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## VIGIE-MED : Impact des changements climatiques à l'échelle régionale et adaptation par la distribution spatiale des ressources hydriques et des systemes de production végétal.

Andre Chanzy, Denis Allard, Marc Bourotte, Philippe Clastre, Hendrik Davi, Jean-Luc Dupuy, Marta Debolini, Sébastien Garrigues, Martine Guerif, Ghislain Geniaux, et al.

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## VIGIE-MED :

Impact of Climate Change at Regional scale and adaptation through the spatial distribution of Water resource and crop systems.

## Metaprogram AAFCC

Final report: results from 2011 to 2014  
*English version*



Month / Year

## INDEX

<b>INDEX</b> .....	<b>2</b>
<b>GENERAL PRESENTATION OF THE PROJECT</b> .....	<b>3</b>
<b>SYNTHESIS</b> .....	<b>6</b>
<b>EXECUTIVE SUMMARY</b> .....	<b>20</b>
<b>HIGHLIGHT(S) OF THE PROJECT</b> .....	<b>23</b>

## General presentation of the project

Titre : VIGIE-MED

Dates et durée du projet : 2011-2014

Budget ACCAF alloué pour le projet : 187k€

### Porteur(s) de projet

Nom : André Chanzy

Unité et Département : EMMAH département E&A

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### Présentation du consortium

Autres unités impliquées : ECODEV, URFM, BioSP, MIA Toulouse, UMR MIA 518 INRA-Agro-Paristech

(Les contributions des unités ASTER, économie Publique et GSE n'ayant pas ou peu participé au projet n'ont pas été prises en compte dans le rapport).

Autres départements impliqués : EFPA, MIA

Effectifs impliqués :

- Permanents :

<b>DR / CR</b>	9
<b>IR / IE</b>	6
<b>AI-B-C</b>	8

- Contractuels :

<b>CDD</b>	1
<b>Post-doctorants</b>	
<b>Doctorants</b>	1
<b>Masters :</b>	15

Hommes.mois mobilisés sur la durée du projet :

- Permanents :

<b>DR / CR</b>	25
<b>IR / IE</b>	22.5
<b>AI-B-C</b>	75.5

- Contractuels :

<b>CDD</b>	6
<b>Post-doctorants</b>	0
<b>Doctorants</b>	36
<b>Masters</b>	75

Stagiaires accueillis (master, doctorants, post-doctorants) :

### **Master**

Balde O., Analyse statistiques des choix de couverts agricoles a` l`echelle parcellaire., stage de master II, 6 mois, Stage INRA M2, 2014.

Boyao, S., Mod`elisation micro-`econom`etrique de l`abandon agricole et des choix culturaux `a l`echelle parcellaire en paca., stage de master II, 6 mois, INRA, UR 767 Ecod`veloppement, 2012.

Drapier, L. Analyse de la causalit`e entre am`enagement routiers et urbanisation., stage de master II, 6 mois, INRA, UR 767 Ecod`veloppement, 2015.

Feindouno, S., D`eterminants de l`abandon agricole en r`egion paca, tech. rep stage de master II, 6 mois, INRA, UR 767 Ecod`veloppement, 2013.

Lopez-Kolkosky, J., Mod`elisation micro-`econometrique de l`urbanisation en paca, stage de master I, 6 mois, INRA, UR 767 Ecod`veloppement, 2013.

Wu, D. Propri`et`e fonci`ere et `etalement urbain, stage de master II, 6 mois, INRA, UR 767 Ecod`veloppement, 2012.

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Bornuat E. 2015. D`etermination de la structure et de la biomasse combustible `a partir de nuages de points acquis par un LiDAR terrestre. M`emoire de soutenance de Dipl`ome d`Ing`enieur INSA Sp`ecialit`e Topographie. 74p.

Cakpo CB 2015. Etude du bilan hydrique en contexte forestier méditerranéen, approche par géophysique, traçage isotopique, modélisation écophysologique. Mémoire de fin d'étude. Master Sciences et Technologies du Vivant et de l'Environnement ; mention (Forêt Agronomie et Gestion des Ecosystèmes), spécialité : « Fonctionnement et Gestion des Ecosystèmes ».

Zhang Z., 2011. Analyse de l'évolution du parcellaire agricole : mise au point d'une méthode de classification fondée sur l'analyse d'images de télédétection et de données vectorielles de différentes natures. Mémoire de Master 1ère année « Génie de l'environnement », Institut EGID, Université Michel de Montaigne – Bordeaux 3, 26 p.

Lejail P., 2013. Création d'une typologie des systèmes agricoles de la région PACA et analyse de son évolution au cours du temps. Rapport de stage de 2ème année D.U.T. Statistiques et Informatique Décisionnelle, IUT d'Avignon, 34 p + annexes.

El Amraoui M., 2014. Les indicateurs écoclimatiques pour l'analyse de la faisabilité des cultures. Le cas d'étude de la vigne en Vaucluse. Rapport de Master « Ingénierie et Gestion des Territoires (IGT) », spécialité « Gestion Agricole et Territoires (GAT) », CIHEAM-IAM Montpellier, Université Montpellier 3, 66 p + annexes.

Ben Mustapha A., 2014. Les indicateurs écoclimatiques pour l'analyse de la faisabilité des cultures. Le cas d'étude du pommier et du cerisier en Vaucluse. Rapport de Master « Ingénierie et Gestion des Territoires (IGT) », spécialité « Gestion Agricole et Territoires (GAT) », CIHEAM-IAM Montpellier, Université Montpellier 3, 78 p + annexes.

Gundogdu U., 2015. Application of ecoclimatic indicators to analyse the quantity and quality feasibility of wine grape production in Vaucluse department (France). Mémoire de Master 2, European Master of Viticulture and Enology, Universidad Politecnica de Madrid, 68 p + annexes.

Thèse :

Bourotte M. Modèles et algorithmes pour un générateur de temps spatialisé (SWgen) prenant en compte les valeurs extrêmes. Co-direction, D. Allard (BioSP, INRA Avignon) et Liliane Bel (UMR MIA/AgroParisTech, Paris) Soutenance prévue en Février 2016.

# **VIGIE-MED**

**Metaprogramme “Adaptation of Agriculture and Forests to Climate Change” (AAFCC)**

## **SYNTHESIS**

**Name of the project leader: André Chanzy**

**Other scientific partners:** Denis Allard, Marc Bourotte, Philippe Clastre, Hendrik Davi, Jean-Luc Dupuy, Marta Debolini, Sébastien Guarrigues, Martine Guerif, Ghislain Géniaux, Patrice Lecharpentier, Claude Napoléone, François Pimont, Hélène Raynal, Eric Rigolot, Albert Oliosio

## **GENERAL CONTEXT**

In many parts of the world, it is vital to preserve vegetation production capacities (provisioning Ecosystem Services (ES)). These are highly dependent on water and soil resources subjected to strong pressures (climate change, droughts, floods, population growth). It is also important to be able to predict the evolution of risks that may affect these services, such as forest fires. Some of the impacts of climate change on crop production systems involve large areas (aquifer, watershed, forest) and the regional level, as an administrative entity, is an important level to make decisions on the adaptation to Climate Change (Grenelle's laws, Agenda 21, master plans of the territory, water management ...). In order to support local authorities and agricultural and forestry occupations, we provide territorial sustainability indicators to assess provisional and regulation ES, water resources, the risk of fire or adaptability to future territorial issues related to the needs and production conditions. In VIGIE-MED, adaptation is seen through spatial allocation of vegetation production systems that must take into account the distribution of soils, water resources and bioclimatic conditions, explicitly. To understand the impact of adaptation measures, it is important to understand land dynamics induced by taking into account other factors such as micro-economic processes or macroeconomic forcing.

