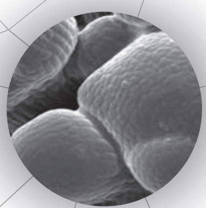
les dossiers
d'AGROPOLIS
INTERNATIONAL
*Expertise of the scientific community
in the Occitanie area (France)*

COMPLEX SYSTEMS
From biology to landscapes



Number 23
February 2019

AGROPOLIS INTERNATIONAL

agriculture • food • biodiversity • environment

With its headquarters in Occitanie region, Agropolis International brings together an outstanding group of organizations and institutions involved in agricultural and environmental sciences.
Agropolis International—an association founded by research and higher education institutes with the support of the French government and local authorities—continues to provide an open space for collective expertise and collaboration.

Agropolis International fosters links between different stakeholders involved in agriculture, food, environment and biodiversity sectors:
- Institutions of the regional scientific community
- Foreign and international research organizations
- Local authorities
- Technology transfer, innovation and economic development stakeholders
- Civil society structures

By marshalling such a broad range of institutions and backed by an outstanding scientific community, **Agropolis International has become France's leading agroenvironmental research hub addressing issues affecting Mediterranean countries and the Global South.**

Agropolis International—a forum for exchange and dialogue, training and capitalization of knowledge, a think tank, a support structure for collective projects and international outreach, and a place to host structures and events—applies and tailors its expertise acquired over the past 30 years to the major missions entrusted by its members.

Agropolis International is structured around a broad range of research themes corresponding to the overall scientific, technological and economic issues of development.

Research and training themes of the Agropolis International community:
- Agronomy, cultivated plants and cropping systems
- Animal production and health
- Biodiversity and aquatic ecosystems
- Biodiversity and land ecosystems
- Economics, societies and sustainable development
- Environmental technologies
- Food: nutritional and health concerns
- Genetic resources and integrative plant biology
- Grapevines and wine: regional specific supply chain
- Host-vector-parasite interactions and infectious diseases
- Modelling, spatial information, biostatistics
- Water: resources and management

A few figures regarding the East Occitanie scientific community:
- 27 higher education and research institutions
- 35 interinstitutional and interdisciplinary open research infrastructures
- 150 training courses
- 2,700 researchers and teachers in 74 research units
- 300 expatriate researchers in 50 countries
- 5,000 French and international students
- 1,000 international researchers hosted

Complex systems research expertise in Occitanie region

On 1 January 2016, the former French Languedoc-Roussillon and Midi-Pyrénées regions merged to become the new Occitanie/Pyrénées-Méditerranée region (2015 French territorial reform). This issue of *Les dossiers d'Agropolis International* thus showcases the scientific actors conducting research activities related to complex systems throughout this new region—for the first time. The scientific community includes 44 research teams (research units, service units, hosting and project teams, and observatories). Several federative research bodies oversee the scientific activities of the teams: an institute, six laboratories of excellence (LabEx), an equipment of excellence project (EquipEx) and a Convergence Institute. Finally, several French national and European research infrastructures and data and computation centres essential for managing complex systems are also based in Occitanie.

This *Dossier*, launched in 2013 by Fabien Boulier and finalized by Isabelle Amsallem (Agropolis International), aims to enhance awareness of the Montpellier complex systems research community within the framework of the French National Network for Complex Systems (RNSC). Meanwhile, with the recent inclusion of the Toulouse research community, Occitanie has become one of the most outstanding hubs of research in this field at national and European levels! In this fresh setting, Agropolis International is perfectly fulfilling its role of promoting the scientific expertise harboured in this new region in a field that has clearly emerged from a relatively marginal initial situation. Moreover, not primarily striving to reduce the complexity of the phenomena studied is becoming increasingly important, both intellectually and operationally. Ways must also be found to address these issues amidst the wealth of interactions involved, and in a world that is ever more interlaced with social and natural processes!

Although not comprehensive, this *Dossier* will provide readers with an overview of these regional scientific stakeholders through specific examples of activities they develop in relation to complex systems in three main thematic areas: Data collection and management; Understanding and analysing complex systems; and Different applications of the complex systems approach.

Finally, among the many training courses offered in Occitanie region in relation to complex systems —irrespective of whether or not they lead to a degree—only a few examples of training courses specifically devoted to gaining a more in-depth understanding of complex systems are presented. However, a broad array of degree courses (from undergraduate to PhD levels) are available that explore complex systems. A list of these training opportunities may be found on the websites of Agropolis International (www.agropolis.org/training) and the *Université Fédérale de Toulouse Midi-Pyrénées* (https://en.univ-toulouse.fr/courses-all).

Bernard Hubert
Advisor to the President of Agropolis International

Complex Systems
From biology to landscapes

Summary

Cover photos:
Apical meristem of *Arabidopsis thaliana.* © Jan Traas
Stochastic simulation of a mango tree. © F. Boudon/CIRAD/INRIA
Spatial distribution of *Aedes Albopictus* densities in Réunion. © Annelise Tran/CIRAD/Alborun project (ARS Indian Ocean)
Illustration from Pixabay released under © CC0 public domain

Foreword

Complex systems have emerged as a focus of cross-disciplinary research over the past 30 years. In the wake of the pioneering work of the Santa Fe Institute in the United States and the research centre headed by Ilya Prigogine in Brussels in the 1980s, centres conducting research on complex systems have emerged in Italy, Spain, UK, Poland, Hungary and France. Meanwhile, researchers have also founded an international association (Complex Systems Society[1]), specialized journals, and international conferences are held regularly. The field is especially well organized in France, including regional centres (Paris-Île-de-France, Rhône-Alpes, Toulouse, Rennes and Normandy) and thematic networks, all of which are embedded in the French National Network for Complex Systems (RNSC), which fosters coordination and brainstorming on the topic. Within the scope of Agropolis International, we felt it was essential to draw up a comprehensive inventory of research on complex systems in Occitanie region (France), focusing on topics ranging from living organisms to the environment and land management, with emphasis on biology, ecology, geology, hydrology, agronomy, human and social sciences. The approaches often involve modelling, while also relying on both quantitative and qualitative data.

But what do we understand by complex systems? An article published in *Natures Sciences Sociétés*[2] refers to Laplace's Demon, as described in his Philosophical Essay in 1814[3], as being, "An intellect which at a certain moment would know all forces that set nature in motion, and all positions of all items of which nature is composed….it would embrace in a single formula the movements of the greatest bodies of the universe and those of the tiniest atom; for such an intellect nothing would be uncertain and the future just like the past would be present before its eyes." This implies knowing the initial situation of all beings in the universe—a data issue—while also recognizing all the laws of nature—a dynamics issue. Contemporary science has shattered this dream of such a demon, indeed: quantum physics has introduced absolute uncertainty, which makes it impossible to ascertain the state of the universe at any given time; chaos theory implies that a very slight initial difference can spawn completely different novel behaviours (*Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?*); and the scale-dependence of dynamic interactions often makes it impossible to deduce the overarching behaviour of a process solely on the basis of the elementary component properties—this is called emergence. Understanding contemporary challenges, particularly those concerning adaptation to global change and territorial management, and then intervening in these major systems with their multiscale interaction dynamics, cascading, feedback and emergence phenomena, requires the development of new tools at the crossroads of various disciplines and Big Data, all pooled under the moniker 'complex systems science'. These tools cannot rely solely on one scientific discipline, they require more integrated expertise and practices that combine field experiments and models. All of these features presently characterizing complexity are addressed through new methods developed

1. http://cssociety.org
2. Deffuant Guillaume, Banos Arnaud, Chavalarias David, Bertelle Cyrille, Brodu Nicolas, Jensen Pablo, Lesne Annick, Müller Jean Pierre, Perrier Edith, Varenne Franck. Visions de la complexité : le démon de Laplace dans tous ses états. 2015. *Natures Sciences Sociétés*, 23 (1): 42-53.
3. Laplace P.S., 1995. *Philosophical Essay on Probabilities*: Translated from the fifth French edition of 1825 with notes by the translator (A.L. Dale), Springer Verlag New York.

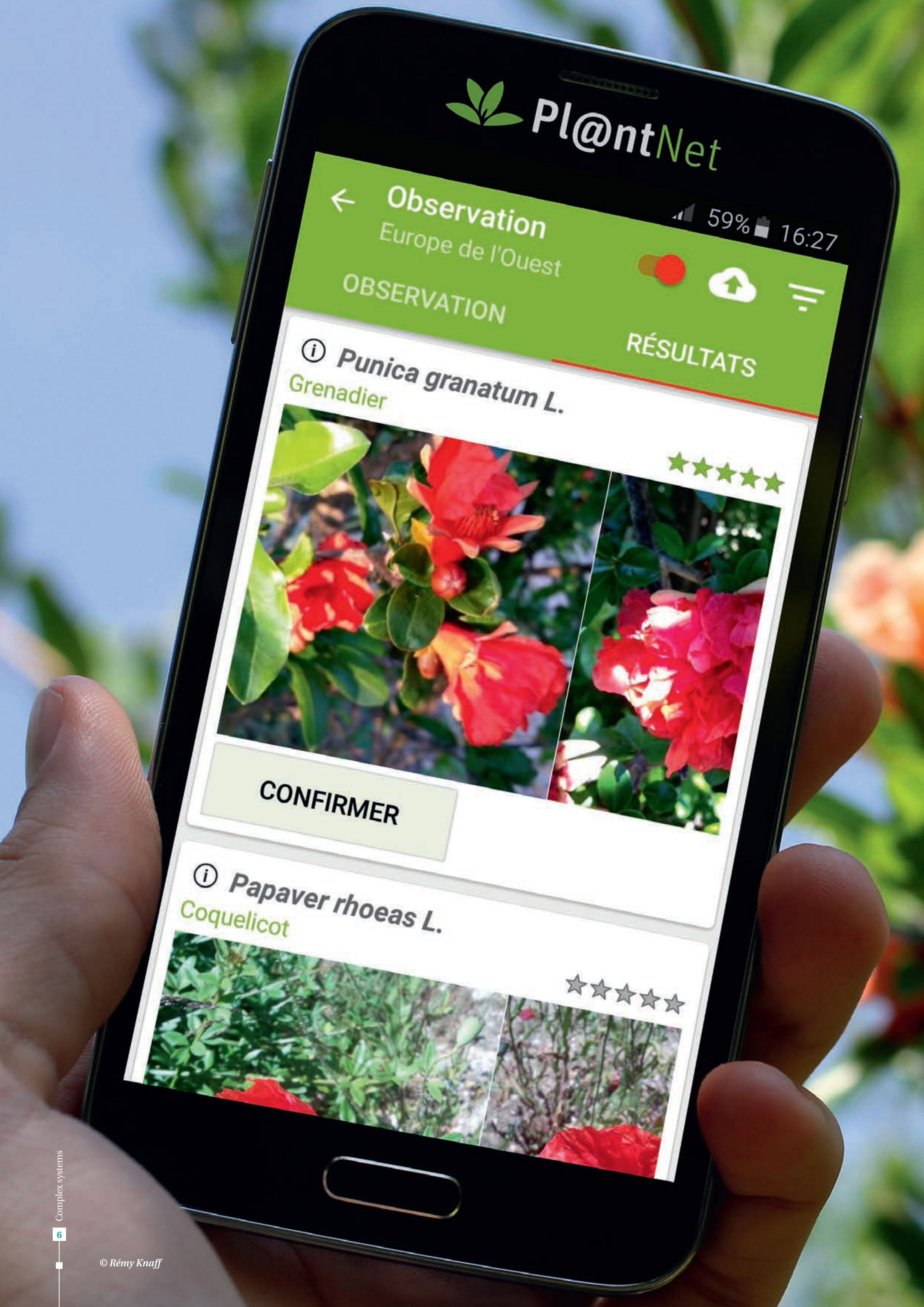
by our research laboratories, and our aim in this *Dossier* was to present a snapshot of them (even partial). We thus opted to structure this document in three main parts to showcase the research under way:

The first part deals with the data—sometimes available in very high volumes—which is essential to gain insight into the state of the systems being studied. Never have there been so many sensors available at all scales, ranging from microscopic to those that produce satellite images, while also serving to track our movements and social network exchanges. This has generated a huge amount of often heterogeneous information that must be collected, processed, integrated and interpreted by assimilating it into our operating models. Infrastructures are emerging in France and Europe to supply, store and process these data.

In turn, the second part focuses on how systems operate, since the thrust is not only to describe (first part) but also to understand how complex systems work. Therefore we organized the contributions according to the scales of the systems studied, ranging from intracellular mechanisms to the functioning of geoecosystems and territories (i.e. 'anthropized spaces', or even better, 'socioecosystems'), including individuals (plants or animals), populations and ecosystems (approached without human input, but is this still conceivable?). Many methods have been developed to account for these complex operations based on differential equations, networks, or individual-centric models—sometimes combined—according to the analysis scales.

Finally, the third part deals with application of the complex systems approach to meet contemporary challenges. Our review spans from technical and social organization to systems monitoring via so-called observatories, while discussing—from many standpoints—participatory management initiatives that take a multitude of issues into account, as well as decision-support systems.

