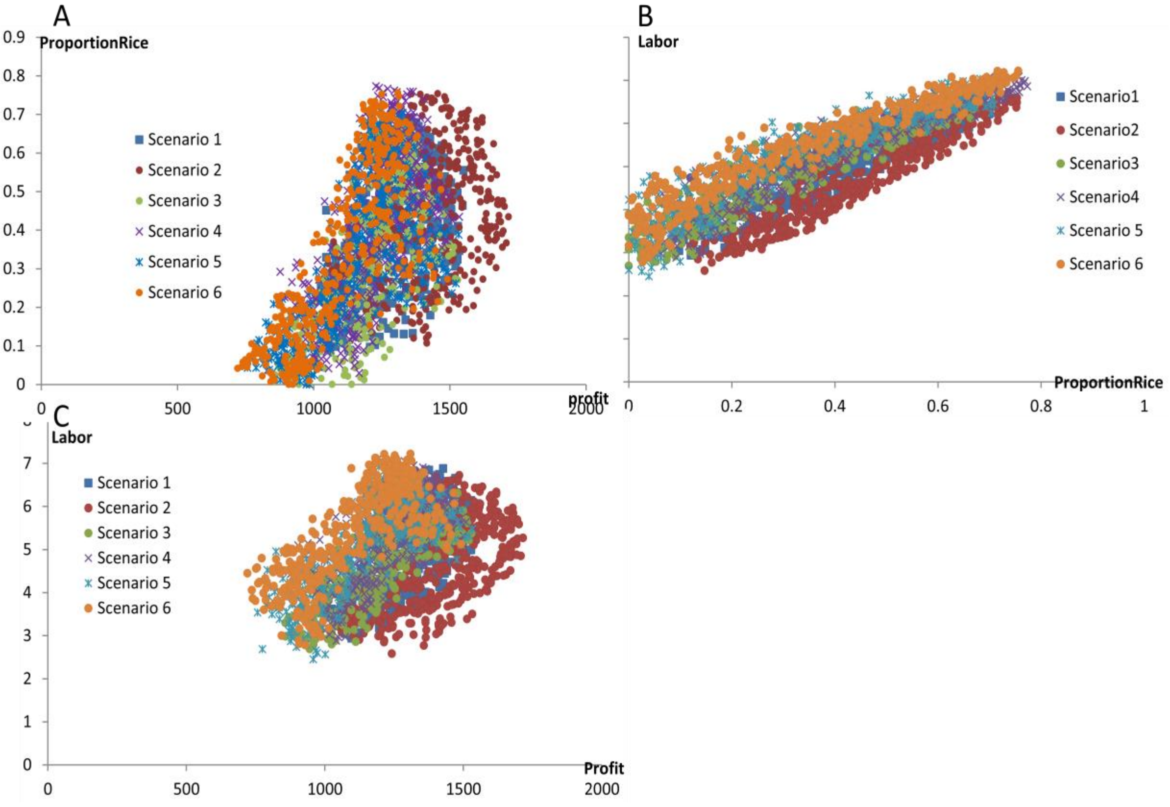


Figure 9. Analysis of three common indicators (profit, labor and proportion of rice) for the 6 scenarios.

3.4 Comparison of selected solutions at the landscape level

For each scenario three solutions were selected from the set of alternatives to demonstrate the differences between alternatives that performed well in terms of one or more of the objectives. The solutions are coded using the number of the scenario and a letter for the objective: P for profit; L for labor; R for proportion of rice; E for pesticide emissions; N for nitrogen loss and D for drainage (Table 8). For instance, solution 2R is the alternative with the largest proportion of rice in Scenario 2.

In general the high profit solutions get medium rice proportion and are characterized by high labor requirement. Large proportions of rice solutions need even more labor than high profit solutions and achieve lower profit. Low labor demand solutions will be companied by very low proportion of rice and low profit.

Comparing the same category of solutions between Scenarios 1 and 2, the outcome is quite different. The high profit solution in Scenario 2 (solution 2P) gets 1716 euro/ha, 11% higher than solution 1P in scenario 1. And similar for large proportion of rice, solution (2R) in Scenario 2 gets 0.75 compared to 0.70 for solution (1R) in Scenario 1. Regarding to low labor demand, solution (2L) in scenario 2 only requires 2.77 h/ha labor, while solution (1L) in scenario 1 needs 3.56 h/ha labor.

Table 8. Representative solutions from Scenario 1 ‘Business as usual’ and Scenario 2 ‘Green is beautiful’.

Solution	Profit (EUR/ha)	Rice proportion	Labor (h/ha)
Scenario 1 ‘Business as usual’			
1P. High profit	1550	0.55	6.06
1R. Large proportion of rice	1286	0.70	6.21
1L. Low labor demand	1243	0.12	3.56
Scenario 2 ‘Green is beautiful’			
2P. High profit	1716	0.43	5.27
2R. Large proportion of rice	1456	0.75	6.60
2L. Low labor demand	1357	0.16	2.77

In scenario 3, It is interesting to compare solution 65 and 313, the difference of profit for these two solution is not so big, while rice proportion has a huge difference, 0.67 for solution 65 and 0.15 for solution 313 (table 9). This demonstrates that different crop rotation can achieve similar economic value for greatly different proportion of rice.