The general aim of the project was to build a regional modelling framework to represent on the one hand, the dynamics of land use with respect to socio-economic context and adaptation options and on the other hand, a set of indicators describing land functioning in terms of vegetation production, the associated risks (drought, fire) and water resources. The ACCAF funding was to be used as starter to initiate an ANR project, which has unfortunately not been selected. Thus the project helped to initiate the necessary bricks regional modelling without allowing to integrate all.

The territorial base was the western PACA region, which includes the districts of Vaucluse and Bouches-du-Rhône. This area offers significant diversification of land uses with rapid changes from one use to another (urbanization, abandonment, crop systems) and prospects of significant climate change, the Mediterranean being often considered as a hot spot for changes. The project was mainly carried out by the teams of "Adaptation to Global Changes" pole of the INRA -PACA centre and the geomatics platform GeOpen4S was mobilized to support the data base.

## **GENERAL OBJECTIVES**

The general orientations of the project outlined in the previous section have been developed according to four axes:

- Consolidation of the territorial database (land use, socio-economic, political, soils and climates) in the departments of Vaucluse and bouches-du-Rhone on the Geomatics platform GeOpen4S.
- Calculation of different indicators at the regional level on crop production (agriculture and forestry), the fire risk and water resources and application, according to the indicators, on the plain of CRAU (agrosystems), the massif of Ventoux (forest) or the entire study area (fire hazard).
- Modeling land use changes and agricultural production systems based on micro-economic, social, political, geographical and agricultural potential and their development in a context of climate change.



- To better represent climate variability, we developed a simulation tool able to generate sets of multivariate meteorological series, multi-site, with proper reproduction of extreme events. We limited ourselves for the moment to stationary chronics.
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## **METHODOLOGICAL ELEMENTS (AND POSSIBLE DIFFICULTIES)**

### **A) ESTABLISH A REGIONAL DATA BASE**

#### **Contribution to the development of a collective tool for data management**

The resources of the GeOpen4S platform (Geomatics Service of the INRA PACA centre) has been used to host the data (postgre data base, NAS storage server), bring them to knowledge through a cataloging tool (GeoNetwork), and publish some of the data to make their use within the community VIGIE-MED, easier (Lizmap and Geoserver). In this regard, the implementation of VIGIE-MED was at the initiative of engineering work around the tools offered by the platform. In particular, we explored the links between the map server and catalog offering to a user, identifying a given data via the catalog, the immediate view on a basemap without using a third party tool. This work has helped democratize the use of the catalog for “spatial” data and is now regularly used by other users of the platform who want to valorize such data.

#### **Constitution of a database for the analysis of land use change dynamics**

A first work focused on the improvement of the parcel database developed by ECODEV to better monitor the parcel changes and the factors driving land use changes (LUC), in partnership with the other teams involved in the Urbansimul project (see highlight “Partenariat”). All the existing plots from the French land registry databases (PCI, MAJIC) from 2007 to 2014 have been acquired in order to obtain a historical land registry ensuring a better geo-localization of land tenure information and on farm structure (RPG<sup>1</sup>, CCMSA and MSA<sup>2</sup> databases). The acquisition of these different data sources guaranteed a geo-localization rate of about 99%. Moreover, all the planning documents were integrated on vector format for the years 2000-2015. Thus, in the PACA Region, changes on 4.5 million parcels could be assessed (built or not, physically or statutorily building, crop type, irrigation, evolution of the plots, changes on land tenure and price).

A second task consisted on the improvement of the parcel database historical series for the factors driving the LUC at different spatial and temporal changes. For each parcel, around thirty variables have been acquired going from the distances (from the villages, public equipment, road networks, environmental hotspots), spatial configuration (shape, number of parcels to be crossed in order to reach the main roads) and land tenure type (private, public, size of the property). At the municipality level, a series of key indicators have been obtained from the RGA<sup>3</sup> database of 2000 and 2010 about agricultural practices (crop rotation, economic return, irrigation, conventional or biological

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<sup>1</sup> Parcel identification system (Common Agricultural Policy declarations of farmers)

<sup>2</sup> Agricultural health Assurance system. This database includes yearly individual information on farms and farmers (restricted access)

<sup>3</sup> General agricultural census

management). The RGA data at farm level allowed to obtain a classification of farm system typology and they offer a greater historical depth (1970-2010) than the databases like the MSA which are limited to 10 years.

A third work focused on the assessment of the MSA database quality at the parcel level, as a reference for the validation of remote sensing classification based on the combined use of the agricultural parcel boundaries and crop type classifications. MSA data have the advantage to connect plots and farms, which is relevant information for many analyses. However, their use for remote sensing validation was not considered as satisfying because of the errors in farm's declarations and of inappropriate land-use classification. At the same time, two classification procedures have been realized. The first one is focused on the fuel mapping starting from an inventory of the forest formation from high-resolution images rapideye (5 meters). The obtained classification has around twelve LU and vegetation structure classes going from the type dense woodland, sparse, unopened, on which we can distinguish hardwood or softwoods. The second one consisted of a LU class series on 6 time laps for the period from 1975 to 2014 realized for the Crau plain.

### **Characterisation of the biophysical environment**

The SAFRAN meteorological data (historical serie from 1960 to 2013]) and climate projections QQA1B scenario [1960-2100]) were included in a database, and a tool allowing users to get files compatible with our climate models biophysical specifying the grids of interest and the required period. Regarding the soil map, the reference profiles (~ 800 on Vaucluse) were digitalized in the DONESOL data base handled by INFOSOL<sup>4</sup>. From these data, the soil hydraulic properties were estimated via pedotransfer functions.

## **B) PLANT PRODUCTION AND WATER RESOURCES INDICATOR CHARACTERIZATION**

The desired indicators were the vegetation production, the drainage to characterize the aquifer recharge, the water balance of aquifers and the fire hazard. The aim of the project is to produce such indicators at the annual time scale and with high spatial resolution (<km) to account for the complex spatial heterogeneity in Mediterranean environment. For the fire part, hazard maps were produced. These are the required elements for the assessment of production losses or degradation of some ecosystem services related to forest fires. They are also used as the foundation of regulatory policies to protect property and people.