Nicolas Arnaud (UMR GM),
Bertrand Jouve (XSYS)
and Jean-Pierre Müller (UPR GREEN)


Pl@ntNet
Observation
Europe de l'Ouest
59%
16:27
OBSERVATION
RÉSULTATS
Punica granatum L.
Grenadier
CONFIRMER
Papaver rhoeas L.
Coquelicot

© Rémy Knaff

Complex systems, data collection and management

The systems covered in this *Dossier*, irrespective of the field—ecology, biology, health, society, environment or economy—come under the complex systems umbrella. Several theories could be put forward for their analysis, such as the systemic approach with three focuses of analysis: structure, function and dynamics.

Chapter I is devoted to data collection and management—a legitimate choice as data are essential for understanding and analysing the complexity of systems, as well as designing models to gain insight into and even predict future evolutionary patterns of these structures. This chapter first covers system monitoring, whereby raw data is collected under different conditions. The harvested data are then processed in order to validate and 'shape' them so as to facilitate their sharing and incorporation in processing streams for analysis and modelling purposes. Finally, the ways of facilitating and sharing access to these data are also presented.

The first part of this chapter focuses on data harvesting. Given the range of different fields and the intrinsic complexity of systems, the collected data are also highly varied and often inherently heterogeneous. Collection of these data requires tailored protocols, backed by human or instrumental sensors implemented in relatively elaborate organizations. This section thus presents:
• a collective initiative dealing with plant biodiversity surveys via large networks of observers and mobile phone apps
• experiments carried out in multidisciplinary projects on environmental issues using input from interfaced sensors
• satellite monitoring-based experiments for studying complex environmental systems
• finally, the use of software sensors developed as part of more formal analyses.

Collected data must enhance the understanding of the studied system and confirm the formulated hypotheses. This requires data interpretation through various types of processing or processing chains involving digital or symbolic data analysis approaches, after confirmation of the data quality. The second part is focused on mapping of these data through various articles regarding:
• the crucial issue of data quality and strategies for detecting anomalies, and for data preprocessing, rectification and consolidation via various preprocessing steps
• an example of a complete data processing chain resulting in a modelling proposal on the evolution of the Lez karst aquifer
• a method for developing a cerebral anatomy preoperative prediction tool based on modelling performed using magnetic resonance imaging processing chains
• a data assimilation system derived from satellite imaging (surface soil moisture and leaf area) to improve assessments of vegetation carbon uptake quantities via photosynthesis
• knowledge building through a combination of various data collection systems (spatial and field observations, surveys, participatory tools) to address local development issues in southern Africa
• production of a multidisciplinary knowledge system by multi-agent modelling based on studies of small rodents and their parasites carried out at different gene to ecosystem levels
• a graph-based agrosystem conceptualization approach to integrate and interrogate multidisciplinary knowledge and expertise, as applied to a problem of Syrah grapevine dieback
• a qualitative modelling approach to understand the functioning of microbial communities
• a satellite image analysis method based on an ontological rationale.

Data availability and dissemination are essential for their maximum use, reuse and processing by all stakeholders requiring such data. However, there are several open issues regarding these data. Is it possible to readily access and use these data (even for nonspecialists)? How can such data be best shared while ensuring their sustainability? The last part of this chapter is focused on this provision and straightforward use of data through different examples:
• The information system of the Observatory for Science of the Universe-Observatory for Research on the Mediterranean Environment (OSU OREME) collects and references various environmental data via standardized metadata and controlled terminology. It also offers a plethora of interactive imaging tools for data cross-tabulation.
• A smart data storage proposal: collected unformatted data can be stored in data lakes with a variety of directories and governance rules.
• An approach to heterogeneous big data mapping based on definitions of environmental data heterogeneity and variety.

Finally, the boxes showcase several entities and tools that support the scientific community for data collection and management:
• OSU OREME is an environmental data observatory that supports interdisciplinary activities, mainly in the Mediterranean region.
• The laboratory equipment enhancement project (EquipEx) GEOSUD provides the scientific community and public policy stakeholders with satellite image packages and processing services. It is a key component of the Theia Land Data Centre.
• Finally, the National Computing Center for Higher Education (CINES) offers very large-scale storage and archiving facilities, as well as high-throughput digital computing clusters.

Nicolas Arnaud (UMR GM), Thérèse Libourel (UMR ESPACE-DEV) and Pierre Maurel (EquipEx GEOSUD)

Complex systems, data collection and management

The research units and teams conducting activities on one (or several) themes mentioned in this chapter are listed in the following chart. Dark green areas indicate a theme that is the main focus of the research team, while pale green areas represent other themes in which it is also involved. The location of an article is indicated by the page number.

1.1. Data harvesting
1.2. Data interpretation
1.3. Data provision: accessibility and interoperability

Research units and teams Complex systems, data collection and management**	**1.1**	**1.2**	**1.3**
AMAP • Botany and Computational Plant Architecture	p. 9		
ASTRE • Animals, Health, Territories, Risks & Ecosystems		p. 15	
B&PMP • Biochemistry & Plant Molecular Physiology			
CBGP • Centre for Biology and Management of Populations		p. 16	
CeMEB • Mediterranean Centre for Environment and Biodiversity			
CEFE • Center for Functional and Evolutionary Ecology			
CINES • National Computing Center for Higher Education			p. 21
CNRM • National Centre for Meteorological Research		p. 14	
DIMNP • *Dynamique des Interactions Membranaires Normales et Pathologiques*			
DYNAFOR • Dynamics and Ecology of Agriforestry Landscapes	p. 10		
Eco&Sols • Functional Ecology & Bio-geochemistry of Soils & Agro-ecosystems		p. 18	
ESPACE-DEV • Space for Development		p. 12/18	
GEODE • Environmental Geography			
GEOSUD • GEOinformation for SUstainable Development			p. 21
GRED • Governance, Risk, Environment, Development			
HSM • HydroSciences Montpellier		p. 12	
IES • Institute of Electronics and Systems	p. 9		
IMFT • *Institut de Mécanique des Fluides de Toulouse*			
IRIT • Toulouse Institute of Computer Science Research			
ISE-M • Montpellier Institute of Evolutionary Sciences	p. 9		
ITAP • Information-Technologies-Environmental Analysis-Agricultural Processes			
L2C • *Laboratoire Charles Coulomb*		p. 13	
LBE • Laboratory of Environmental Biotechnology	p. 11	p. 18	
LGP • *Laboratoire Génie de Production*			
LIRMM • Montpellier Laboratory of Computer Science, Robotics and Microelectronics	p. 9		p. 20
LISST • Interdisciplinary Laboratory Solidarities, Societies and Territories			
MISTEA • Mathematics, Computer Science and Statistics for Environment and Agronomy	p. 11	p. 18	
MIVEGEC • Genetics and Evolution of Infectious Diseases			
NUMEV • Digital and Hardware Solutions and Modelling for the Environment and Life Sciences			
OREME • Observatory for Research on the Mediterranean Environment			p. 19
SMS • Structuring of Social Worlds			
SYSTEM • Tropical and Mediterranean Cropping System Functioning and Management		p. 17	
TETIS • Spatial Information and Analysis for Territories and Ecosystems	p. 10		p. 20
TULIP • *Towards a Unified Theory of Biotic Interactions: Role of Environmental Perturbations*			
Virtual Plants project team • French Institute for Research in Computer Science and Automation			
XSYS • Toulouse Institute for Complex Systems Studies			
#DigitAg • Digital Agriculture Convergence Lab			

**See the detailed chart on page 72 listing all of the research units and teams in Occitanie and all of the themes covered in this *Dossier.*

Data harvesting

Streamlined plant biodiversity surveys through extensive observer networks

The recent boom in smartphone tools and apps, combined with the development of many participatory science initiatives, has led to the emergence of huge biodiversity observatory networks. These networks now have unprecedented field survey data production and analysis capacities thanks to digital mobile and smart tools. Tens of thousands of people contribute daily to plant biodiversity surveys (Europe, the Americas, Africa) via the Pl@ntNet platform that is devoted to plant identification and botanical observation sharing. These participants have access to automated identification tools that rely on real-time image analysis algorithms. This enables them to produce and share many field observations, while contributing to data quality assessments. These observations are used for different Pl@ntNet services and research projects depending on their collaborative qualitative assessment results.

Participants have a range of profiles (hikers, hobby and professional gardeners, farmers, researchers, etc.), behaviours and involvements depending on their interest (which is hard to define) for a specific type of data (observations regarding specific landscapes or plant groups, data quality analysis according to their location, the taxonomic or thematic context). The type of data of interest to each participant depends on many factors (produced or analysed data volume, involvement history, available data volume, etc.). This typology is crucial with regard to the sustainability of participant involvement. The joint research unit (UMR) AMAP and the ZENITH research team (of the French Institute for Research in Computer Science and Automation, INRIA) develop algorithms to take participants' interest into greater account based on analyses of the data they produce. This research will ultimately help streamline the involvement of extensive networks mobilized through the Pl@ntNet platform so as to better fulfil participants' expectations and maximize their participation, especially in the production and analysis of data relevant for them and for their associated research projects.

Contact: contact@plantnet-project.org
Collaborators: P. Bonnet (UMR AMAP), A. Joly (INRIA, ZENITH research team, UMR LIRMM), H. Goëau (UMR AMAP), A. Affouard and J.-C. Lombardo (INRIA, ZENITH research team, UMR LIRMM)
For further information: https://plantnet.org

Illustration: see page 6.

Benefits of smart sensors

In recent years, because of the diverse range of implementable sensors available and measurement frequencies required, researchers have been prompted to design and use standalone data acquisition systems to collect data required for monitoring natural environments. Through various projects, researchers have thus been making choices on types of data to collect, implementation protocols and types of sensors to be implemented, including:

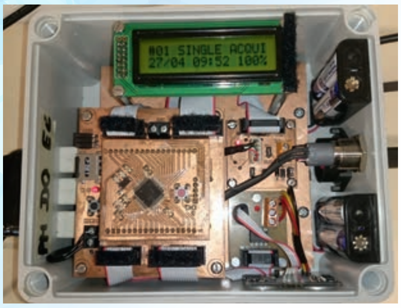
- the power supply for onboard systems: by battery or external supply (solar cells, EDF network) depending on the complexity of the system
- the size of the system and thus the number and technology of onboard sensors
- the quantity of data to collect and transmit
- the data transmission mode (and thus the amount of transmitted data and transmission time): storage (USB flash drive), WiFi transmission, GSM network, etc.
- the data acquisition frequency related to the transmission mode. Note that data preprocessing, which is possible via very low power consuming processors, minimizes transmission by performing an initial interpretation
- the resistance of equipment that is often sensitive to harsh external conditions (temperature, humidity, etc.)
- sensor data acquisition requires accurate location of fixed sensors supplemented by a geolocation sensor (often GPS) for mobile acquisition systems.

Various sensors are used depending on the project:

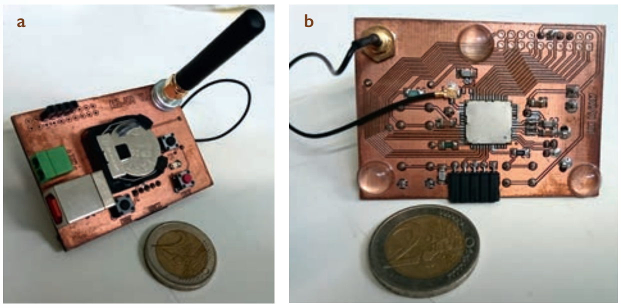
- For studying the impact of abiotic environmental factors on the living habits and behaviour of animal species under natural conditions, data are acquired using sensors that measure the illuminance, temperature, humidity, salinity, pH, conductivity and water level, sometimes using different imaging technology (infrared, etc.).
- For collecting, storing and processing ecological data to qualify and describe wildlife movements, animals are monitored via GPS/GSM tracking using specific transponders. Airborne drones and university nanosatellites are promising options for monitoring areas where network infrastructure is lacking.