In scenario 4, as there is tradeoff between rice proportion and nitrate drainage it is reasonable to find solution either with high rice proportion and high nitrate drainage or low rice proportion with low nitrate drainage. For example solution 192 got high rice proportion (76%), in return the nitrate drainage is also very high (7.00 kg/ha). Similar to scenario 6, in scenario 5, there is tradeoff between rice proportion and drainage, the objectives of high rice proportion and low drainage can’t be achieved at the same time. For instance solution 295 got low drainage (336889 $m^{3)}$; in return the rice proportion is also very low (0.21).

In scenario 6, the values for solutions for each indicator maximized or minimized are systematically lower to best values achieved in the other scenarios. This is due to the fact that in this scenario, the six indicators are used simultaneously. Solution 64 has a rice proportion of 0.51, the second highest proportion crop is soybean, grown on 16 fields, the third highest being maize grown on 11 fields. The other crops keep at a low proportion. 58 fields are organic while 20 fields are conventional, and 45 fields get low input.

Compare high profit solution group, solution 210 in scenario 3, solution 219 in scenario 4 and solution 292 in scenario 5 got almost the same amount profit, while only solution 64 in scenario 6 get a relative low profit. For large rice proportion, besides solution 65 in scenario 3 (0.67), all the other solutions in scenario 4, 5, 6 exceed 0.7.

Regarding to the drainage, solution 295 in scenario 5 get very low amount of outflow water for 336889, compared to 395087 for solution 387 in scenario 6.

Table 9. Representative solutions from Scenario 3 ‘Healthy fish’, Scenario 4 ‘Cyanophycee devil’, Scenario 5 ‘Empty Vaccares’ and Scenario 6 ‘Let’s dream’, evaluated for profit (€/ha), proportion of rice, labor requirement (h/ha), pesticide losses (…/ha), nitrate loss (kg/ha) and drainage volume (m^3).

Solution	Profit(EUR/ha)	Rice proportion	Labor	Pesticide loss	Nitrate loss	Drainage
Scenario 3 ‘Healthy fish’						
3P. High profit	1530	0.27	5.37	4.34		
3R.Large rice 3E. proportion	1321	0.67	6.41	5.04		
3E. Low pesticide emission	1290	0.15	4.86	0.24		
Scenario 4 ‘Cyanophycee devil’						
4P. High profit	1535	0.43	5.49		10.16	
4R. Large rice proportion	1296	0.76	7.00		11.49	
4N. Low nitrate loss	1212	0.14	4.88		1.13	
Scenario 5 ‘Empty Vaccares’						
5P. High profit	1532	0.38	5.47			448282
5R. Large rice proportion	1244	0.71	6.43			1248881
5D. Low drainage	1404	0.21	5.39			336889
Scenario 6 ‘Let’s dream’						
6P. High profit	1468	0.51	6.06	4.19	10.70	941896
6R. Large rice proportion	1310	0.76	7.22	9.06	13.36	1361911
6D. Low drainage	1456	0.21	5.34	3.97	7.15	395087

3.5 Analysis of the 'Let's dream' scenario at the landscape level

In Figure 10, relationships between the different indicators are presented. Figure 10a shows globally a positive relationship between labor and profit, however, different levels of profit can be achieved for the same level of labor, and *vice versa*.

The relationship between rice proportion and profit shows the same tendency (Figure 10b). Maximizing rice proportion generally lead to an increase in the amount of pesticide loss, nitrate leaching, drainage water labor (Figure 10f, 10g, 10h, 10i).Labor required is proportional to rice proportion (Figure 10f) so as drainage and pesticide loss and nitrate leaching (Figure 10m, 10n).

The relationships between nitrate leaching and pesticide loss is not obvious (Figure 10o). This is mainly due to the different combinations from 1600 farming activities we defined. In other words, to reach the same amount of nitrogen loss, farming style, crop and preceding crop could be different, so the pesticide application strategies could also be different for each solution, which means different amount of pesticide loss for same nitrate leaching. The linear relationship between drainage water and rice proportion (Figure 10h) results from the hydrology model of the drainage basin. In our selected area, the rice area is under the lower limit (see equation 2a, b and c) leading to a constant value for the volume of irrigation water for each ha of rice. However if we choose bigger area (exceed the lower limit), this relationship will change according to the hydrology model. The slight difference of drainage water at same level of rice proportion results from the allocation of the rice fields. In different irrigation basin, each hectare of rice gets different constant value for drainage.