### **Indicators on crop production and water resources**

The approach taken is to implement ecophysiological based models to represent, through a multi-local approach, the vegetation production, mortality in the case of forest cover and water exchange with the environment (irrigation, drainage). The models used were the STICS crop model for arable crops and grassland, the CASTANEA model forests and model ISBA-Gs on other types of surface. Two zones

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<sup>4</sup> French soil survey service

were modeled: the Ventoux for forests and the plain of the Crau for cultivated areas. In the latter case, a coupling of the surface model was done with the aquifer MODFLOW model for understanding the impact of climate change on the water table.

We have been working on the adaptation of the models and namely CASTANEA to the plant covers taken into account. CASTANEA was parametrized for 4 species (*Quercus ilex*, *Quercus pubescens*, *Fagus sylvatica* and *Abies alba*) and literature review enable us to determine the ecophysiological characteristics of two additional species (*Pinus silvatica* and *Cedrus atlantica*) facilitating their inclusion in our future analysis. The model was validated on fir growth data and a mortality module was developed and validated (Davi and Cailleret submitted).

Our efforts were focused on the implementation of these models trying to take into account the spatial variability using the available information layers. Soil characterisation is still a critical point at the Regional level. Regarding forests case, surface water reserves were estimated by re-analysing data from 86 soil pits. High content of coarse material ( $65\pm 16\%$ ) and low soil depth ( $51\pm 21\text{cm}$ ) lead to very low surface available water capacity ( $\text{AWC}=30\pm 6\text{mm}$ ). Nevertheless, through isotopic analysis, we showed that Beech, Fir and evergreen oak are able to draw up to 50% of their water needs in the epikarst (Cakpo 2015). Taking these reserves into account, available water capacity increases to  $51\pm 13\text{mm}$ . For soils of the plain of Crau, we performed an analysis of variance on observations of soil profiles, which allowed us to identify five soil classes, for which we applied the average parameters. For the climate, there are no spatial products adapted to mountain areas. Altitudinal gradients of temperature, humidity of the air and precipitation were characterized from a weather station network. The SAFRAN data were used in CRAU plain. In that case, variables such as precipitation have been found to be more accurate than interpolations between stations. Finally cropping practices, in particular the management of irrigated grass has been the subject of specific developments to produce their spatial and temporal representation.

Developments have been made to transfer in the RECORD modelling platform the informatics codes of the climate generator (WACS-GEN) and Regional-STICS<sup>5</sup> model. The methodology has been to rely on the following services offered by the RECORD platform: i) dynamic coupling ii) decision modeling module and iii) the package encapsulating the STICS crop model. To be able to externalize the representation of cropping practices that could be the result of complex processes integrating the spatial organization of the territory and climate change, we coupled the STICS model with a decision module. Furthermore, a workflow was designed and developed to manage multisimulations the resulting coupled model STICS/Decision. As a pre-existing workflow was developed on Matlab, interoperability between RECORD and Matlab had to be designed and implemented beforehand. A difficulty encountered concerned the execution time of coupled models. This problem is being resolved.

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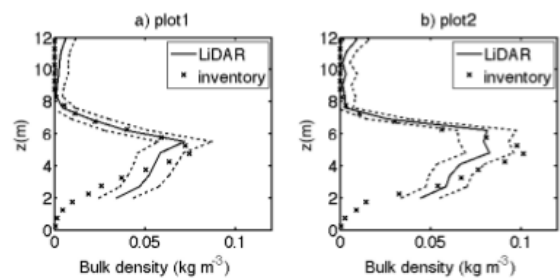
<sup>5</sup> <https://www6.inra.fr/agadapt/Regional-planning/Model/Regional-STICS>

### Fire hazard assessment

*Quercus pubescens* is the first deciduous species of PACA Region. Combustibility of Pubescent oak communities is little known, but, in the climate change context, an increased fire risk is expected in these communities. In the framework of the VigieMed project, the main *Quercus pubescens* forests have been visited with the support of the Vaucluse Forest Service and three representative and contrasted plots have been installed (Mont Ventoux, Monts du Vaucluse and Luberon). On each site, an exhaustive fuel inventory has been carried out aiming at characterising potential fire behaviour. For generalisation purposes, allometric relationships for biomass assessment by fuel diameter classes have been fitted on *Quercus pubescens* and associated shrub species like *Juniperus*. This work enabled to get a deeper knowledge of the most representative fuel types to be integrated in the fire hazard map.

A new method based on LiDAR data was implemented to replace this time consuming inventory approach. It enabled for the first time to assess the 3D distribution of foliar biomass on small plots. Combining water content theory and light calibration, it could become a reference method for fine fuel characterisation and non destructive vegetation monitoring in the global change context. Our method succeeded in reproducing vertical distributions of foliar biomass on 4 pubescent oak plots with various tree heights and densities. LiDAR based distributions are quite close from those obtained with the “inventory method” (Figure 1).

Figure 1. Leaf bulk density profiles estimated on 4 *Quercus pubescens* plots with the LiDAR-based (solid line and confidence intervals in dashed lines) and inventory-based methods (extract from Pimont et al. 2015).



Vaucluse fire hazard map drawing up was based on the above mentioned forest types map. A post treatment was performed to refine vegetation types allocation using geo-referenced land use data bases as well as indices derived from satellite pictures like NDVI. Using a topographic map background and a land registry, post treatment also enabled to refine some vegetation types at the wildland-urban interface with different fire behaviour resulting from both habitat density and in between vegetation. Crossing with IFN layer finally made possible the identification of dominant forest tree species. Vegetation types combustibility was assessed using existing knowledge from literature or new results from this project namely on pubescent oak areas. Fire hazard map was built on the whole Vaucluse department by combining on each point of the vegetation map the expected wind speed and local topography to estimate fire line intensity as well as fire rate of speed under reference conditions (wind and drought level).

## C) REPRESENTATION OF GLOBAL CHANGES DRIVERS

### Stochastic Weather Generator

Developing a multi-site, multivariate stochastic weather generator has necessitated to build and define new multivariate spatio-temporal class of stochastic models. This new, flexible class allows to model

the complex multivariate interactions between space, time and the variables. This model has been validated on two datasets, in Britany and on the VIGIE-MED study area.

In addition, the generator WACS-gen that was previously developed at BioSP has been implemented on the RECORD platform. This generator allows the daily simulation of five weather variables. It is divided in an “estimation” part for characterizing the parameters of the generator, and a “simulation” part which does the actual simulation for a given set of parameters.

### **Land use change and agricultural system change modeling**

This phase of the project aims to develop a modeling tool that integrates both the changes between agricultural and urban lands (or natural) and also the intra-agricultural changes. Thus, it seeks to represent the process of urbanization or agricultural abandonment and their possible future development in an area such as the Mediterranean basin, where we observe at the same time a strong urbanization dynamic and the abandonment of agricultural production in marginal areas. Moreover, this phase would also try to understand and represent more specific agricultural processes, such as the intensification of agricultural practices, parcel fragmentation or extensification of agricultural systems. These trajectories have relevant effects on the landscapes and on the ecosystem services provided by agricultural areas. Understanding these ongoing processes can facilitate the understanding of adaptive systems that maintain in the future agricultural and ecosystem functions of interest.