Contacts: G. Despaux (UMR IES, Institute of Electronics and Systems), gilles.despaux@umontpellier.fr, L. Gavotte (UMR ISEM), laurent.gavotte@umontpellier.fr
Acknowledgements: C. Moulia (UMR ISEM), T. Libourel (UMR ESPACE-DEV), L. de Knyff (UMR LIRMM)

▼ *Examples of sensors.*
© Laurent de Knyff



▲ *Multisensor datalogger for aquatic environments.*



▲ *Very long-range and ultra low-power data transmitter for environmental sensors in inaccessible areas. (a) Top view with antenna and button cell (b). Bottom view with microcontroller and integrated radiofrequency transmitter.*

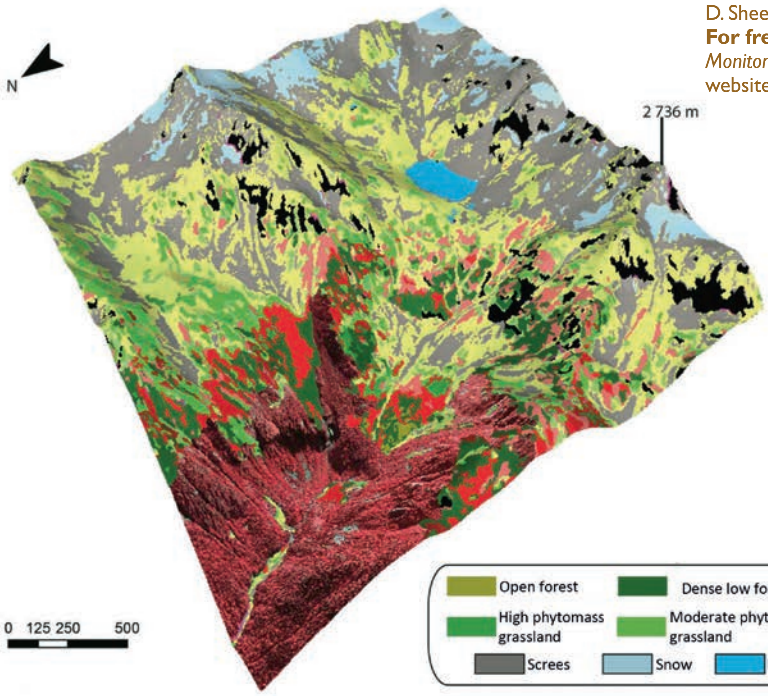
▲ *Multichannel GPS tracking device for monitoring animal positions.*

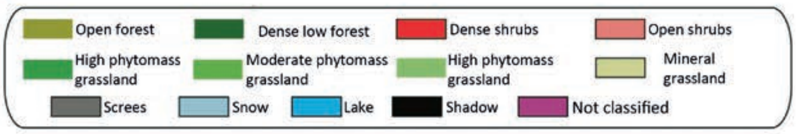
Satellite observations for the study of complex environmental systems

Recent improvements in Earth observation capabilities (new satellites, shared image access and open access) combined with advances in the treatment of big data, has enhanced continuous monitoring of complex environmental systems. Remote sensing is used extensively nowadays for studying socioecological systems, i.e. landscapes and their dynamics. It provides ways to identify different levels of human pressures and practices (e.g. urbanization, fragmentation, agricultural and silvicultural practices). Ecological processes that occur at different organization levels and spatiotemporal scales (growth, biomass production, phenology) can thus be assessed, while mapping the results of these interactions (fallowing, intensification). The evolutionary trends of phenomena (outliers, gradient, cycle) could also be identified along with the so-called 'essential biodiversity variables': species presence and abundance, local species richness and spatial distribution of communities. These indicators are obtained through a combination of spatial and spectral information, without necessarily having to produce land-use maps. Their estimation by coupling modelling with remote sensing is based on the synergy between *in situ* data and image-derived measurements. Studies carried out by research units on this topic have, for example, led to:

- detection of agroecological infrastructures and ecological continuities
- identification of forest species by time-series imaging and stand structure assessments based on LIDAR measurements
- physiognomic mapping of natural vegetation habitats in France and characterization of permanent grasslands (species richness, practices)
- development of large- and medium-scale species distribution models (e.g. bird-habitat models) and prediction of certain ecosystem services (regulation, production)
- mapping of services, including cultural ones, associated with the biodiversity value to gain greater insight into socioecological systems
- determination of the spatiotemporal dynamics of a forest landscape and its impacts on biodiversity.

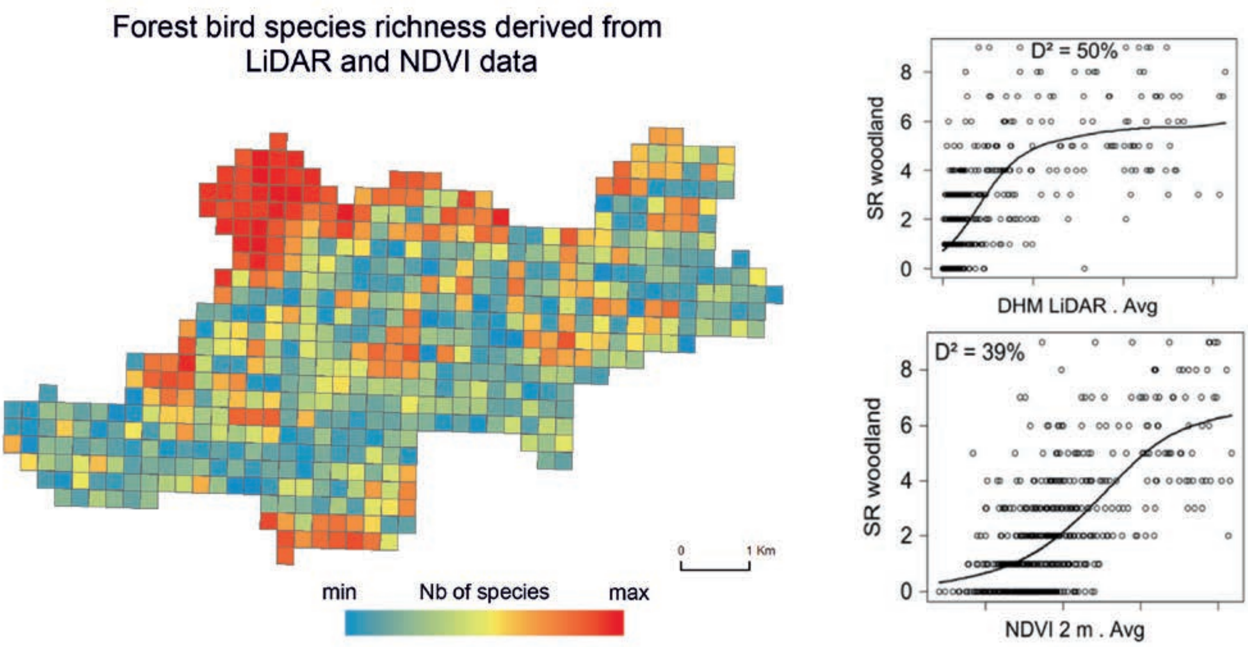
Contacts: S. Luque (UMR TETIS), sandra.luque@irstea.fr,
D. Sheeren (UMR DYNAFOR), david.sheeren@ensat.fr
For free download: *A Sourcebook of Methods and Procedures for Monitoring EBVs in Tropical Forests with Remote Sensing* (GEO BON website) at http://geobon.org/products/books



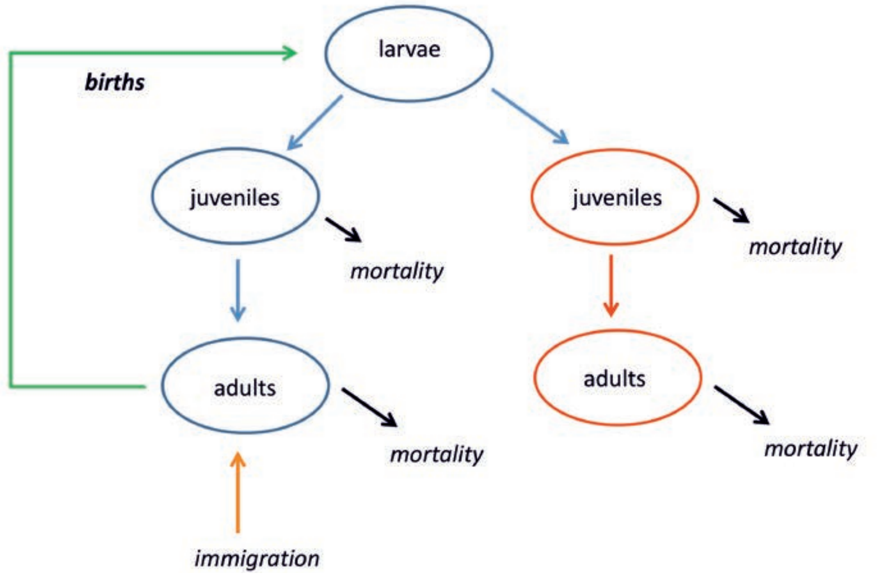


◀ *Example of habitat mapping methods tailored to mountain habitats (see CarHAB project). Application of these methods on the mountain scale in the French department of Isère resulted in the development of a high spatial resolution environmental database.* © Thierion et al.

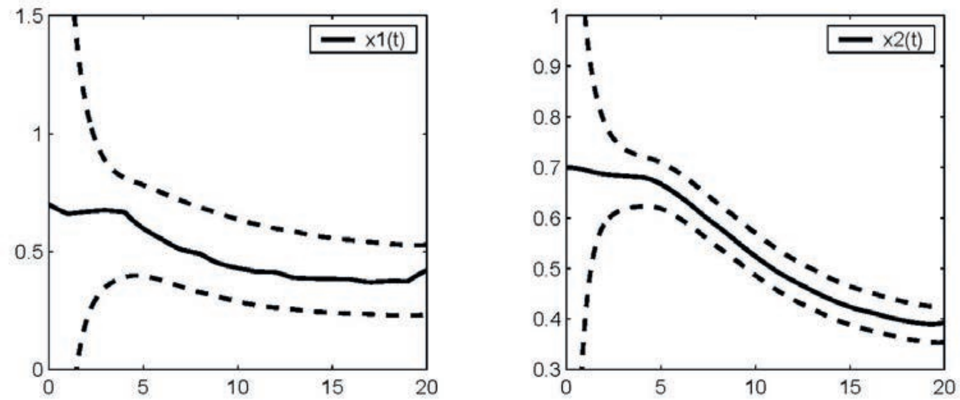
▼ *Avian species richness in forest environments estimated from LIDAR and NDVI data.*



Sheeren D., Bonthoux S. et Balent G. 2014. Modeling bird communities using unclassified remote sensing imagery: effects of the spatial resolution and data period, *Ecological Indicators*, 63, pp. 69-82.



▲ *Figure 1. Simply by observing infertile adult populations (red), all other populations can be reconstructed over time.*
From De Dreuzy J.R. and Rapaport A., 2013. Mieux gérer les ressources naturelles, Les mathématiques de la Terre, Textes et Documents pour la Classe *(TDC). 1062: 20-23.*



▲ *Figure 2. Populations x1 and t x2 (solid lines) were not measured. Dashed lines represent guaranteed boundaries provided by interval observers.*
From Rapaport A. and Gouzé J.L., 2003. Parallelotopic and practical observers for nonlinear uncertain systems. International Journal of Control. *76(3): 237-251. https://doi.org/10.1080/0020717031000067457*

Software sensors for bioprocesses

Sensors available for biological monitoring often do not provide continuous measurement of all variables describing reaction progress (or they are unreliable or too expensive). Through a mathematical model, these unmeasured variables can nevertheless be reconstituted over time as a function of other available measurements using software sensors (e.g. Kalman filters). Specific mathematical conditions are required for building these software sensors, especially the observability property (i.e. the possibility of reconstructing the state of a system from observation data). Not everything is possible of course. Studies on this property allow sensor selection (from among those available) to enable the reconstruction of unmeasured variables (See *Fig. 1 above*).

The sensor choice is not always intuitive for large or complex systems. Some terms of the biological model are at times poorly known or uncertain (e.g. growth rate depending on the climatic conditions). When the statistical data are not sufficiently abundant to support probabilistic hypotheses on uncertain situations, but the poorly known terms are functionally bounded, 'interval observers' can be implemented.

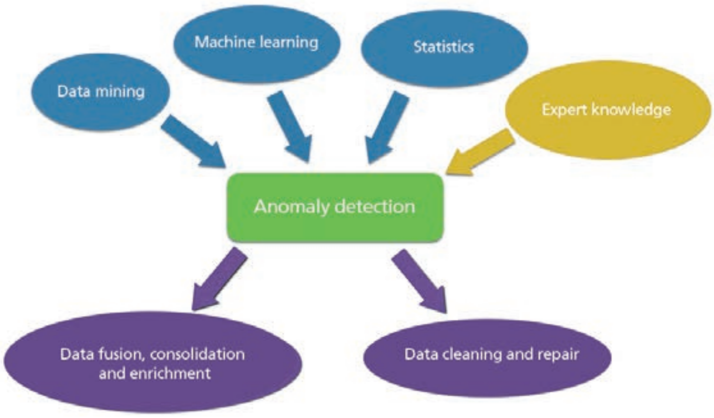
Instead of means and variances, guaranteed lower and upper values can be determined for each unmeasured variable over a time course. A pair of software sensors is thus obtained rather than a single one (see *Fig. 2 above*). This guaranteed approach is well adapted to transient bioprocesses (tanks containing microorganisms that transform matter, e.g. fermenters, digesters and water purification bioreactors), where there is a risk of biomass washout when their concentrations are too low, which has to be detected as early as possible. Mathematically, this technique is based on the cooperativity property of dynamical systems, which is not always verified by models but can be applied more conservatively to combined variables.

Contacts: J. Harmand (UPR LBE), jerome.harmand@inra.fr,
A. Rapaport (UMR MISTEA), alain.rapaport@inra.fr

Data interpretation

Strategies for data anomaly detection, repair and consolidation

Automating anomaly detection in a dataset and more generally during the analysis of data from complex systems is essential. It impacts data-supported decision making and involves techniques such as machine learning, statistics, and data mining. The data type, associated information (or metadata), types of anomalies to consider, their interlinkage, and the type of results required to characterize the target system will determine the choice of algorithm to use, as well as the entire pipeline of data preprocessing, cleaning, correction, fusion, and consolidation. These are the key elements for dealing with anomaly detection issues, while also being at the core of our expertise and research studies. When anomalies are detected, they can be corrected to a certain extent by experts of the application domain, who check and validate the results obtained by the different data correction and consolidation strategies using constraints, rules and knowledge specific to their field. The interpretability of our results— to ensure that they could be readily explained and understood by end-users—is crucial to be able to refine, parameterize and finally validate anomaly detection and correction strategies in an applied setting.