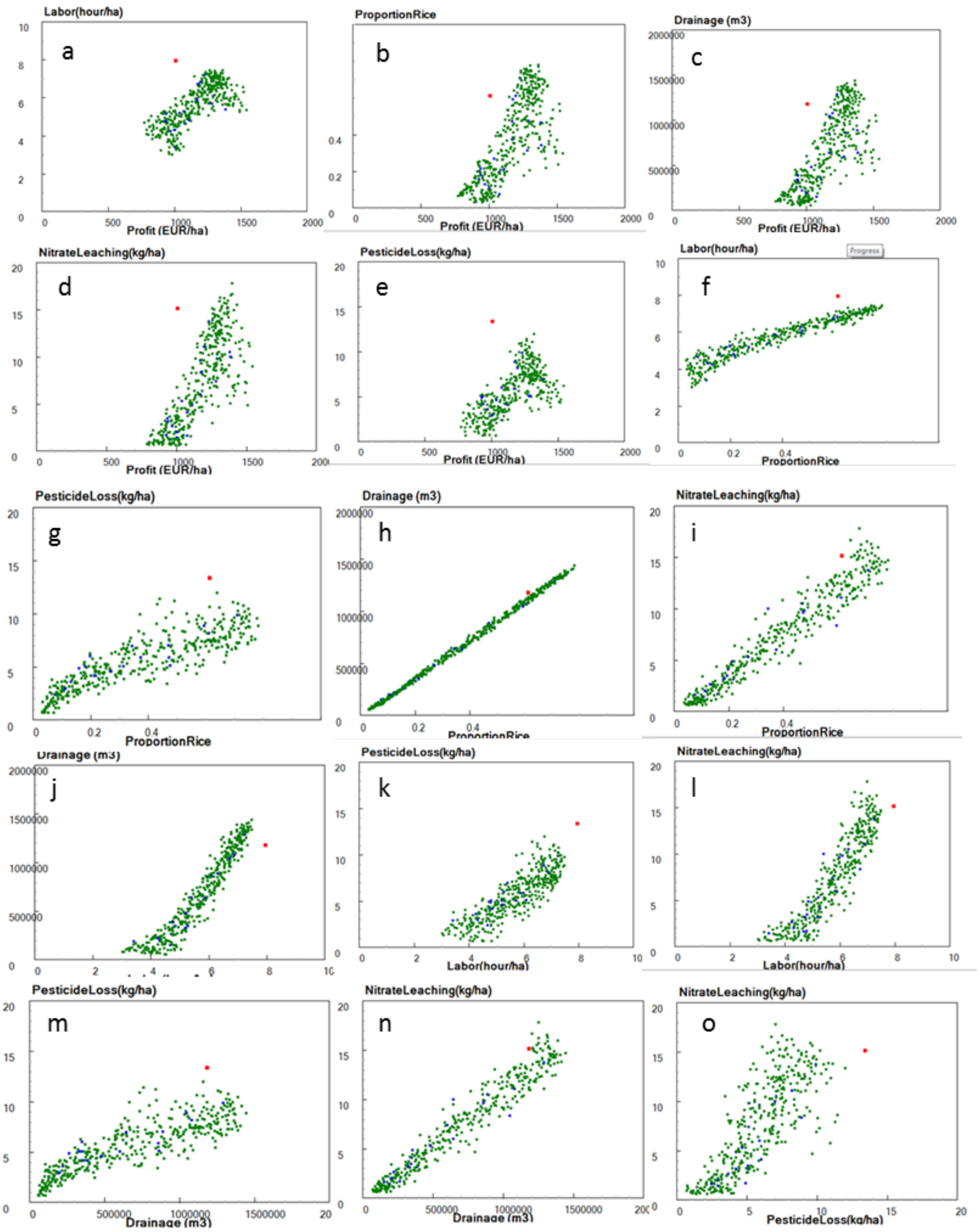


Figure 10. Outcome of all six indicators from Landscape IMAGES for scenario 6

Table 10 present three solutions for scenario 6 selected on the basis that their rice proportion is similar. However, the pesticide losses differ greatly between the three solutions, with values ranging from 0.21 to 2.73 kg/ha, while the pesticide input level varied less and non-proportionally. Solutions 363 and 18 have almost the same rice proportion and IFT, while the pesticide loss is tremendously different. The reason for this difference is the spatial location of rice fields within different irrigation basin. These different sub-basins have different irrigation and drainage flows for the same amount of rice area.

Table 10. Spatial analysis for pesticide loss.

Solution	Pesticide loss unit	Rice proportion	IFT
363	0.21	0.045	0.43
74	0.92	0.046	0.20
18	2.73	0.046	0.41

3.6 Multiscale analysis of scenario 6

In table 11, we compare the indicator differences between the initial state of the system and a selected solution at, the farm, irrigation basin and regional (landscape) level. (For the rice proportion at regional level the solution decreased 11.9%, while in irrigation basin 8 there are more decreasing (33.89%) and in irrigation basin 16, rice area increased by 22.4%. At farm level, Farm 15 decreased 25.7% and Farm 33 decreased 29.3%. The difference between irrigation basin level and farm level does not match the regional level individually. Same as profit and labor, the difference between initial set and selected solution seems inconformity among irrigation basin and farms. This table proves that tradeoffs occur in the model at the different levels.

Table 11. Indicator difference between initial set and selected solution at all levels.