A first work focused on the characterization of farming systems at the farm level, in order to identify trajectories that are not only changes in land use, but also take into account the structure of the farm and its management. For this objective, the agricultural census data at farm level have been analyzed. The applied method consisted on four phases: 1) definition of a farming system typology; 2) analysis of spatio-temporal dynamics of farming systems (farming system trajectories); 3) identification of the factors driving the past dynamics and 4) statistical regression analysis of the relation between the drivers and the spatial distribution of the farming system changes, in order to explain the past changes and develop a forecast for possible future changes. The case study for the phase is the Vaucluse department, because the relevant amount of data available in this area. Moreover, the department is characterized by a high level of farming system variability. The developing method will be applied mainly at the farm scale, representing the farming system trajectories, and also at the municipality level, giving the change rate on the existing farming.

A second part of the work was focused on the characterization of the parcel evolution (land tenure, structure, land cover). The structural evolution of the parcel system (fusion, division, extension) between 2007 and 2014 was realized for 8 classes through the geographic analysis of the parcel geometry and land tenure units: these evolutions are frequently precursors of urbanization or equipment installations. A similar work was carried out on the land tenure characterization depending on the type and number of owners, the right type and mutations (number of sales and prices). Finally, developments on the urban areas were assessed (built / non-built, number of rooms, height and built-in floor, type of residential-commercial-industrial local). The intersection of these three types of evolution has enabled a very detailed and comprehensive inventory over 4 million parcels changes, constituting a unique database in France to characterize all paths of changes leading to different local

forms of building production. This data can be the base for a statistical modeling of parcel state, largely based on the work within the project Urbansimul<sup>6</sup>, which enlarges the binomial approaches to multinomial ones, allowing to consider multiple possible evolution of a single parcel.

## OVERVIEW OF THE RESULTS

### A) INDICATORS CHARACTERIZATION ON VEGETATION PRODUCTION AND WATER RESOURCES

#### Agricultural production and water resources on the plain of CRAU

The simulator consisting of the surface model (Regional STICS) and the aquifer model (MODFLOW) was evaluated on data collected at several farms (for agricultural production and irrigation of grasslands at the farm level), water flow records at the channel inlet and outlet (to assess water taken from irrigation throughout the irrigated area) and piezometry for balance of water recharge and withdrawals at the aquifer level. The results show that the orders of magnitude are respected and that the simulator represent the interannual variability (Figure 2). In particular, one can see the drop in groundwater level in the years 2004-2007 corresponding to a succession of dry years and a return to normality thereafter with more rainy years. The annual cycle observed in the wells P42 is related to gravity irrigation and illustrates the weight of it in the recharge process.

Simulations on the impact of climate change were performed on a 2030-2050 period with the A1B and RCP8.5 scenarios. These were coupled with changes in land use for different development scenarios leading to a reduction of 6 to 11% of irrigated grass and with a 30% drop of water allocation from the Durancian system. This decline is realistic considering various possible evolutions such as reduced rainfall on Alpine mountains, increasing the minimum flow or water allocation less favorable to agriculture.

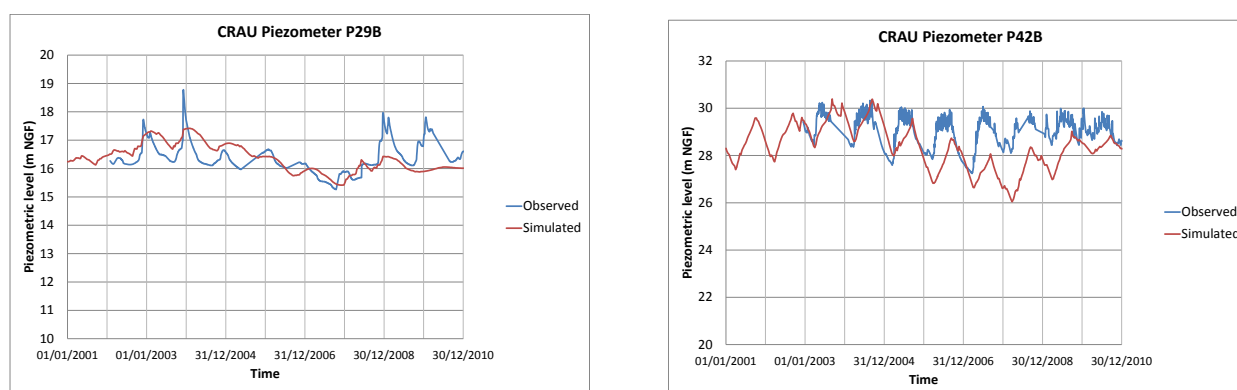


Figure 2 : comparison of measured and simulated piezometric levels in two wells of the Crau Plain .

<sup>6</sup> URBANSIMUL is a tool for analyze and simulate land use cover and its tenure at parcel scale for the whole PACA Region. Around this project, many research initiatives are organized in the INRA PACA center for the land use modeling (Vigie-med ACCAF, Lumecos, PRECOS). This tool handles all geographic and land information currently available and the vast majority of existing physical and legal constraints, in a series of statistical and geographic rules, and it makes them available for public actors in charge for local management through a secure web server. The data used for URBANSIMUL are continuously validated through a module allowing to the users (public land policy managers and urban planners) to correct and insert new data. Urbansimul provide to public actors for urban planning an automatic identification of parcels fully or partially available for urbanization.

Considering climate change alone, the most significant change concerns the evapotranspiration especially on grassland (7%), wetlands, orchards and forests assuming there is no limitation of water. For annual crops, evapotranspiration only increases slightly due to the reduction in the crop cycle. In the case of grasslands, increased global demand will result in increased irrigation needs, which has no impact on groundwater recharge. With regard to the precipitation area, cumulative rainfalls remain stable as well as the inter-annual variability. In terms of crop production, grass production was rather positively impacted with a 10% increase in production mainly due to the increase in temperature and the lengthening of the growing season.

The reduction in water allocation for agriculture by 30% strongly affects the aquifer water recharge. A drop of the piezometric level is then foreseen under irrigated grassland areas. The redistribution of water released by the loss of cultivated land plots on the remaining will very partially mitigate the process.

### Climate change effect on Mont-Ventoux forest growth

Growth of the main tree species of interest was simulated from 1960 to 2100 (scenario A1B) by 200 meters altitudinal strips. Simulations were carried out on 3 available water capacities and 3 levels of vegetation cover closure from first quartile, mean and last quartile of measured values. Following scenario A1B, temperatures are expected to increase 3,7°C by 2080, leading to a 25% water stress. Our simulations showed that Beech and Fir photosynthesis would increase 21% and 25% respectively, when respirations would increase 110% and 75% respectively. We expect a strong growth decrease, estimated to 35% for the Beech and 43% for the Fir. But before 2080, lethal thresholds (negative available water capacities) are expected to be crossed (Figure 3). Fir should totally disappear from Mont-Ventoux by 2030 and Beech by 2050. Fir decline will be quickest at low elevation, whereas we didn't find any elevation effect regarding Beech. Nevertheless, acclimatization potentialities were not taken into account in this study, which is focused on a single cohort.