▲ *Key areas of anomaly detection.*

Contact: L. Berti-Equille (UMR ESPACE-DEV), laure.berti@ird.fr

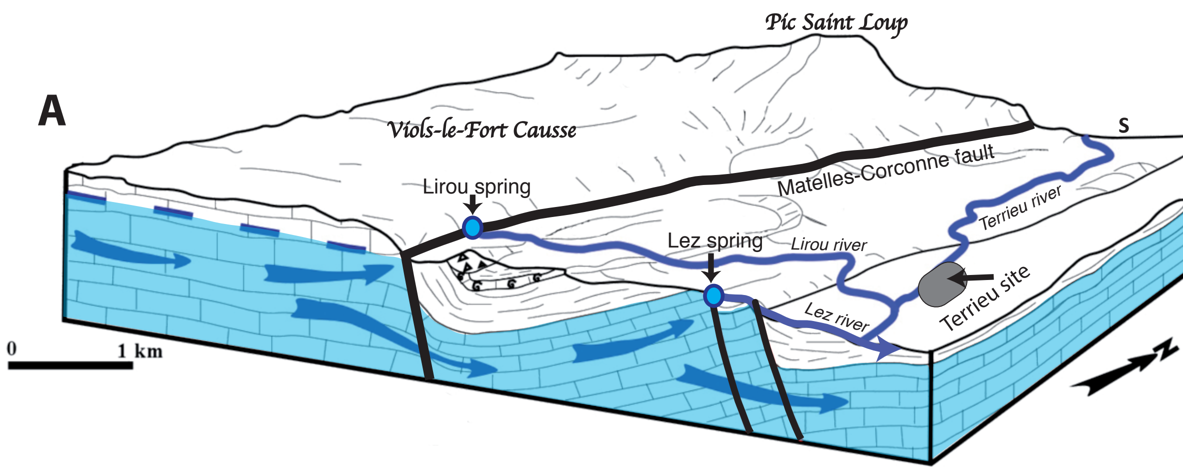
Modelling karstogenesis of the Lez karst aquifer (Hérault, France)

Karst aquifers in southeastern France are characterized by many overlapping karstification phases. In this Mediterranean setting, the Messinian age (6-5.3 My)—when the depth of the Mediterranean Sea substantially increased (up to -1,500 m)—has been clearly identified as a key period regarding the karstification of carbonate aquifers in the Mediterranean Basin. Other studies have, however, revealed evidence of karstification periods prior to the Messinian salinity crisis. The polyphase karst history could thus be summed up by two major scientific questions: (1) What different karstification phases impacted our current karst network? (2) How could these impacts be quantified to obtain the most accurate picture of the spatial distribution of the network?

The polyphase karst evolution in the Lez aquifer (Hérault, France) was thus modelled to address these questions (*figure below*). These first modelling tests revealed a major karstification pattern affecting the aquifer on a regional scale, located at the interface of Berriasian-Jurassic carbonate formations and with an early late Jurassic origin. This pattern was extended by karstification during recent phases with the evolution of karstification being focused in this area. Since, according to various modelling tests, this phenomenon could only take place prior to the Berriasian sedimentary deposits, the existence of an epikarst in the late Jurassic throughout our study area seems to be the most reasonable explanation, in agreement with observations reported by Bodeur (1996) in the eastern part of our area.

Contact: V. Leonardi (UMR HSM), veronique.leonardi@univ-montp2.fr

▼▶ *Block diagram representing the Lez karst aquifer (Hérault, France) (A) including a model of the karstogenesis of this aquifer: creation of karst conduits during the Messinian age between the Lirou and Lez springs (B next page).*
From Leonardi, V., Massonnat G., Planteblat C., Gal C., 2016. Karst genesis modelling of a regional Mediterranean aquifer (Lez, France). Presented at the 43rd IAH Congress, 25-29th September, 2016, Montpellier, France.

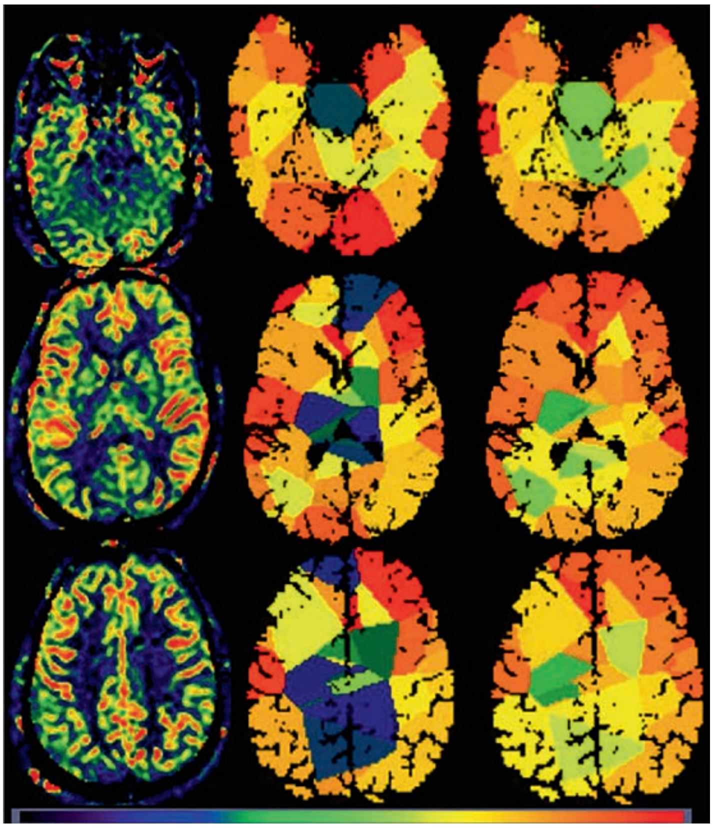


Development of a preoperative planning prediction tool – a new approach to MRI mapping of anatomical-functional brain connectivity

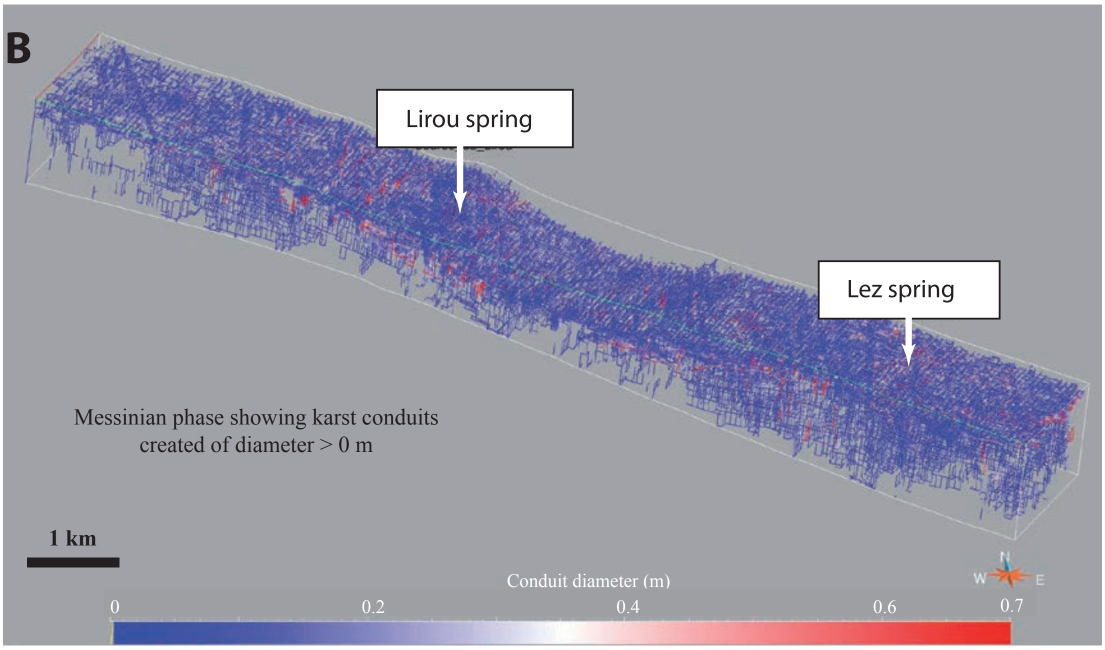
Brain imaging research in both fundamental and clinical settings has two major goals. The first is to enhance our ability to supply new diagnostic markers that could serve as an alternative to invasive examinations, particularly in a surgical context. The second is to participate in the development of sound multiscale brain function models. Local interactions are increasing between the Neurosurgery and Neuroradiology Departments of the Regional University Hospital of Montpellier, computer science (UMR LIRMM) and physics (UMR L2C, theoretical physics research focus) laboratories of the *Université de Montpellier* (UM). This has led to a collaboration ranging from neuroradiological assessments and surgical operations to the development of data processing chains and original models for the analysis of functional magnetic resonance imaging data of patients. Finally, Montpellier's university hospital structure facilitates the pooling of these skills at a single site while playing a facilitating roll in this interaction.

Many clinical studies have already established the reputation of the *Institut d'Imagerie Fonctionnelle Humaine* (I2FH) platform and the analytical tools that it has developed. Regarding fundamental neuroscience, a first original modelling step was achieved with the development of a global individualized model of intracranial circulation based on the combination of many imaging modalities. The figure on the right shows a comparison of measured and simulated cerebral perfusion data at the whole brain scale. From this modelling standpoint, future steps will be focused on the application of mean-field models using brain imaging data with the aim of building new analytical tools that will take into account the wealth of highly relevant yet still underexploited data derived from our university hospital centre.

Contact: F. Molino (UMR L2C), francois.molino@umontpellier.fr



▲ ***Cerebral perfusion: raw values and relative to different brain areas.*** *The first column shows a map of the raw flow obtained by arterial spin labelling, the second column shows the relative flow estimated by the model for each brain region, while the third column shows the mean database value.© CONNECTOME/UMR L2C research team*



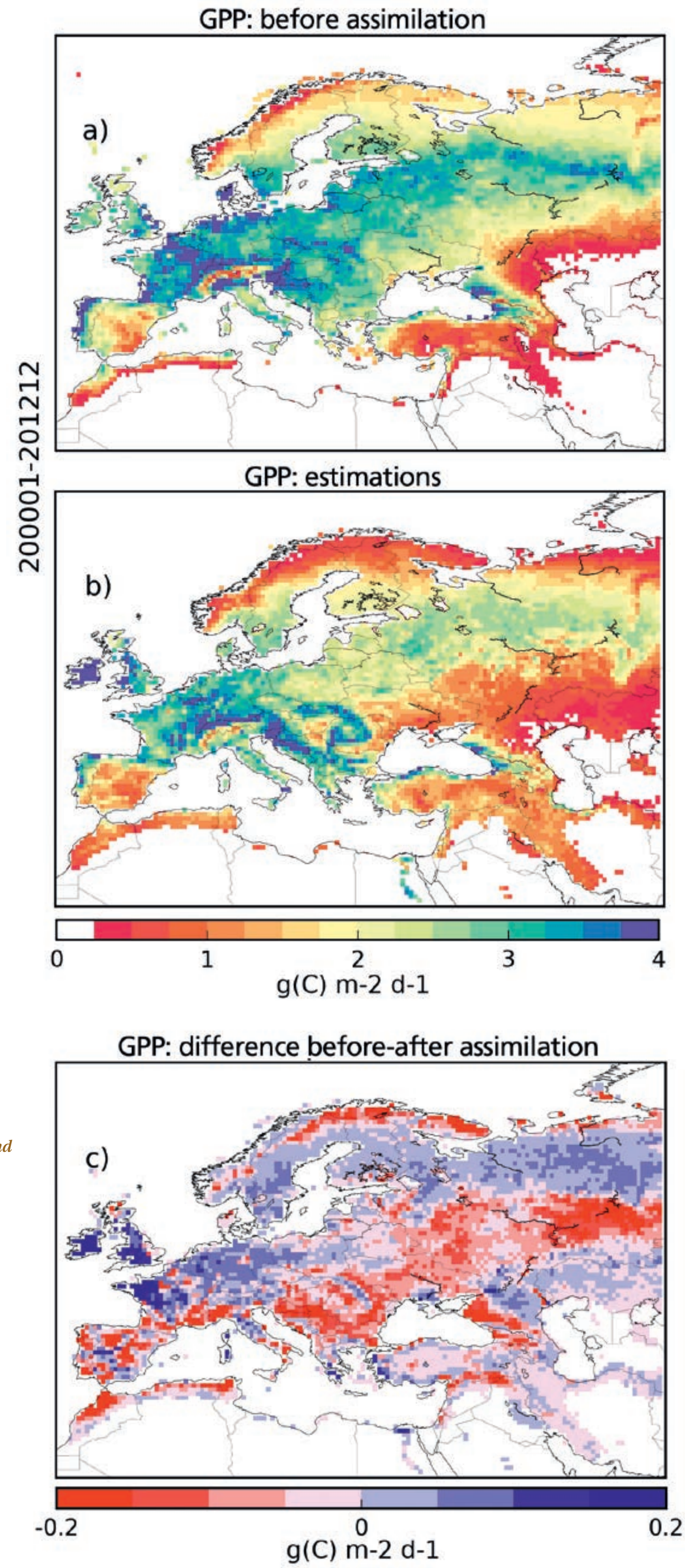
Assimilation of satellite-derived observations for vegetation monitoring

Simulations of the Intergovernmental Panel on Climate Change (IPCC) indicate that the frequency of droughts and heatwave periods is increasing with climate change. Observing and understanding the evolution of land surface parameters such as vegetation or the soil water status under these extreme climatic conditions is a major scientific challenge for the adaptation to climate change. Satellite-derived observations have the advantage of being available on a global scale and repeated over time. Many such observations related to the hydrological cycle and vegetation are already available. Access to some unobserved parameters is possible by combining land surface modelling with these satellite-derived observations. Data assimilation is a digital method that enables consistent integration of such high volumes of observations in land surface models while representing the processes involved.