	Rice proportion			Profit(euro/ha)			Labor(h/ha)		
Level	Initial	Solution 342	Difference	Initial	Solution342	Difference	Initial	Solution 342	Difference
Regional	0.59	0.52	-11.9%	956	1386	+45.0%	7.70	6.04	-21.6%
Irrigation basin 0	0	0.46	-	825	1494	+81.1%	-	-	-
Irrigation basin 8	0.77	0.51	-33.8%	971	1429	+47.2%	-	-	-
Irrigation basin 16	0.49	0.60	+22.4%	1035	1092	+5.5%	-	-	-
Farm 15	0.74	0.55	-25.7%	1019	1385	+35.9%	8.2	5.90	-28.0%
Farm 20	0	0.46	-	825	1494	+81.1%	5.53	6.38	+15.4%
Farm 33	0.62	0.44	-29.3%	859	1284	+49.5%	8.04	6.19	-23.0%

4. Discussion

4.1 Knowledge learned from Camargue

At field level, the dynamic of pesticide and nitrogen concentration in water of paddy fields highly depends on the application of pesticide and nitrogen amount and date respectively. For pesticide, IFT is an important variables as it decides the application varieties and amount, as the pesticide model is based on hydrology model, inflow water and drainage water will also influence the pesticide concentration. For nitrogen, farming style is an important variables, which effects the nitrogen application times and amount. There is a big difference between organic farming and conventional farming. Hydrology is another factor that changes the nitrogen concentration.

At farm level, it is interesting to find the indicator change difference between farms .

At regional level, trade off can be found between environmental indicators (minimize pesticide leaching, nitrogen leaching and drainage) and the other indicators (maximize profit, minimize labor, maximize rice proportion), however the application of the LandscapeIMAGES model also showed that different spatial configurations of the agricultural system can improve the different indicators. For example while maintaining the same composition (i.e. the same proportion of rice), the simulations could lead to different economic performances and impacts. For the same input level, farming system and rice proportion, changing the spatial location of rice fields can lead to decrease the pesticide loss and nitrogen loss.

4.2 Advances and limits

4.2.1 Advances

The model can show results at different level: at field level, it can calculate the dynamics of pesticide and nitrogen concentration in water of rice; at farm level and regional level, it could show total amount of pesticide leaching, nitrogen leaching and drainage for the whole rice growing season. The excel model integrated several existing models and was implemented into the spatial analysis model LandscapeIMAGES, that was used to prioritize the indicators with spatial allocation.

The model can be used not only in Camargue, but also other paddy fields. If applying this model to other region, hydrology model should be replaced.

4.2.2 Limits

Through this modeling approach, the relationships between the hydrological functioning, pesticide balance and nitrogen cycling in rice agricultural systems was analyzed. Pesticide and nitrogen balance depend greatly on the hydrological functioning of the rice fields, as notably the drainage water being the medium for pesticide and nitrogen losses.

What’s more we perceive the importance of applying model in agriculture. It can analyzing complicated weather, climate and soil data, make prediction on the future movement and improve the efficiency of farming system,

In some basins, the water used for irrigation is not pumped from the Rhone River but from drainage channels of other irrigation basin. The irrigation inputs of nitrogen and pesticides highly depend on the upstream irrigation basin. In this version of the model, we considered the same input value for nitrogen and pesticide as if the water was pumped from Rhone River.

The total area of the selected area is 105.15ha, to reach the lower limit of the original irrigation SIV equations for irrigation basin 8, at least 0.61 rice proportion of the total area (Figure 11a) should be achieved to reach the lower limitation (and all the rice should belong to irrigation basin 8) which is only a few number of solutions according to the graphs from LandscapeIMAGES, while most of the solutions are below that range. We changed the lower limitation to 0ha, so the irrigation volume would change according to the rice area.

Figure 12a shows that when the rice area is within the range of values (here forced), the relationship between the rice proportion and the drainage is not linear. When the rice proportion increases, there is interesting phenomenon that the slope becomes more and more flat (figure 12a).

With increasing rice proportion, the range of pesticide loss as well as nitrogen leaching is becoming wider (figure 12b, 12c), the reason is that when rice proportion is higher, there would be more rice grow at selected region, allocation of rice fields affects more.

Irrigation basin 8: Original SIV equations:

SIV = 20500 if RiceArea <65 (6a)

SIV = -349.42*RiceArea+43126 if RiceArea >= 65 and RiceArea <= 81 (6b)

SIV = 15000 if RiceArea > 81 (6C)

I changed the lower limit of rice area to 0 ha,

Irrigation basin 8: new SIV equations:

SIV = -349.42*RiceArea+43126 if RiceArea <= 81 (7a)

SIV = 15000 if RiceArea > 81 (7b)

Irrigation basin 16: SIV is constant value 25000

Irrigation basin 0:

SIV = 15000 if RiceArea <65 (8a)

SIV = 279.28 * RiceArea - 3094 if RiceArea >= 65 and RiceArea <= 83
(8b)

SIV = 20000 if RiceArea > 83 (8C)

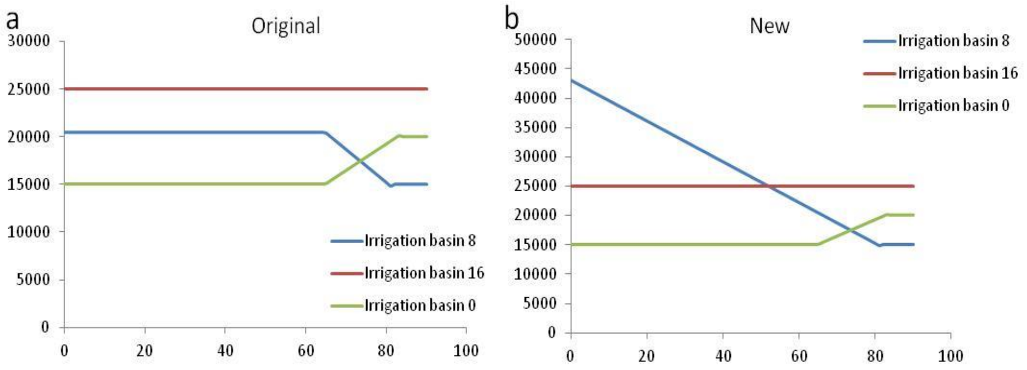


Figure 11. The relationship between rice area and SIV for both the new and original equations