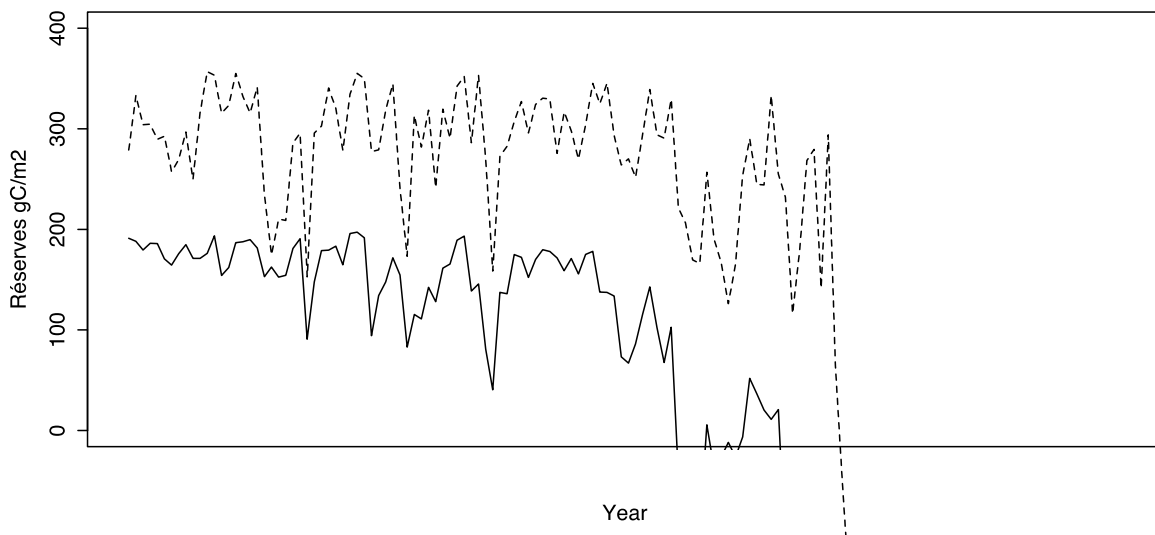
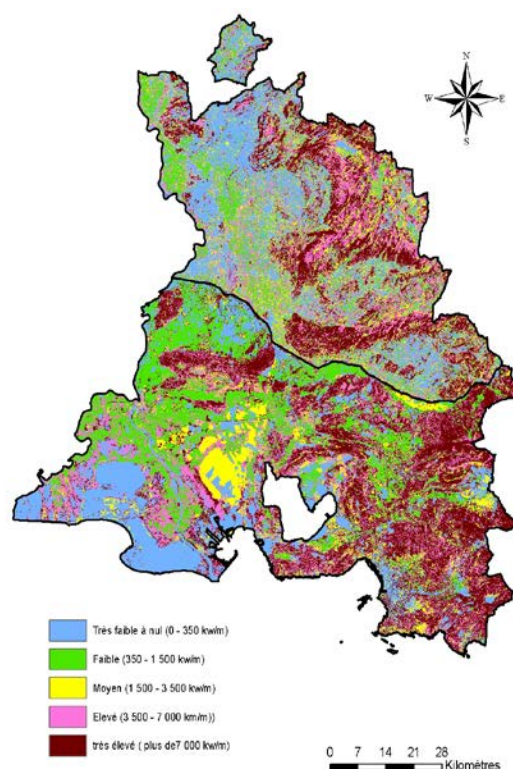


Figure 3: Projection of Beech (dashed line) and Fir (solid line) available water capacities with scenario A1B on the elevation RANGES WHERE SPECIES ARE PRESENT (1100-1500 m for the Fir and 900-1700 m for the Beech)

## Forest fires

Vegetation classification carried out on Vaucluse satellite picture dated from August 2010, resulted in 34 different vegetation types. Local fire line intensity is a component of fire hazard : very low (0 – 350 kw/m) ; low (350 – 1500 kw/m) ; medium (1500 – 3500 kw/m) ; high (3500 – 7000 kw/m) and very high (>7000 kw/m). Above 7000 kW/m, it is admitted that a fire cannot be controlled any more, even with aerial means, except in the initial phase. Forest communities of the study area showed fire intensities ranging from high to very high, except on high elevation areas mostly localised in Vaucluse. An elevation lift up of thermophilous species is expected under climate change which could lead to a fire hazard increase at medium or high elevation. A higher hazard is also expected for species already present at medium elevation: *Quercus pubescent* level of Spanish Catalonia has already been affected by mega-fires (Solsona, 24 000 ha in 1998). Declines expected at the Beech and Fir levels by the end of the century prefigure deep combustibility changes in these forest communities. Tools implemented by URFM (stand dynamics, water balance and fire models) will make possible in a near future the necessary predictions on a wide range of both climatic scenarios and vegetation communities. For this purpose, there is a need to better understand and predict plant response to drought (tree, but also shrubs and grasses) and its consequences on plant biomass, water content and structure. The map produced by the project doesn't take into account another fire hazard component, fire occurrence (the probability of fire spread on a given point of the map), resulting from fire ignitions frequency and surface. Fire frequency is much higher in Bouches-du-Rhône than in Vaucluse. This is mainly due to population density and transportation network differences. These factors should be integrated for a complete fire hazard assessment. Fire frequencies can be modelled by statistical approaches as a function of factors related to human activities, producing projections under different land use scenarios.



*Figure 4 Fire hazard map for Vaucluse and Bouches-du-Rhône*

## B) REPRESENTATION OF GLOBAL CHANGE DRIVERS

### Development of the Stochastic Weather Generator

In Bourotte et al. (2015, submitted to Spatial Statistics), a new valid, non-separable, flexible class of multivariate spatio-temporal covariance functions has been defined. This mathematical result opens a new modeling avenue for the analysis of all kinds of multivariate spatio-temporal data. A new estimation method, based on pairwise composite likelihood has been tested with success. Compared to



previous models, prediction and simulation performances have been improved on two different datasets. A prototype code has been written and tested on the VIGIE-MED study area.

Thanks to the VIGIE-MED project, the teams involved in this work have been put at the forefront of the community of researchers working on stochastic weather generators. The support of ACCAF has been a key element for pursuing a research program on this topic.

### Land use change and agricultural system change modeling

Concerning the intra-agricultural changes, in the study area we identified three main trajectories:

- Specialization of the existing production, evolving through more rentable systems, sometimes using production labels (e.g. from vineyards for low-quality wine production to vineyards for AOP wine production) and less diversified.
- Intensification of some farming system types, with a stronger use of inputs and irrigation
- Extensification of agricultural production. This trajectory is quite specific for an area where there is a strong touristic demand, so the agricultural systems tend to go through other functions than production (rural tourism, landscape valorization).