The CNRM joint research unit has developed data assimilation systems tailored for land surfaces in the SURFEX* modelling platform. The aim is to constrain the ISBA (interactions between soil-biosphere-atmosphere) land surface model with satellite-derived soil surface moisture and leaf area index observations, etc. These sequential data assimilation systems have been successfully implemented in a global water and carbon flow monitoring chain. The adjacent figure highlights the impact of the assimilation of these satellite-derived data on vegetation gross primary production (GPP, the quantity of carbon sequestered by vegetation via photosynthesis) in the Euro-Mediterranean region (2000 and 2012). Daily GPP estimates derived from the spatialization of FLUXNET** site observations are used for assessments. GPP was shown to be better represented by the ISBA model after assimilation, i.e. simulated values closer to the FLUXNET observation values.

Contacts: C. Albergel, clement.albergel@meteo.fr,
J.-C. Calvet, jean-christophe.calvet@meteo.fr (UMR CNRM)
For further information: www.umr-cnrm.fr/spip.php?article1022

*SURFEX Earth Surface Modelling Platform: www.umr-cnrm.fr/spip.php?article145
** Spatialization of FLUXNET data: www.bgc-jena.mpg.de/geodb/projects/Home.php



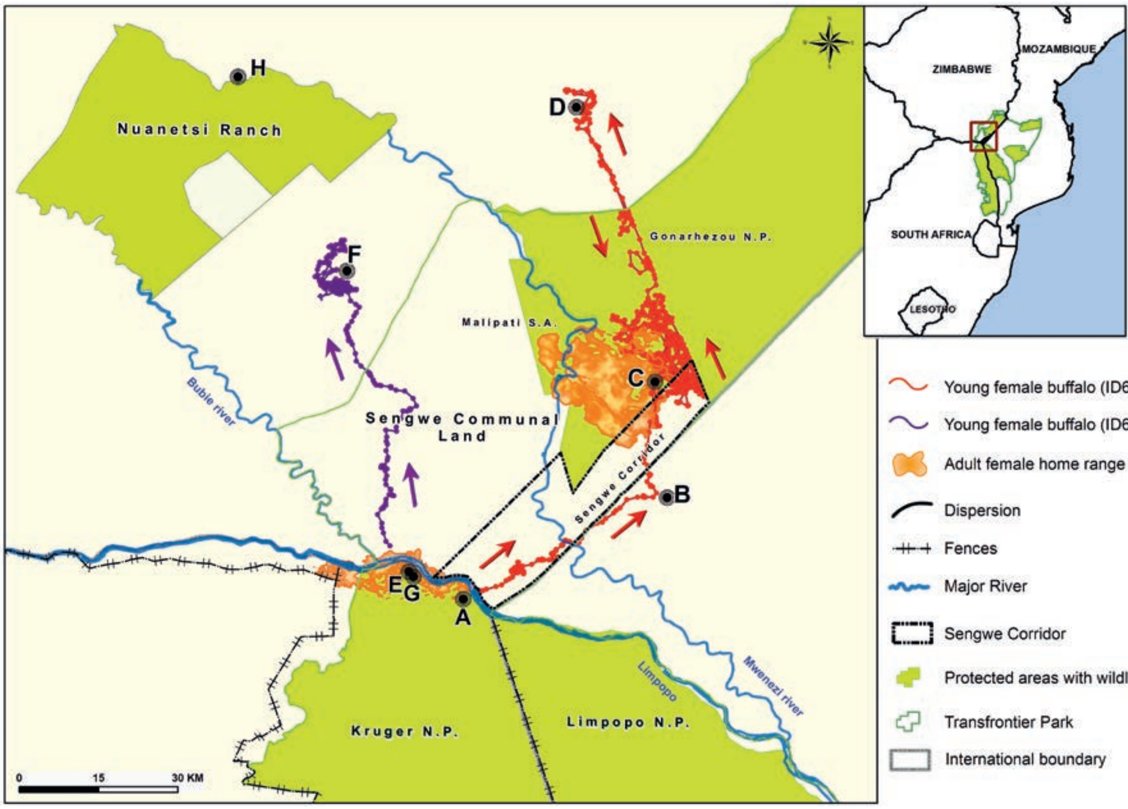
▶ ***Mean gross primary production (GPP) between 2000 and 2011.***
(a) Simulated by the ISBA model before assimilation.
(b) Values obtained by spatialization of FLUXNET site observations.
(c) Differences between GPP represented by the ISBA model before and after the assimilation of satellite-derived soil moisture and leaf area index observations.

Telemetry to study behaviours and interactions between wild and domestic ungulates at the edges of protected areas

In southern Africa, the permeability of borders between land uses, such as protected and communal areas, is conducive to wildlife-livestock interactions. It is essential to gain insight into these interactions and their determinants to enhance the management of interfaces between wildlife, livestock and humans. These interfaces catalyse some issues that are essential for the success of initiatives geared towards facilitating the coexistence of local development and biodiversity conservation. How can cattle and livestock access to natural resources such as pasture and water be achieved without competition? How can disease transmission between animals and between animals and humans be mitigated? And how can wild carnivore predation of cattle be hampered?

Contacts: A. Caron (UMR ASTRE), alexandre.caron@cirad.fr,
D. Cornelis, daniel.cornelis@cirad.fr (UPR F&S, Forests and Societies)
and M. de Garine-Wichatitsky (UMR ASTRE), degarine@cirad.fr
For further information: www.rp-pcp.org

In such socioecosystems—which are by definition complex—the use of telemetry, especially via satellite (i.e. fitting GPS tracking collars on animals provides their geolocation at each predefined time step), can help to: (i) describe the behaviour of wild species that adapt to these interfaces; (ii) understand livestock farming practices and discuss them with farmers in their risky landscapes; and (iii) analyse wildlife-livestock interactions and the key factors involved. All of the collected spatial data (associated with vegetation maps, surveys on livestock rearing practices and epidemiological studies) can generate knowledge to support decision-making and management processes. This knowledge is presented, discussed and used in a participatory process between all stakeholders (farmers, wildlife managers, professional hunters, etc.). The ultimate aim is to mainstream this type of tool in local management scenarios to promote integrated management of these interfaces.



▲ ***Example of telemetry data.*** *Adult female buffalo home range (orange area) in the Great Limpopo Transfrontier Conservation Area (GLTFCA) and movement patterns of young female buffalo (red and purple lines) through the land uses and countries (a-b-c-d) from Kruger National Park towards Mozambique and Zimbabwe for the red line (g-e-f) and from Kruger in South Africa towards communal areas of Zimbabwe for the purple line. This type of behaviour had not previously been described in young female buffalo. © Marie Gely, adapted from Caron* et al., Emerging Infectious Diseases*, 2016.*

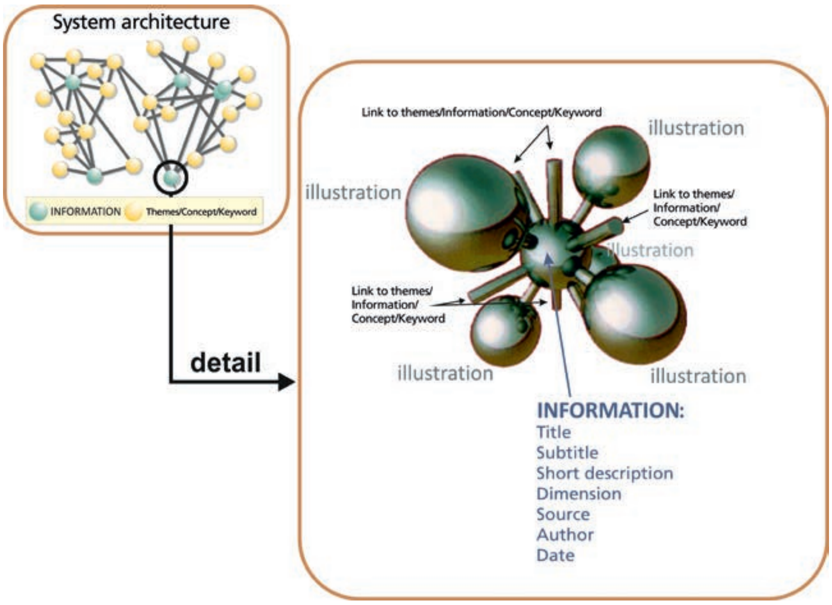
© Daniel Cornelis/CIRAD © Michel de Garine-Wichatitsky/CIRAD

▲ ***Adult female African buffalo (left) and a livestock farmer and his cow (right) inhabiting the same GLTFCA area.*** *The two bovines were fitted with GPS tracking collars to be able to record their geolocation data over a 1-2 year period.*

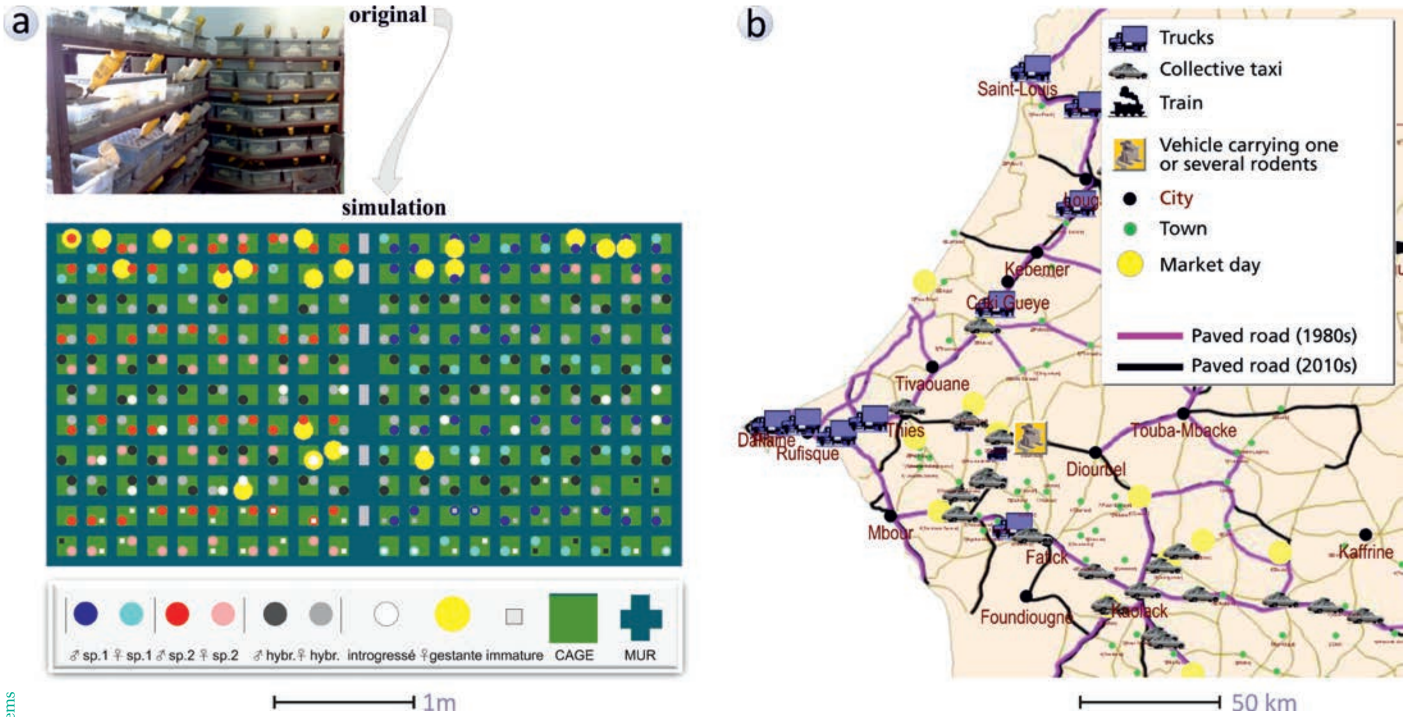
Linkages within a formal body of knowledge related to multidisciplinary issues

In a given research domain, field experiments and observations raise a range of questions for the concerned disciplines. Knowledge acquired by each one represents contributions required to gain insight into the observed natural phenomenon. In the case that interests us, a method is sought to dovetail this wealth of knowledge within the same formal assembly so as to produce the most integrated vision possible of the functioning of communities and populations of rodents and their parasites in different environmental situations. Three avenues are explored to understand this complexity: questions, knowledge and modelling: semantic analysis of interviews of researchers helps understand the field of assessment to represent; structuring of unit information within a network of keywords provides a structured representation of scientific knowledge (*Fig. 1*); and finally a multiprotocol model facilitates the identification of generic terms essential for the production of spatiotemporal dynamics. This latter approach, based on multiagent system computer modelling, enables development of a software architecture linking research at different levels—from genes to ecosystems—in this domain (*Fig. 2*). The three combined approaches generate a knowledge typology conducive to the organization of complex multidisciplinary projects.