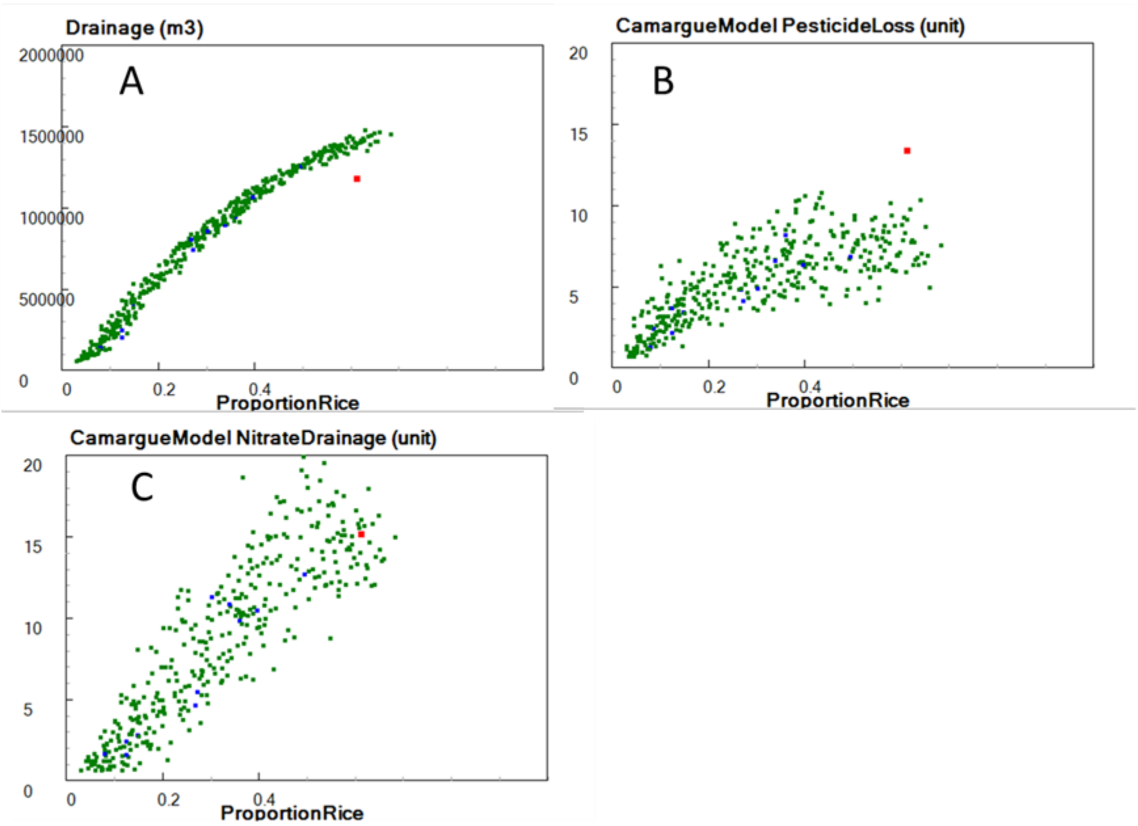


Figure 12. Output of LandsacpeIMAGE for new irrigation SIV equations

The model developed for LandscapeIMAGES relies on a lot of assumptions and input data, which makes the model have some errors. To build the pesticide and nitrogen models that needed daily information related to the water balance, we had to assume that input and output were constant during the whole rice growing season. This included daily irrigation input, daily rainfall, daily drainage, daily evapotranspiration, and the water depth, as our hydrological model was run at a time step of a year. The inconformity between model and reality could cause errors. Seepage water from the rice fields in the model is set as 0, which could cause big errors when there is much seepage.

Concerning the nitrogen fertilization, it usually occurs in 3 applications. The first application **is** before sowing of the rice crop in April or May. After field operations to break-down soil clumps, N, P and K fertilizer is applied on the top of the dry soil surface and incorporated with a rotary harrow. At tillering and around panicle initiation additional N may be applied in quantities ranging from 30 to 50 kg N ha-1 per application. This fertilizer is spread into the floodwater (Stutterheim, 1995). In our nitrogen balance model, the first application was not included as it was not applied in water and as the model used here cannot simulate the nitrogen in dry soils.

The model is lack of calibration and validation with the observed data from experiments about pesticide and nitrogen.

4.3 Future development

In order to improve the model calibration, some measurements and experiments should be conducted:

In the current model version, the values of concentration of ammonium and nitrate for the irrigation water are hypotheses; they should be measured in each irrigation channel, so the value of input ammonium and nitrate can be calibrated more accurately.