The spatial identification of these trajectories (Fig. 5) can be considered as a land management tool, because it is possible to link the observed dynamics with the agro-pedological potentiality of the area and also with a series of socio-economic factors. Moreover, the proposal of possible adaptation strategies necessarily involves the identification of dynamic in action and their determinants on which we can act.

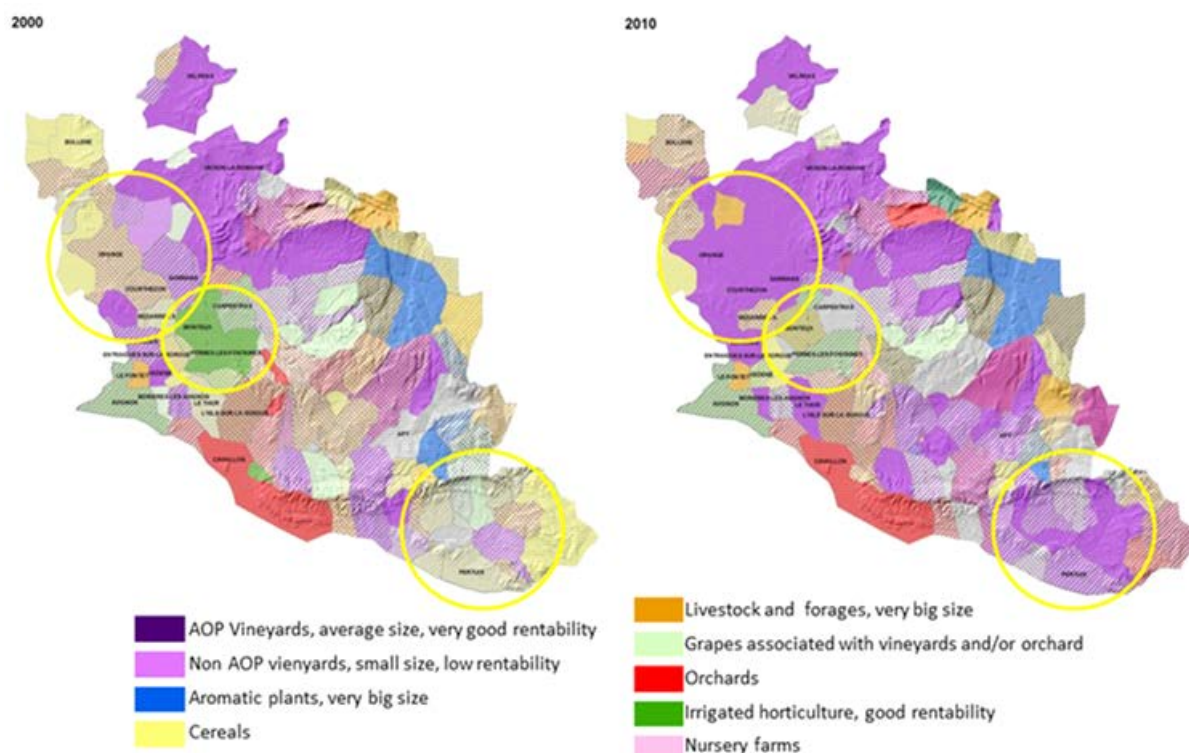


Figure 5 : maps of agricultural production systems at municipality level in the Vaucluse department for 2000 (left) and 2010 (right). Areas with strong changes are identified by the yellow circles.

The tools and methods developed in the modeling framework of soil occupations rely heavily on the works within the Urbansimul project. The statistical estimators we thought to use were based on an extension of the linearized GMM for logit models with spatial autocorrelation, which were studied for the binomial case. The extension to the multinomial case and the multinomial panel case were unsuccessful, with a presence of bias in the estimation of spatial dependence parameters associated with different choices in land use. At the end of this project, in collaboration with an INRA postdoctoral funded under another project from late 2014, we were finally able to design and validate a approximated maximum likelihood estimator (Mendel- Elston method) suitable for probit binomial with spatial dependence, estimable on large samples (submitted article), whose extension to the multinomial case does not seem to pose any major difficulties. An R package has been developed to make available to the scientific community this new type of estimator (the ProbitSpatial package will be posted on CRAN website at the beginning of 2016).

Empirical work on the identification of factors affecting the soil occupation changes have mainly relied on binomial probability models of change to explain urbanization plots (not built / constructed, non-building / Building) (see Diallo-Geniaux 2015 submitted). A work of evaluating the effects of land supply (changing zoning of urban planning documents) on prices was conducted (Geniaux et al. 2015): the causal assessment methods applied to spatial data were also intended to be reused to calibrate the scenario simulation models in future research on this topic.

Finally, the LUC model developed in Urbansimul, which relies Vigie-Med, has been redesigned to articulate a model of LUC probability at parcel scale (Diallo and Geniaux 2015) and a small area population forecast model (municipal scale) (Lopez-Kolkosky and Geniaux 2015) to estimate the volume of new housing and their spatial distribution.

To be able to produce land management scenarios and their impact on territorial indicators, we need to consolidate the tools developed in particular by finalizing the model of change based on a multinomial choice. To do so, the estimator of the maximum likelihood approach opens interesting prospects.

## **IMPACT OF RESEARCH: PRACTICAL IMPLICATIONS, RECOMMENDATIONS, PRACTICAL OUTPUTS, EXPLOITATION AND DISSEMINATION**

- Practical implications:

Developments made in the RECORD modelling platform have a generic scope, which increases the functionality of the platform (interface with Matlab, implementation of multi-simulation coupling STICS with a decision model and integration into a workflow for multi-simulation) and its relevance to address climate change.

The mathematical research established in Bourotte et al. (2015) is general. It opens a new modeling avenue for all kinds of multivariate spatio-temporal data.

- Recommendations and possible limits:

The results of the Ventoux and the plain of the Crau lead to very clear results about the future of certain tree species (beech, fir) or the impact of climate change on the Crau aquifer at medium term (2030 -2050). At that term, the future of the aquifer is more conditioned by the arbitration of the water allocation of the Durance than the impact of climate change.

- Practical outputs, exploitation and dissemination:

The Regional STICS-MODFLOW software suite is now implemented at the SYMCRAU, the Crau aquifer management syndicate, for its prospective studies. One person has been hired for this. The SICAS, Canal des Alpines manager contacted us to see if a similar operation as that at the Crau could be carried out on their area. Finally, the modelling suite was mobilized by the students of the University of Avignon for a study on the aquifer Avignon.

Regarding the stochastic weather generator, a prototype code has been written, thereby providing a proof of concept. After the PhD thesis funded by the project VIGIE-MED, additional work will be required to transform this code into a publically available code. Further funding will be need.

The Innovation in Agricultural event was dedicated to the adaptation of Mediterranean forests to climate change. The event was organized in Avignon in November 2015. It brought together 100 participants and led to the publication of Volume 47 of the journal Agricultural Innovations.