Contact: J. Le Fur (UMR CBGP), lefur@ird.fr



◀ ***Figure 1. Structure of a navigation system in a knowledge domain devoted to the linkage of multidisciplinary and multiformat knowledge.***
(a) Information of various origins is associated by hyperlinks to various descriptors (date, source, keyword, etc.); users can move from item to item via thematic trails blazed by each information item. The network is gradually built through the input of new information.
(b) Detail of the internal structure of an information item: application of the system to various multidisciplinary domains leads to a parsimonious structure for the definition of scientific information that is compatible between disciplines. For further information: http://centreinfo.science



▲ ***Figure 2. Two distinct examples of simulations performed with the same platform.***
(a) Animal breeding experiment involving hybridization of twin African rodent species.
(b) Simulation of the movement/colonization dynamics of commensal rodents in Senegal. Linkages between disciplines facilitates building of a broad range of different simulation models at specific spatiotemporal scales. Each represented protocol or case study constantly enhances previous approaches while also benefitting.
From Le Fur et al., *2017. A Simulation Model for Integrating Multidisciplinary Knowledge in Natural Sciences. Heuristic and Application to Wild Rodent Studies. Proc. 7th Internat. Conf. Simul. and Model. Method., Technol. and Applic. (Simultech), Madrid, July 2017: 340-347. www.scitepress.org/DigitalLibrary/Link.aspx?doi=10.5220/0006441803400347*

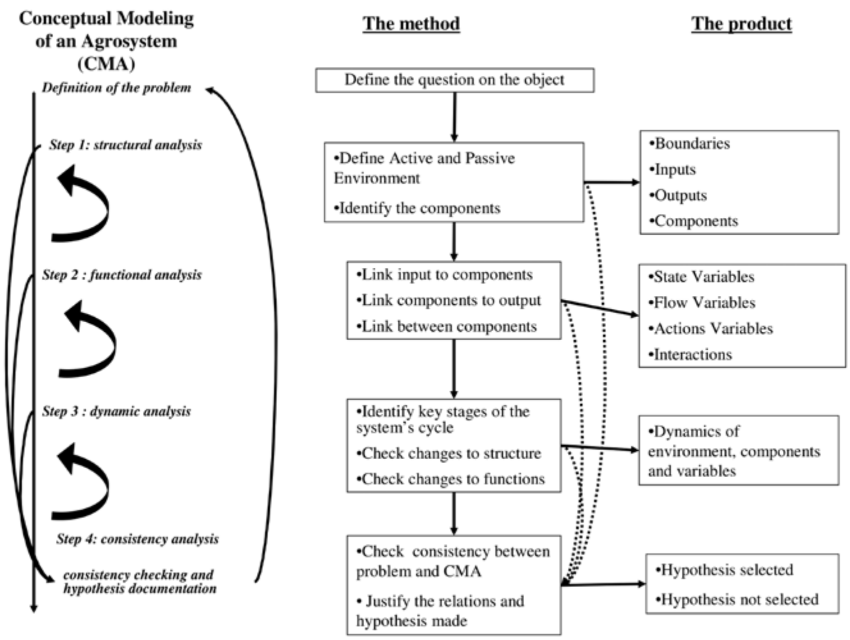
Conceptualization of an agrosystem issue – methodological basis and an example in a vineyard

Knowledge from various disciplines must be integrated to be able to address agronomic issues and design cropping systems. To ensure that this integration is scientifically sound and operational when interacting with stakeholders (farmers, consultants, etc.), it must take place in a systemic framework, which necessitates relationships between the technical system, environment, biophysical processes and the agrosystem performances and services. The protocol for the conceptualization of an agrosystem issue developed by the SYSTEM joint research unit (UMR) enables formalization of a target agrosystem along with its limits, structure, basic biophysical processes and other interacting systems. It pools scientific knowledge of various disciplines, as well as expert knowledge in a shared framework—an agrosystem conceptual model (CMA). CMA is a structured set of knowledge and hypotheses that can be queried via graph extraction. One example, which was dealt with in collaboration with the French Wine and Vine Institute, involved the development of hypotheses to explain the problem of dieback of vine plants of the Syrah grape variety. CMA—by integrating expert knowledge, especially regarding plant physiology, pathology and vineyard management—condensed over 20 years of fragmented research findings on this complex syndrome, which in turn were used to draw up hypotheses that were subsequently tested experimentally, with the results being interpreted using the model. This conceptualization approach provides a formalized systemic agronomy framework and is being used in many research projects, including the formalization of indicators to support the agrosystem transition process*, the design of innovative technical systems** and the development of digital models that explain parameter-process links. It also serves as a support tool for systemic agronomy and agroecology courses coordinated by UMR SYSTEM at Montpellier SupAgro.

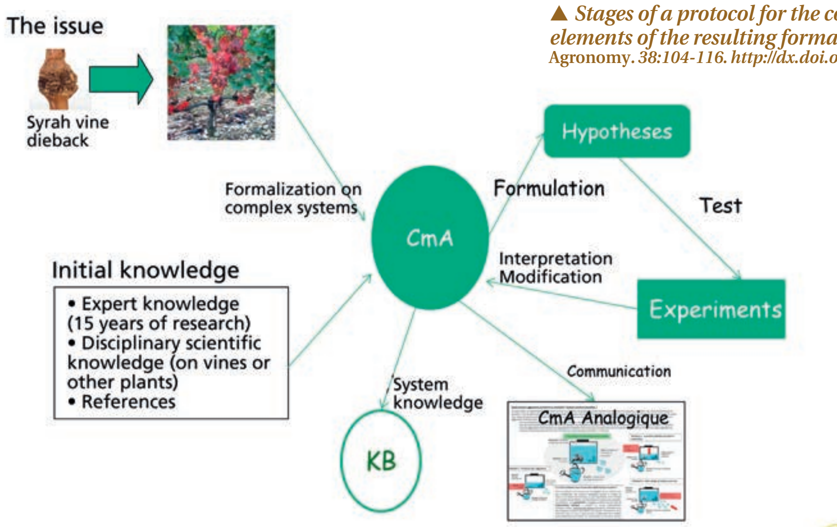
© UMR SYSTEM

Contact: R. Métral (UMR SYSTEM),
raphael.metral@supagro.fr

* Aidy Project (Integrated analysis of organic viticulture conversion dynamics): www6.inra.fr/viticulture-bio
** EcoViti Project: www.vignevin.com/recherche/vigne-et-terroir/ecoviti.html



▲ *Stages of a protocol for the conceptualization of an agroecosystem and the main elements of the resulting formalized system.* From Lamanda N. et al., 2012. European Journal of Agronomy. 38:104-116. http://dx.doi.org/10.1016/j.eja.2011.07.004



© UMR SYSTEM

▲ *Conceptualization of an agrosystem to pool knowledge and define an experimental programme on a complex system. Formalization of interdisciplinary knowledge concerning a Syrah vine dieback problem led to the development of a conceptual model (CMA) that was used to define an experimental programme.*

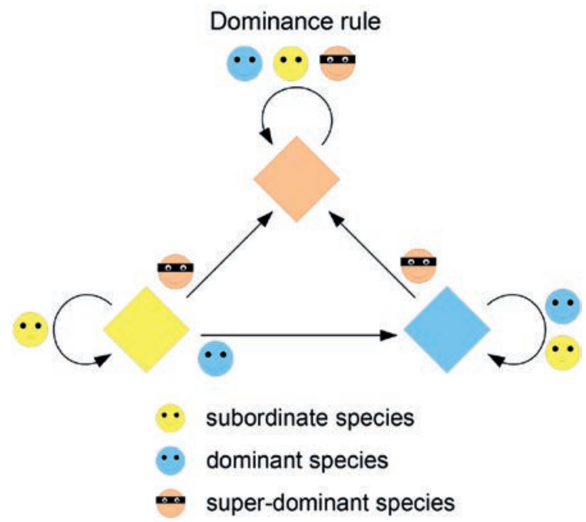
Qualitative modelling of microbial community functioning

Observation of microbial communities reveals interactions between their constituent entities (operational taxonomic units or species) when the community performances can be compared with those of isolated entities. From a microbial ecology standpoint, it is essential to gain insight into these interactions to be able to predict the performances of microbial communities (e.g. biogas production). Most models consider interactions in pairs (predator/prey, consumer/resource) although experience shows that interactions between more than two entities is common (facilitation, inhibition). However, the formalization and study of models that take more complex interactions into account are hampered by the combinatorial explosion in the number of possibilities (with 100 entities, there are roughly 5,000 possible 2 x 2 interactions, and around 4 million 4 x 4 interactions). Hence, in practice the number of possible assemblies that can be observed is limited.

Eco&Sols and MISTEA joint research units (UMRs) have proposed a new qualitative modelling approach to understand this complexity*. This approach is based on a classification of entities and entity communities, with community classes being determined by rules regarding interactions between entity classes. This approach has, for instance, generated a description of the behaviour of microbial communities of different sizes formed with seven isolated strains. On average, 3-strain communities performed better than isolated strains and than 7-strain communities. The observed behaviour was accurately described by three strain classes interacting according to a dominance rule, i.e. a common interaction pattern in ecology. Actually the probability of obtaining a certain community class is maximal for a 3-strain community.

* Studies carried out as part of a research project supported by the French National Network for Complex Systems (RNSC).

Contacts: B. Jaillard (UMR Eco&Sols), benoit.jaillard@inra.fr, J. Harmand (UPR LBE), jerome.harmand@inra.fr, A. Rapaport (UMR MISTEA), alain.rapaport@inra.fr



▲ *The presence of a dominant or even super-dominant species in a community implies that the community performs in a dominant or super-dominant way. From Jaillard* et al.*, 2014.* Functional Ecology*. 28: 1523-1533.*

Knowledge modelling – spatiotemporal ontologies (landscape, biodiversity, images)

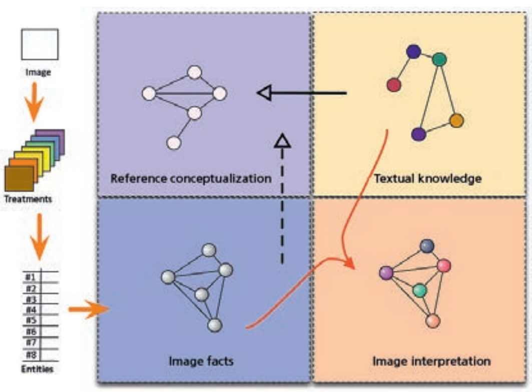
The analysis of complex systems at various spatiotemporal scales based on different types of monitoring data is a major challenge in many scientific areas. Two key elements are involved in these analyses, i.e. knowledge of various scientific experts and monitoring data. Regarding the former element, through knowledge engineering, the explicit formalization of this knowledge in ontology form is an advance in terms of sharing and capitalization. For the latter element, satellite imaging —thereby shifting the focus from a local to a more global scale—enables assessment of vast areas, thus reducing the need for field monitoring. Various projects enabled us to explain how ontology-formalized knowledge can generate innovative solutions via satellite image analysis by reducing the semantic gap*:

• The use of ontologies for automated satellite image interpretation regardless of the analysis paradigm (pixel or object). The interpretation is the result of reasoning based on contextual knowledge (built from expert knowledge) regarding image subjects extracted previously by processing (see *Fig. 1 below*).

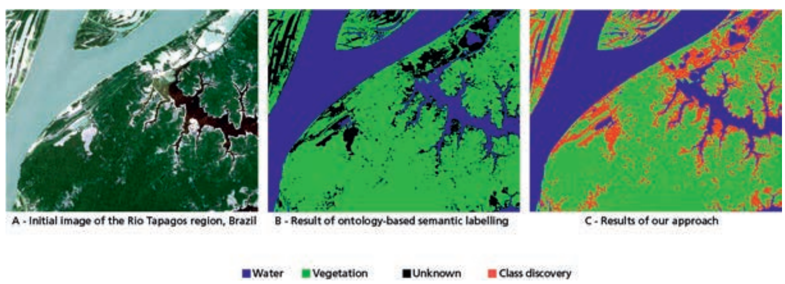
• Joint exploitation of ontology-based reasoning and unsupervised pixel classification. This reasoning enables semantic pixel labelling from knowledge derived from the target domain. The generated labels then serve as a guide for the classification task, which facilitates discovery of new classes while also enhancing the initial labelling. Figure 2 shows an applied example.

Contacts: I. Mougenot, isabelle.mougenot@umontpellier.fr, T. Libourel, therese.libourel@umontpellier.fr, S. Andres, samuel.andres@yahoo.fr and H. Chahdi, hatim.chahdi@yahoo.com (UMR ESPACE-DEV)

* Images are described digitally whereas users are interested in their semantic content. Determining relationships between digital and semantic levels is a challenge that must be addressed to overcome the so-called 'semantic gap'.