The various rate of N-transformation process including k_v, k_h, k_n and k_d should be calibrated using comparison between simulations and observed data. Here again, data were not available for the Camargue case study to allow such calibration and value used were obtained from the literature. . For nitrogen model the concentration of ammonia and nitrate in water should be measured at daily step. For pesticide model, concentration of varieties of pesticide in water and soil should be measured at daily step.

Validating such a model could be costly and time consuming, as it should be achieved at different levels, first at field level, pesticide and nitrogen dynamics should be validated, at irrigation basin level, hydrology model can be validated by the measurement of inflow water and outflow water. For regional level, the leaching of pesticide and nitrogen can be validated by measuring the concentration of pesticide and nitrogen in drainage water.

Improving the sub-model for nitrogen balance to include the first nitrogen application in the soil is another important objective. Some models already exist to predict the exchange between the soil and water layer, for example the GlEAMS-PADDY model (Chung et al., 2003). However, several information for parametering this model are lacking to apply it in Camargue, some further experiments are required for modeling nitrogen loading from soil to water. The input data for nitrogen model that have to be measured is nitrate and ammonia concentration in both irrigation water and rainfall water; this could be the average during the whole rice growing season. For pesticide, all varieties of pesticides in inflow water should be measured. When validating such model, the concentration of nitrogen and pesticide in the paddy fields should be measured every week, then make the dynamic graphs of pesticide and nitrogen and compare it with the graphs we get from our models.

While running the model in LandscapeIMAGES We see inconformity solution range for different scenarios, there are three reasons could cause the difference:
First one is reality constrains, which means the outcome is limited by some reality conditions. For example in scenario 2 only organic farming are allowed so only half of the activities can be used in the simulation compared to other scenario which results in smaller area of the scenario.
The second reason could be number of solution, the scenario is simulated but the iterations (number of improvement of the solution in the model) are not enough, which means there are more solutions will be formed if run for more iteration.
The last reason is indicator problem, as more indicators are added to the simulation more dimension are added, the hyper volume of solutions would increase.
So we could improve the accuracy of the model by running more iteration.

5. Conclusion

The objectives of the work was to prioritize and improve the spatial distribution of crops in farms to minimize water use, pesticide loss and nitrogen loss to the environment with equal level of economic performance and labor required.
After the work several goals have been achieved:
First the integrated model has been made to calculate the pesticide, nitrogen and hydrology balance at different levels.
Then using LandscapeIMAGES, spatial analyze was achieved. For all the six scenarios, indicators were calculated. And get graphs of the relationships among all the indicators. Trade-off between indicators is clarified.
Also the spatial influence on pesticide leaching is found during the work.
Although this model still has some limits, it can be quite useful for simulating spatial biophysical processes in agricultural systems. It can also be applied in other cases with same structure while sub-models and parameter would change.
The lack of model is calibration and validation, with further work, it can be more accurate.

References

ANSELIN, L. 1988. *Spatial econometrics: methods and models*, Kluwer Academic Pub.

ANTONOPOULOS, V. 2008. Modeling of water and nitrogen balance in the ponded water of rice fields. *Paddy and Water Environment,* 6**,** 387-395.

BRINER, S., ELKIN, C., HUBER, R. & GR T-REGAMEY, A. 2012. Assessing the impacts of economic and climate changes on land-use in mountain regions: A spatial dynamic modeling approach. *Agriculture Ecosystems and Environment,* 149**,** 50.

CAMBARDELLA, C. & KARLEN, D. 1999. Spatial analysis of soil fertility parameters. *Precision Agriculture,* 1**,** 5-14.

CHAUVELON, P. 1998. A wetland managed for agriculture as an interface between the Rhone river and the Vaccares lagoon (Camargue, France): transfers of water and nutrients. *Hydrobiologia,* 373/374**,** 181-191.

CHAUVELON, P., SANDOZ, A., HEURTEAUX, V. & BERCEAUX, A. 2001. Satellite remote sensing and GIS used to quantify water input for rice cultivation (Rhône delta, France). *IAHS PUBLICATION***,** 446-450.

CHAUVELON, P., TOURNOUD, M. G. & SANDOZ, A. 2003. Integrated hydrological modelling of a managed coastal Mediterranean wetland (Rhone delta, France): initial calibration. *Hydrology and Earth System Sciences Discussions,* 7**,** 123-132.

CHUNG, S.-O., KIM, H.-S. & KIM, J. S. 2003. Model development for nutrient loading from paddy rice fields. *Agricultural Water Management,* 62**,** 1-17.

COMORETTO, L., ARFIB, B. & CHIRON, S. 2007. Pesticides in the Rhône river delta (France): basic data for a field-based exposure assessment. *Science of the Total Environment,* 380**,** 124-132.

COMORETTO, L., ARFIB, B., TALVA, R., CHAUVELON, P., PICHAUD, M., CHIRON, S. & HOHENER, P. 2008. Runoff of pesticides from rice fields in the Ile de Camargue (Rhone river delta, France): field study and modeling. *Environmental Pollution,* 151**,** 486-93.

DELMOTTE, S. 2011. *Evaluation participative de scénarios: quelles perspectives pour les systèmes agricoles camarguais?* , Montpellier SupAgro.