The results obtained in VIGIE-MED contributed strongly to the synthesis on climate change in the PACA region (coordinated by the GREC – PACA group) on water issues, agriculture and forest.

The project has contributed to improve the Urbansimul software that was selected by the PACA region as territorial dynamics analysis tools. An important IT development work will be carried out to make the software operational.

### **PERSPECTIVES**

The VIGIE-MED project was structuring at Avignon (less with more distant partners) to harmonize, within the “Adaptation to Global Changes” pole of the INRA-PACA centre, studies on various ecosystems related to territorial dynamics. There is a real willing to maintain this level of structuring to coordinate developments on the shared study area and on the geomatics Geopen4S platform.

Results obtained during the PhD funded by VIGIE-MED will be the basis for further developments. A PhD thesis has started on the definition of new stochastic models based on stochastic version of some PDEs modeling the atmosphere. Research will be undertaken for adding a multi-site module in WACSGen. The project DESIRES will provide funding for the development of publically available codes based on the prototype obtained within the VIGIE-MED project.

Concerning the spatial dynamic analysis of landscapes, we have been involved in the VITAL project, which has been accepted as part of the FACCE-JPI call for projects. A project, A-WISEMED submitted to the ERANET med has unfortunately not been selected.

VigieMed project was an incubator of project LiDARFORFUEL co-founded by PACA Region and INRA. This project will develop an operational method for a non destructive measurement of vegetation structure which will be very useful in the global change context.

### **MORE INFORMATION**

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- Cakpo CB 2015. Etude du bilan hydrique en contexte forestier méditerranéen, approche par géophysique, traçage isotopique, modélisation écophysologique. Mémoire de fin d'étude. Master Sciences et Technologies du Vivant et de l'Environnement ; mention (Forêt Agronomie et Gestion des Ecosystèmes), spécialité : « Fonctionnement et Gestion des Ecosystèmes ».
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# EXECUTIVE SUMMARY

## TITLE OF THE PROJECT

### VIGIE-MED

Impact of Climate Change at Regional scale and adaptation through the spatial distribution of Water resource and crop systems.

## SHORT SUMMARY

Vigie-MED aims to evaluate adaptation strategies to climate change by the location of vegetation production systems and the allocation of water resources at regional land level. The project aims to develop tools to represent changes by developing a spatiotemporal climate simulator and land use change model parameterized by socio-economic contexts and strategy of adaptation to global change. Adaptation option assessment is based on indicators characterizing the capabilities of crop production, water resources and hazards such as forest fires

## EXTENDED SUMMARY

Some of the impacts of climate change on crop production systems involve large areas (aquifer, watershed, forest) and the regional level, seen as an administrative entity, is an important level to make decisions on the adaptation to climate change. In order to support local authorities and the agricultural and forestry sectors, we provide territorial sustainability indicators to assess the plant production capacity, water resources, the risk of fire or adaptability to future territorial challenges related to the needs and production conditions. In VIGIE-MED, adaptation is seen through spatial allocation of plant production systems that must take into account the distribution of land, water resources and agro-pedoclimatic potential, explicitly. To understand the impact of adaptation options, it is important to understand the resulting land use dynamics by taking into account other factors such as micro-economic processes or macroeconomic forcing.

The conceptual framework of the approach in Vigie-Med is to consider land planning options (water infrastructure, zoning, development of a sector) and to study the impact on land use while taking account the dynamics specific to the area and those induced by external forcing. The land use map thus obtained is then mobilized in biophysical and hydrological models to calculate indicators on plant production, tree survival, the risk fire or the status of groundwater resources. The models are parameterized by the climate, it is then possible to make projections with climate scenarios and assess the consequences in the future of land planning options. This ambitious project had to rely on a broader project (submitted to ANR), which unfortunately was not accepted. Therefore, the project has made progress on the implementation of certain parts of the proposed framework without being able to put the entire implementation process. Therefore, the more specific objectives were as follows:

- Calculation of different indicators at the regional level on crop production (agriculture and forestry), the fire risk and water resources.

- Modelling land use and agricultural production systems changes based on micro-economic, social, political, geographical and agricultural potential and their development in a context of climate change.
- To better understand climate variability, we developed a simulation tool able to generate sets of meteorological variables, multi-site, with proper reproduction of extreme events.

This work relied on the Mediterranean context considered as hot spot of changes. The study area covers the Vaucluse and Bouches-du-Rhône district with a focus on sub-entities (Vaucluse, Ventoux, Crau plain) depending on the work objectives. An important task of the project was to supply the spatial information system hosted by the GeOpen4S platform of INRA-PACA center. The main results are given below.

**Towards a multivariate climate simulator taking into account the spatial dependencies.** We built a new class of space-time covariance and multivariate functions, valid, non-separable and flexible. This mathematical result is new and at the forefront of current research in the field of multivariate statistical methods. An estimation method, based on pairwise composite likelihood, has been successfully tested. This opens the possibility to produce spatio temporal series of climate data reproducing temporal variability and the occurrence of extreme events while respecting the spatial coherence.

**Modeling of land use for the representation of territorial dynamics.** The scientific challenge was to represent all changes affecting our studied areas namely urbanization, agricultural abandon and changes in crop production systems. The approach being statistical, parcel database in the Vaucluse has been greatly enriched by gathering information from various sources. This gives us a base to better monitor changes in parcel use and the factors that influence the land use changes. At the farm scale, we identified the main paths in the last decade showing a specialization on high-value crops, intensification of production systems or extensification where there are tourism issues. At the field scale, progress on statistical estimators binomial (simulating a choice between two options such as urbanization or maintaining agriculture) allow us to consider addressing multinomial choices necessary to represent crop production changes. The URBANSIMUL model simulating urbanization was improved adopted by the region and an important development is underway to make it operational for local authorities. The challenge now is to understand the weight of soil and climatic factors in the changes and to assess the relevance of simulations when an adaptation option has to be considered.

**The future of the Crau aquifer depends mainly on arbitration of water allocation for irrigation.** The scientific and methodological issue was to parameterize the STICS crop model over a regional area, taking into account the spatial variability of the climate, soil and farming practices. A modeling suite was developed (Regional STICS/MODFLOW) and evaluated on historical data. Simulations show in 2050 an increase of the water needs of about 3-12% depending on the crop. However, the increase was partly balanced at the area scale by the decrease of irrigated surface. By contrast, a 30% decrease of water allocation have a major impact on the aquifer.

**Beech and fir threatened on the Ventoux.** The CASTANEA model was parameterizes on the main tree species and a new mortality module has been added and validated in the case of fir. Simulations according to the A1B climate scenario, with an increase of 3.7 ° C between the current period and after

2080, led to an increase of water stress (25%) and a sharp decline in growth (35% beech and 43% for Sapin). But before 2080, the lethal thresholds (negative reserves) are crossed. Fires would disappear completely by 2030 and the Beech by 2050.