▲ *Figure 1. Overview of the semantic interpretation principle. From Andrès S., 2013.* Ontologies dans les images satellitaires : interprétation sémantique des images. *Computer Science PhD thesis. UM, France.*



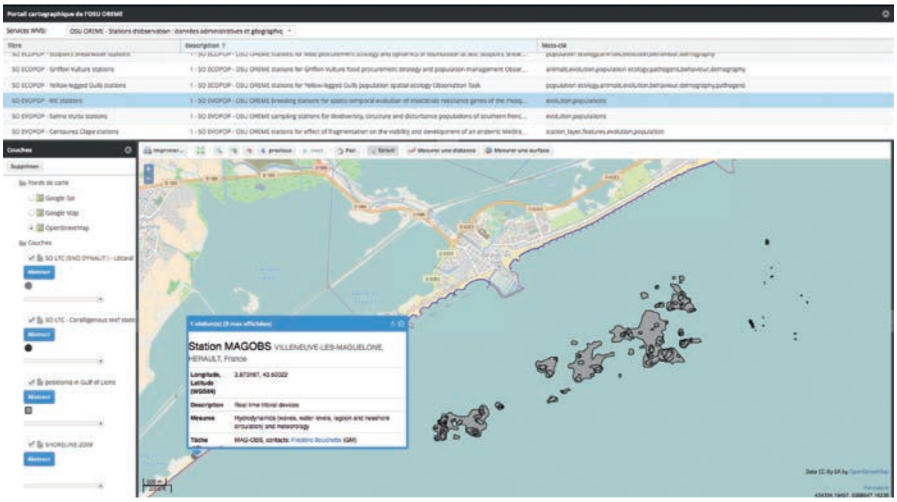
▲ *Figure 2. Application of the approach to an image of the Amazon region, Brazil. From Chahdi H., 2017.* Apports des ontologies à l'analyse exploratoire des images satellitaires. *Computer Science PhD thesis. UM, France.*

Data provision – accessibility and interoperability

OSU OREME Information System

Scientists studying complex systems must be able to cross-tabulate data that is highly heterogeneous—i.e. derived from various communities, each with its own languages and focuses of interest—which they are not necessarily familiar with. The OSU OREME Information System platform aims to meet this challenge. Scientific teams associated with the Observatory are thus proposed data structuring, standardization, visualization and cross-tabulation services from spatial, temporal and semantic standpoints. The first step is to describe datasets using metadata to enable comparisons of the different research subjects. The platform uses controlled terminology and interoperable description formats to help users pinpoint similarities with initially unknown datasets with a scientific link to the complex system under study. The second step is to overcome the heterogeneity in the harvested data formats. The platform thus relies on interoperable structuring and dissemination tools, such as relational databases and standardized cartographic servers.

To promote a mutual understanding of the different research subjects expressed in languages and domains with a variety of values, the platform standardizes the underlying data in common reference systems (hydrographic, taxonomic, measurement units, etc.). This ensures the semantic interoperability of the different data sources. Moreover, the system relies on relationships between entities defined in these reference systems (e.g. taxonomic classification), thus enabling data aggregation at various scales (e.g. species, family, etc.) while also facilitating their comparison. Finally, by relying on data dissemination standards (e.g. those of the Open Geospatial Consortium), the platform implements spatiotemporal data cross-tabulation through interactive and dynamic visualization tools—cartographic portal, time-series visualization tool, etc.



Contact: E. Servat, eric.servat@umontpellier.fr
For further information: https://data.oreme.org

◀ *Data from different map servers may be visualized and queried via the OREME cartographic portal.*

OSU OREME and its missions

The Observatory for Science of the Universe-Observatory for Research on the Mediterranean Environment (OSU OREME), which was recognized by the French Institute of Science of the Universe in 2007 and by the UM Board of Directors in 2009, is a UM-hosted school. It includes eight joint research units (UMRs) that conduct research in science of the universe, ecology and biodiversity fields. The Observatory focuses studies on environmental and human-induced changes and their impacts, particularly on variations in Mediterranean environments and their vulnerability. In addition to its educational remit, OREME implements sustainable large-scale observation resources while having recognized scientific and technical expertise in a broad range of fields encompassing physical, chemical and biological environments in the Mediterranean region. The Observatory uses its 17 observation services (SOs) (several of which are nationally accredited) and its shared platforms—Information System (*see above*), AETE-ISO geochemistry platform, and MEDIMEER platform for marine experiments using mesocosms—to fulfil its goals. OREME forges links between scientific communities—ecology, biodiversity and science of the universe—to foster joint research on signals collected by SOs at different spatiotemporal scales. One of OREME's main challenges concerns its ability to harvest, integrate and share heterogeneous data associated with these disciplines to reveal complex correlations. The key feature of these correlation initiatives is the detection of systematic signals to assess the impacts of global and/or anthropogenic changes and gain insight into the mechanisms involved in these environmental impacts. The missions of OREME are thus to:

- support systematic observation activities
- support the building of open, shared and internationally referenced environmental databases
- foster the sharing of analytical resources (observation, experimentation, modelling)
- serve as a local hub for national observatory networks while being a major stakeholder in Mediterranean-oriented initiatives.

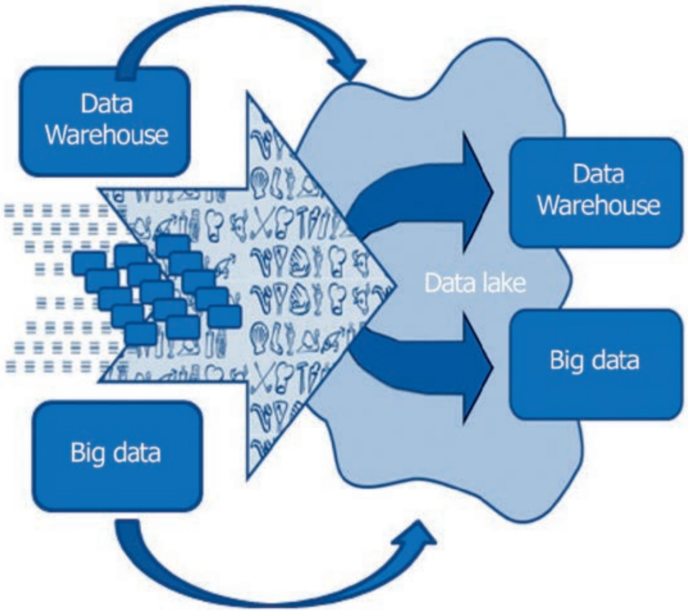
OREME
OBSERVATOIRE DE RECHERCHE MÉDITERRANÉEN DE L'ENVIRONNEMENT

Contact: E. Servat, eric.servat@umontpellier.fr
For further information: https://oreme.org

Smart data storage – from repositories to data lakes

Storage impacts how data will be processed to extract new information and knowledge. There are several types of data repositories, each with its advantages and drawbacks regarding the time when the stored data are filed or processed. Data warehouses emerged in the 1990s to serve as data storage facilities specifically tailored for addressing pre-established indicators for which an oriented decision-making structure is required. Data lakes with a novel architecture have emerged in recent years to meet big data management challenges. They are often compared to data warehouses while facilitating storage of enormous quantities of data which are subsequently transformed into information. But what are the differences between these two systems?

Data lakes—more than data warehouses—are associated with heterogeneous sources of raw data. We talk about ELT (extract, load and transform) and not ETL processes, with transformation carried out after loading. Data lake users thus differ from data warehouse users and are generally computer scientists who can implement technical tools for handling and analysing large amounts of data. Contrary to data warehouses, data lakes facilitate data storage without prior knowledge on the indicators and reports they will address. Metadata management is a key challenge in both cases. Although no consensual definition currently exists, a data lake could be defined as a collection of data that are:
• raw
• open format (all formats accepted)
• conceptually pooled at a single location but potentially non-materialized
• targeted for data scientists
• associated with a metadata catalogue and a set of data governance rules and methods.



▲ *Architecture of an information system including a data lake.*
© Cédrine Madera

Contacts: A. Laurent, laurent@lirmm.fr, C. Madera, cedrinemadera@gmail.com (UMR LIRMM)

Mapping of heterogeneous big data

The big data research issue is usually put forward when dealing with the enormous volumes of currently available data (or so-called 'infobesity'), as defined by the 3Vs—volume, variety and velocity. Heterogeneous data processing focuses on the 'variety' dimension. Here we are particularly interested in the mapping of data that is highly heterogeneous from syntax and semantic standpoints. In practice, for researchers, this approach can be crucial for linking knowledge from different sources (e.g. survey data vs. scientific publications, web documents vs. satellite images). Such broad-scale data processing can have several benefits, such as new knowledge discovery, data mainstreaming, linking researchers, etc.

The research question could be formulated as follows: how could thematic, temporal and spatial information from various data sources be mapped to generate a common framework? The TETIS joint research unit (UMR)—with extensive skills in heterogeneous data mining for food security, animal epidemiological surveillance and crop monitoring applications—is conducting a global analysis on the definition of heterogeneity and interoperability with three dimensions: (1) thematic, (2) spatial, and (3) temporal . Relevant features specific to these three dimensions have been defined by using: symbolic, statistical, and semantic methods, and natural language processing (NLP) methods for mining textual data. Specific representations are needed to meet the requirements of the implemented applications.

Contacts: J. Fize, jacques.fize@cirad.fr, M. Roche, mathieu.roche@cirad.fr and M. Teisseire, maguelonne.teisseire@irstea.fr (UMR TETIS)

For further information:
http://textmining.biz/Projects/Songes
www.cirad.fr/nos-recherches/resultats-derecherche/2016/veille-sanitaire-sur-le-webun-outil-pour-prevenir-la-propagation-desmaladies-animales

▶ *Mapping of heterogeneous data.*

GEOSUD – a major tool to democratize satellite imaging access

Satellite images contain valuable data for research and public action with regard to studies and management of complex systems in agricultural, environmental and territorial development fields. Yet satellite imagery is struggling to develop, mainly because of the cost and complexity of its use. The main challenge of the GEOSUD* project is thus to reduce these barriers while proposing tailored services to a range of users. Based on a pooling strategy, GEOSUD provides access on a licensing basis to very high spatial resolution satellite imagery (50 cm to 5 m) through a web portal to benefit all French public stakeholders and for noncommercial uses. GEOSUD archives include annual homogeneous coverage of France since 2010, in addition to images of specific areas of interest. A satellite receiving station was also set up in Montpellier in 2014, providing users with access to SPOT 6-7 images from around the world. In partnership with the National Centre for Space Studies (CNES) and the National Institute of Geographic and Forest Information (IGN), the recently launched DINAMIS platform will extend free access to satellite images—and to a set of complementary images—from 2018 to 2025. Moreover, in late 2017, GEOSUD began offering web image processing services whereby images may be analysed remotely via clusters installed at CINES (see below). The scientific community can use these services to develop and disseminate new image processing chains and image-derived products (e.g. biogeographical parameter maps: forest biomass, soil moisture, agricultural landscapes, natural habitats, etc.). GEOSUD pools (end of 2018) 520 member bodies and over 700 user accounts, providing these beneficiaries with access to images, training materials and supporting expertise. Since 2012, GEOSUD has been one of the cornerstones of the Theia Land Data Centre, which brings together the French land cover remote sensing community.

Contact: P. Maurel, pierre.maurel@irstea.fr
For further information: http://ids.equipex-geosud.fr

* Funding via a government-region plan contract/European Regional Development Fund (CPER/FEDER) and the Investments for the Future Programme (PIA) as a laboratory equipment excellence project (ANR-10-EQPX-20).

National Computing Center for Higher Education (CINES)

CINES is a Montpellier-based French public administrative body accountable to the Ministry of Research. It offers exceptional computing facilities to the entire scientific community in its national statutory strategic missions:

- intensive digital computation for simulation of major scientific challenges
- long-term electronic data archiving for scientific heritage preservation
- national IT platform hosting as part of the national computing resource pooling strategy.

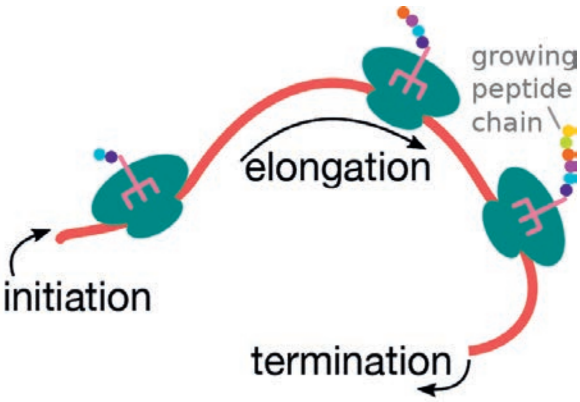
These missions are supported by highly secure Tier 3+ infrastructure (including two general power supplies) and around 60 expert agents, engineers and technicians who ensure optimal processing and use of the resources, while providing training, assistance and support for users. CINES runs state-of-the-art equipment such as the OCCIGEN supercomputer that was acquired by the civil society *Grand Équipement National de Calcul Intensif* (GENCI), which is currently one of the most powerful computers in Europe. This supercomputer—with a capacity of 3.5 petaflops* and 5 petabytes of associated storage space—enables 752 million h/year of computation for extreme simulations. Long-term archiving (accredited by the *Archives de France* Interministerial Department) enables very long-term preservation of digital information, thus overcoming the problem of the obsolescence of physical media and ever-changing software formats and standards. The archiving service can manage all types of digital data—scientific (from observations or computations), heritage (journals, manuscripts, educational data, etc.) or administrative. CINES is the official centre for archiving electronic theses. It has been certified as a national data centre for education and research by the Digital Infrastructure Committee within the framework of the Digital Steering Committee. Through the computer hosting facilities of CINES, users can readily benefit from the centre's exceptional infrastructure to securely and inexpensively accommodate strategic environments (computers of IRSTEA, UM, etc.).