DELMOTTE, S., LOPEZ-RIDAURA, S., BARBIER, J. M. & WERY, J. 2010. How to evaluate the impacts of the extension of innovative farming systems at the regional scale? Scenario analysis of organic agriculture in the Camargue. hal-00520233.

GROOT, J. C. J., JELLEMA, A. & ROSSING, W. A. H. 2010. Designing a hedgerow network in a multifunctional agricultural landscape: Balancing trade-offs among ecological quality, landscape character and implementation costs. *European Journal of Agronomy,* 32**,** 112-119.

GROOT, J. C. J., ROSSING, W. A. H., JELLEMA, A., STOBBELAAR, D. J., RENTING, H. & VAN ITTERSUM, M. K. 2007. Exploring multi-scale trade-offs between nature conservation, agricultural profits and landscape quality—A methodology to support discussions on land-use perspectives. *Agriculture, Ecosystems & Environment,* 120**,** 58-69.

INAO, K. & KITAMURA, Y. 1999. Pesticide paddy field model (PADDY) for predicting pesticide concentrations in water and soil in paddy fields. *Pesticide Science,* 55**,** 38-46.

KHOR, E. F., TAN, K. C., LEE, T. H. & GOH, C. 2005. A study on distribution preservation mechanism in evolutionary multi-objective optimization. *Artificial Intelligence Review,* 23**,** 31-33.

LAMBIN, E. F. 1997. Modelling and monitoring land-cover change processes in tropical regions.

Progress in physical geography, 21**,** 375-393.

LIGTENBERG, A., WACHOWICZ, M., BREGT, A. K., BEULENS, A. & KETTENIS, D. L. 2004. A design and application of a multi-agent system for simulation of multi-actor spatial planning. *Journal of Environmental Management,* 72**,** 43-55.

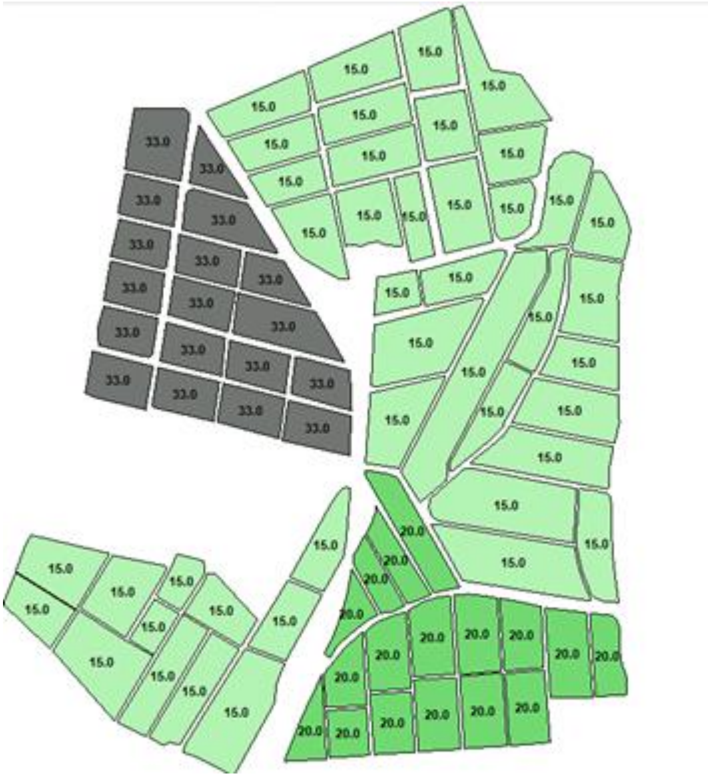
RAILSBACK, S. F., LYTINEN, S. L. & JACKSON, S. K. 2006. Agent-based simulation platforms: Review and development recommendations. *Simulation,* 82**,** 609-623.

REDDY, K. 1982. Nitrogen cycling in a flooded-soil ecosystem planted to rice (Oryza sativa L.). *Plant and Soil,* 67**,** 209-220.

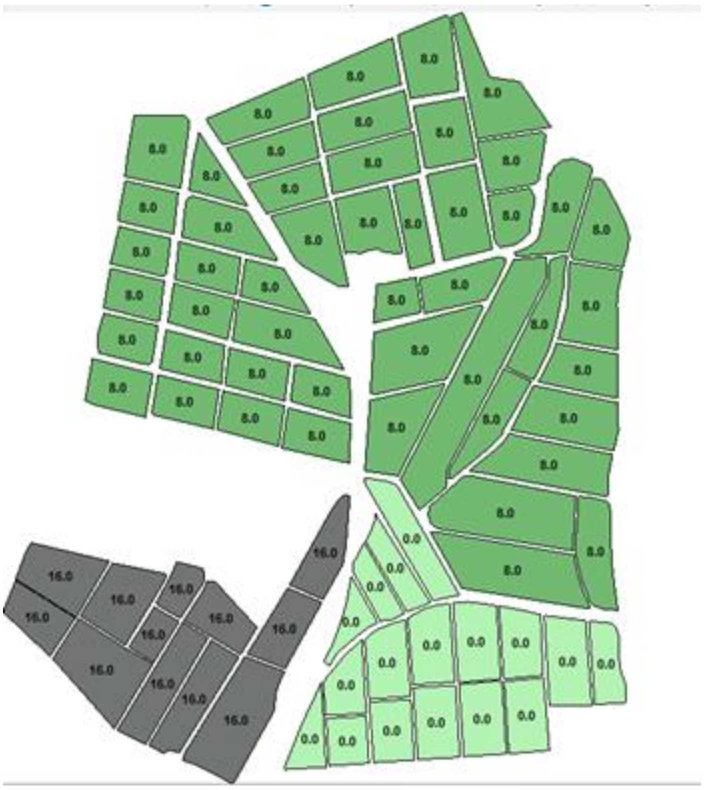
STUTTERHEIM, N. 1995. *Towards Higher Nitrogen Efficiency in European Rice Cultivation: A Case Study for the Camargue, South of France*, Landbouwuniversiteit te Wageningen.