**A strong fire hazard that could extend to higher altitude areas.** The local fire power characterizes a component of the forest fire hazard. The forest types of the study area present a forest fire intensity ranked high to very high, except for natural areas located at the higher elevations. With climate change, we anticipate a rise in altitude of more thermophilic species that could lead, according to experts, to a stronger hazard at medium and high altitudes. The scientific challenge is now to establish the link between the state of forest stands simulated by ecophysiological models and the forest fire hazards.

**KEYWORDS:**

Forest, cropping systems, water resource, fire, land use, modelling, ecosystem services, plant production model; climate simulator; indicators, economy; retrospective analysis; Mediterranean environment

## HIGHLIGHT(S) OF THE PROJECT

### TITLE

**A flexible and non separable class of multivariate and spatio temporal covariance functions**

### CATEGORY

1. A result

### SUMMARY

A new valid, non-separable, flexible class of multivariate spatio-temporal covariance functions has been defined. A new estimation method, based on the composite likelihood pairs, has been tested successfully. Over a series of simulation and on two different sets of data, it was shown that this new model improves all performance criteria in terms of prediction and simulation.

### CONTEXT AND ISSUES AT STAKE

For the analysis of spatio-temporal multivariate data, it is necessary to have random field models consistent with the observed data. It is easy to construct covariance functions such fields by addition or multiplication simpler covariance functions, but the models obtained in this way fail to account for the complexity of interactions between space, time and variables. Having covariance models both flexible and rich enough to capture the complex interactions is an important issue for statistical spatiotemporal data.

### RESULTS

A new valid, non-separable, flexible class of multivariate spatio-temporal covariance functions has been defined. Ce résultat, de nature théorique, est nouveau et à la pointe de la recherche actuelle dans le domaine des méthodes statistiques multivariées. Il ouvre de nouvelles voies de modélisation dans tous les domaines d'application des statistiques pour les données spatio-temporelles.

This theoretical result is new and at the forefront of current research in the field of multivariate statistical methods. It opens new modeling pathways in all areas of application of spatial and temporal data statistics.

### VALORISATION

Bourotte M., Allard, D. and Porcu, E. (2015) A Flexible Class of Non-separable Cross-Covariance Functions for Multivariate Space-Time Data (submitted to Spatial Statistics). ArXiv 1510.07840.

### KEYWORDS

Composite likelihood, Matern covariance; multivariate random fields; separability; spatiotemporal process; spatiotemporal geostatistic



**TITLE**

Module development in the RECORD modelling platform

**CATEGORY**

A technical innovation

**SUMMARY**

To address the multi-simulation in a regional context and climate change, generic modules were developed. The innovations focused on 1) simulation frameworks to represent the simulation units of an area, 2) the coupling of the STICS model with a decision model to have a flexible and open capacity to represent evolution of cropping systems in crop model and 3) the implementation of WACS-GEN climate simulator.

**CONTEXT AND ISSUES AT STAKE**

Regional simulation needs to manage a large number of cases of simulation to represent the spatial variability and simulate long periods. An existing software, MultiSimLib, developed under MATLAB, worked on the STICS standalone version. It has been adapted to use a RECORD model. Meanwhile, the representation of the future needs to address uncertainties. The number of available climate projections is not always enough, it is then necessary to generate climate series stochastically in order to get statistical sample of appropriate size. Finally, climate change has impacts on cropping practices. It is therefore necessary to introduce new decision rules. In order not to change the crop models, a decision module was created and coupled to STICS in order to manage in a flexible and scalable manner, the cropping events in future simulations.

**RESULTS**

The developments have produced the following components:

- Development of a MATLAB / VLE library to manage simulations from the MATLAB environment,
- Visualization feature of simulation data, spatially explicit integrated the Graphical User interface of RECORD
- Implementation of the WACS-Gen climate series generator with a component "estimate" to analyze a past series and estimate the statistical parameters of the generator and "simulation" component to generate the series,
- Coupled model STICS / Decision to represent by an external model cropping event used by the STICS model taking into account the state of the simulated environment,
- Adaptation of the chain multisimulation "MultisimLib".

**PERSPECTIVES**

Improve computing performance of the coupled STICS / decision. Implementation of the spatio-temporal simulator.

**KEYWORDS**

RECORD, STICS, simulation, climate generator, decision model, climate change

**TITLE**

Urbansimul

**CATEGORY**

A remarkable Parteneship

**SUMMARY**

The work carried out as part of VIGIE-MED have maintained a research effort on land use modelling in recent years leading to support the Urbansimul project. This project aims to provide a diagnostic tool and scenario simulation on urbanization in the PACA region to all public actors in charge of urban planning and housing. This tool integrates and analyzes annually more than 40 million record lines from a centralized spatial data on land registers, property and public regulation (zoning planning / environment / risk) in the frame of an agreement between six public partners in the PACA (INRA, Region, DREAL, the Regional Geographic Information Centre, the Etablissement Public Foncier and CEREMA Sud-est which is co-developer).

**CONTEXT AND ISSUES AT STAKE**

Urbansimul provides public players in charge of planning issues (with at the end over than 1500 potential users) pre-processed spatial data, diagnostic reports and simulations for daily implementation of their policy. All documents are available free to users of Urbansimul, which in turn participate in the verification and update of the data; for their part, INRA researchers benefit from this crowdsourcing approach in their prospective modelling of land use.

**PERSPECTIVES AND VALORISATION**

This partnership has been strengthened in 2015 with the inclusion of this project in the new state-region plan contract and with a funding of over 600 000 over three years enabling INRA unit Ecodevelopment to recruit three contractual engineers for three years, renew servers and cover the costs of high availability maintenance.

**KEYWORDS**

Land deposit, urban planning, urban sprawl simulation

**TITLE**

Workshop « Stochastic Weather Generators », Avignon September 17 – 19 2015

**CATEGORY**

Event

**SUMMARY**

This conference brings together the international community of researchers and users of stochastic weather generators. It follows a first conference, held from 29 May to 1 June 2011 in Roscoff, France.

**CONTEXT AND ISSUES AT STAKE**

One goal of the conference was to consolidate a dispersed international community. To do this, a significant portion of the budget was used to invite speakers from Anglo-saxon countries at the forefront in the field: the United States, New Zealand, Great Britain. Also in order to promote the creation of a community, the aim was to maintain relatively low registration fees.

**RESULTS**

The symposium brought together 50 people and there were 27 oral presentations. They can be downloaded from the conference website: <http://informatique-mia.inra.fr/swg2014>. A special issue of the Annals of the ISUP (Allard, 2015) published a selection of articles from this conference.

**PERSPECTIVES**

Following the editions of 2011 and 2014 in Roscoff in Avignon, a third symposium will be held in May 2016 in Vannes.

**EXPLOITATION AND DISSEMINATION**

Allard D. (2015, Editor) Special Issue “Stochastic Weather Generators”, Annales de l’ISUP, 59, 148p.

**KEYWORDS**

Workshop, weather generator