VERBURG, P. H., SOEPBOER, W., VELDKAMP, A., LIMPIADA, R., ESPALDON, V. & MASTURA, S. S. A. 2002. Modeling the Spatial Dynamics of Regional Land Use: The CLUE-S Model. *Environmental Management,* 30**,** 391-405.

1. GIS map of Camargue and select area



Selected area with farm number for each fields



Selected area with irrigation number for each fields

Appendix 2. SIV relationships and constrains for irrigation basins in Camargue

	SIV constant	relationship	if Surf riz ha <	SIV constant surf min		if Surf riz ha >	SIV constant surf max
Tourtoulen	33431						
Cazeau		y = -134,33x + 46136	120	30000		210	18000
Grd Manusclat			200	23500		310	15000
Grd Paty	32082						
Amerique		y = 279,28x - 3094	65	15000		83	20000
Chartrouse		y = -123,51x + 40858	90	30000		200	16000
Louisiane		y = -349,42x + 43126	65	20500		81	15000
Grifeuille Peaudure		y = -165,27x + 64962	80	52000		192	33200
Sambuc		= -480,12x + 166305	240	51105		300	22305
Aube de Bouic		y = -51,47x + 71227	400.00	50627		700.00	35177

Appendix 3. Parameters and transformation rate for pesticides

Pesticide model Parameters

Pesticide	LogKow a	H(-)	DT50 wat	KdAB pH7	KdAH pH7	KdSB pH7	KdSH pH7	Kvol(d-1)	Kdeg(d-1)	Kdes(d-1)
Azimsulfuron	-1.4	6.64E-13	44.5	0.073986	0.053177	0.053177	0.034681	0	0.015576	0.05
Bensulfuron methyl	0.79	7.04E-15	18.5	0.875488	0.629257	0.629257	0.410385		0.037467	0.05
Cyhalofop-butyl	3.32	1.77E-05	0.15	15.20372	10.92768	10.92768	7.126746		4.620981	0.05
Flufenacet	3.2	2.40E-06	54	13.27853	9.543943	9.543943	6.224311		0.012836	0.05
MCPA	-0.81	1.10E-08	13.5	0.143963	0.103473	0.103473	0.067483		0.051344	0.05
Oxidiazon	5.33	1.50E-05	11	146.8419	105.5426	105.5426	68.83214		0.063013	0.05
Penoxulam	-0.6	1.21E-17	2	0.182453	0.131138	0.131138	0.085525		0.346574	0.05

Appendix 4. Constrains for scenario selection:

ORG (0)		Minimum				Maximum			
		AB	AH	SB	SH	AB	AH	SB	SH
Crop	CrpID	0	1	2	3	0	1	2	3
Ble	0	0	0	0	0	3/4	3/4	0	3/4
Colza	1	0	0	0	0	0	1/5	0	1/5
Lentille	2	0	0	0	0	1/6	1/6	0	1/6
Luzerne	3	0	0	0	0	3/4	3/4	0	3/4
Mais	4	0	0	0	0	1/5	1/5	0	1/5
Prairie	5	0	0	0	0	1	1	1	1
Riz	6	1/4	1/9	0	1/9	1/4	1/4	0	1/4
Soja	7	0	0	0	0	1	1	1	1
Sorgho	8	0	0	0	0	1/2	1/2	0	1/2
Tournesol	9	0	0	0	0	0	1/4	0	1/4
Non-rice	10	3/4	3/4	0	3/4	3/4	8/9	0	8/9

CON (1)		Minimum				Maximum			
		AB	AH	SB	SH	AB	AH	SB	SH
Crop	CrpID	0	1	2	3	0	1	2	3
Ble	0	0	0	0	0	3/4	3/4	2/3	3/4
Colza	1	0	0	0	0	0	1/3	0	1/3
Lentille	2	0	0	0	0	1/4	1/4	0	1/4
Luzerne	3	0	0	0	0	3/4	3/4	0	3/4
Mais	4	0	0	0	0	1/2	8/9	0	8/9
Prairie	5	0	0	0	0	1	1	1	1
Riz	6	1/4	1/9	1/3	1/9	1	1	1	1
Soja	7	0	0	0	0	1/2	1/2	0	1/2

Sorgho	8	0	0	0	0		1/2	2/3	1/2	2/3
Tournesol	9	0	0	0	0		0	1/3	0	1/3
Non-rice	10	0	0	0	0		3/4	8/9	2/3	8/9