* 3.5 thousand million billion operations a second.

© CINES

▲ *OCCIGEN supercomputer.* © CINES

Contacts: O. Rouchon (computing), rouchon@cines.fr, M. Massol (archiving), massol@cines.fr
For further information: www.cines.fr


growing peptide chain
elongation
initiation
termination

Motor protein physics

Understanding and analysing complex systems

A complex system consists of many entities (single or more) whose interactions produce a general behaviour that cannot be easily explained solely via the individual properties of the constituents—this is called emergence. Interpersonal interactions overlap individual behaviours. In a social network, for instance, an individual may interact with a group that he/she belongs to and is influenced by—this is called system feedback. The essence is thus to gain insight into temporal and multilevel phenomena. As we have seen in the first chapter of this *Dossier*, the challenge is to collect data, with appropriate storage and calculation capacities, so as to enhance awareness on these different system levels. This, however, is not sufficient because feedback phenomena, or stochastic environmental impacts on the system, give rise to general behaviours with cascading phenomena, while bifurcations in the evolution of the system lead to sudden qualitative changes that are hard to analyse, understand and predict with conventional tools. Specific tools that enable effective use of data are thus needed to highlight the different dynamics of the underlying complex systems.

The research examples presented in this chapter shed light on the diversity of levels investigated and methods developed in the ecological and environmental fields. Questions are usually asked at a given level whereas the methodological approaches are mostly multiscale. The examples were therefore compiled depending on whether the dynamics addressed were situated at the intracellular, intraorganism, population, ecosystem or even territorial management level, while including human and social dynamics.

The first part deals with the dynamics of organisms, ranging from intracellular dynamics to plant genesis, multicellular dynamics (tumours) and phenotypic expression mechanisms. These aspects are approached by presenting network analysis tools (stochastic or not) that are used for modelling gene networks or tumour invasion development, by coupling partial differential equation models or, more generally, using statistical physics tools. These simulation models can be useful in predicting the effectiveness of current or future therapies. Different plant growth models are presented, often based on numerical simulation platforms that offer an alternative to strictly mathematical approaches.

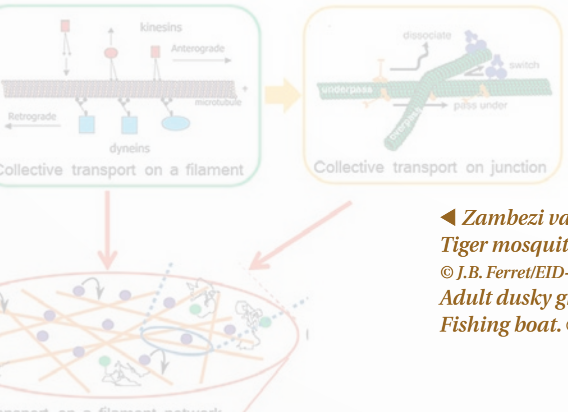
The second part focuses on population dynamics, ranging from those of bacteria to humans, insects, fish and ruminants. Multiscale landscape models, including population-environment relationships or not, are also used to analyse the behaviour of populations (insects, voles, etc.) or the colonization or extinction dynamics of plant species (eelgrass in the Thau lagoon). These models are in the form of multiagent platforms (analysis of small African rodents and their parasites) or stochastic/deterministic hybrid models (biofilms in water purification systems). Several epidemic models (with threshold effects) concerning the transmission of epizootic diseases in Africa: mosquitoes in Vietnam, tiger mosquitoes in southern France and the role of humans and their transportation systems are presented. Anthropobiology studies assess environmental impacts on the biological heritage of individuals and populations.

The ecosystem modelling examples discussed (third part) range from African savanna fire modelling to agrosystem modelling in Morocco, Zambia, Guyana and Chile, as well as land surface biophysics and interactions between water, carbon and energy cycles. Heterogeneous data assimilation methods are used and often require extensive computational resources. The resilience of ecosystems to environmental or human disruptions and the ability to foresee transitional phenomena is a major concern in many studies.

Finally, in the fourth part, the land management models discussed focus on the range of stakeholders involved: the impact of roads and new forms of pollution in Brazil, assessment of the effects of pesticide reductions on vineyard grape production, the impact of seed exchanges on agrobiodiversity in Chile. Several epidemiological models presented are applied to Chagas disease in Brazil, malaria in Guyana and Chikugunya in Indonesia. Some research addresses the multiterritorial scope of primary forest management in Madagascar.

Several very high throughput data and computation centres or experimental platforms are set up in Occitanie region—they are essential for processing data on complex systems, as showcased in special inserts.

Bertrand Jouve (XSYS) and Jean-Pierre Müller (UPR GREEN)



◀ *Zambezi valley (Zimbabwe).* © L. Guerrini/CIRAD
*Tiger mosquito (*Aedes albopictus*), a vector of pathogenic agents.* © J.B. Ferret/EID-Méditerranée
Adult dusky grouper. © Camille Albouy
Fishing boat. © IFREMER

Understanding and analysing complex systems

The research units and teams conducting activities on one (or several) themes mentioned in this chapter are listed in the following chart. Dark green areas indicate a theme that is the main focus of the research team, while pale green areas represent other themes in which it is also involved. The location of an article is indicated by the page number.

2.1. Organism dynamics
2.2. Population dynamics
2.3. Ecosystem dynamics
2.4. Territorial management

Research units and teams** - Understanding and analysing complex systems	2.1	2.2	2.3	2.4
AGAP • *Genetic Improvement and Adaptation of Mediterranean and Tropical Plants*	p. 27/30			
AGIR • *Agroecologies - Innovations - Ruralities*				p. 49
Agro • *Agronomy and Sustainable Development*				
AMAP • *Botany and Computational Plant Architecture*	p. 31	p. 37/38	p. 41	
AMIS • Laboratoire d'anthropologie moléculaire et imagerie de synthèse		p. 38		
ASTRE • *Animals, Health, Territories, Risks & Ecosystems*		p. 39		
B&PMP • *Biochemistry & Plant Molecular Physiology*	p. 29			
CALMIP • Calculateur en Midi-Pyrénées				p. 53
CBGP • *Centre for Biology and Management of Populations*		p. 37		
CEE-M • *Center for Environmental Economics – Montpellier*				p. 52
CEFE • *Center for Functional and Evolutionary Ecology*		p. 34/36	p. 42/44	p. 47
CeMEB • *Mediterranean Centre for Environment and Biodiversity*				
CERFACS • Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique			p. 43	
CESBIO • Centre d'Études Spatiales de la BIOsphère			p. 44	
CNRM • *National Centre for Meteorological Research*				
DIMNP • Dynamique des Interactions Membranaires Normales et Pathologiques	p. 25/26/28			
DYNAFOR • *Dynamics and Ecology of Agriforestry Landscapes*				
Eco&Sols • *Functional Ecology & Bio-geochemistry of Soils & Agro-ecosystems*				
ESPACE-DEV • *Space for Development*		p. 35		
G-EAU • *Water Resource Management, Actors and Uses*				
GEODE • *Environmental Geography*				p. 46/50
GEOSUD • *GEOinformation for SUstainable Development*				
GM • Geosciences Montpellier			p. 40	
GRED • *Governance, Risk, Environment, Development*				
GREEN • *Management of Renewable Resources and Environment*				p. 48/52
HSM • *HydroSciences Montpellier*			p. 42	
IBC • *Computational Biology Institute*	p. 32			
IMFT • Institut de Mécanique des Fluides de Toulouse				
IRIT • *Toulouse Institute of Computer Science Research*				p. 46/50/51
ISE-M • *Montpellier Institute of Evolutionary Sciences*	p. 28	p. 33	p. 41/42	
ITAP • *Information-Technologies-Environmental Analysis-Agricultural Processes*				
L2C • Laboratoire Charles Coulomb	p. 25/26/29	p. 38		
LBE • *Laboratory of Environmental Biotechnology*				
LEASP • Laboratoire d'Épidémiologie et d'Analyses en Santé Publique		p. 38		
LGI2P • Laboratoire de Génie Informatique et d'Ingénierie de Production				p. 53
LISAH • *Laboratory for the Study of Soil-Agrosystem-Hydrosystem Interactions*			p. 45	p. 46
LISST • *Interdisciplinary Laboratory Solidarities, Societies and Territories*				
MARBEC • *Marine Biodiversity, Exploitation and Conservation*		p. 36		
MIAT • *Applied Mathematics and Informatics Toulouse*				p. 46/50/51
MISTEA • *Mathematics, Computer Science and Statistics for Environment and Agronomy*		p. 33		
MIVEGEC • *Genetics and Evolution of Infectious Diseases*		p. 34		
NUMEV • *Digital and Hardware Solutions and Modelling for the Environment and Life Sciences*				
OREME • *Observatory for Research on the Mediterranean Environment*				
SMS • *Structuring of Social Worlds*				
SYSTEM • *Tropical and Mediterranean Cropping System Functioning and Management*				p. 46
TETIS • *Spatial Information and Analysis for Territories and Ecosystems*			p. 45	
TULIP • *Towards a Unified Theory of Biotic Interactions: Role of Environmental Perturbations*				
UMMISCO • *Mathematical and Computer Modeling of Complex Systems*		p. 34/36		p. 50
Virtual Plants project team • *French Institute for Research in Computer Science and Automation*	p. 29/30			
XSYS • *Toulouse Institute for Complex Systems Studies*				
#DigitAg • *Digital Agriculture Convergence Lab*				

See the detailed chart on page 72 listing all of the research units and teams in Occitanie and all of the themes covered in this *Dossier*.

Organism dynamics

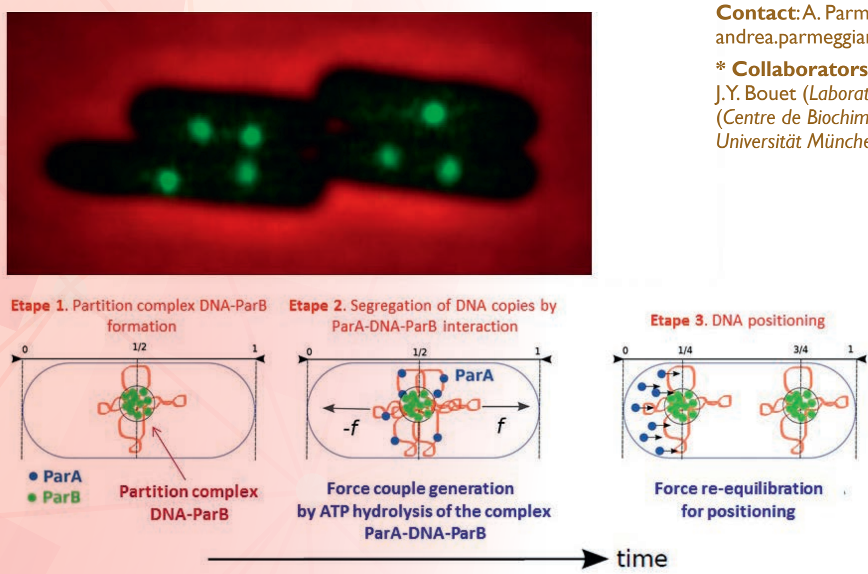
Modelling DNA segregation and positioning in the bacterial genome

Since the discovery of DNA (1952), several generations of scientists have investigated the origin of the movement and controlled positioning of bacterial DNA by segregation systems. Among these latter systems, the ParABS partition complex, which is composed of DNA (ParS) and two protein families (ParA and ParB), is the most widespread—yet the least known—of these systems amongst bacteria. A wealth of data on segregation systems have now been generated by high-throughput genomic approaches and quantitative super-resolution microscopy. For the first time, these approaches enable accurate monitoring of segregation systems while quantifying their molecular properties.

We have been developing physico-mathematical models of these mechanisms since 2015 in collaboration with our biology, biophysics and modelling partners*. This research has led to the discovery—at the microscopic scale—of new properties of biological material composed of DNA and proteins, e.g. the spatial location of ParB proteins around the ParS DNA sequence without any membrane compartments for the confinement or generation of protein stationary waves. These waves enable spontaneous translocation of the bacterial genomic complex (DNA, proteins, etc.) in a highly congested intracellular environment, in addition to the precise positioning and distribution of equal amounts of this material in daughter cells after cell division. Understanding these mechanisms is essential for designing new generation antibiotics and gaining further insight into protein complex mechanisms controlling the DNA state (even in eukaryotic cells with nuclei!), while clarifying the principles governing the organization of material within the cell cytoplasm. Moreover, these systems are of interest to physicists and chemists because the theories describing their functioning can also be applied to the separation of molecules or colloids in the fluid phase, with major potential technological spinoffs.

Contact: A. Parmeggiani (UMR DIMNP/UMR L2C), andrea.parmeggiani@umontpellier.fr

* **Collaborators**: J. Palmeri, J.C. Walter, F. Geniet and J. Dorignac (UMR L2C), J.Y. Bouet (*Laboratoire de Microbiologie et Génétique Moléculaires*), M. Nollmann (*Centre de Biochimie Structurale de Montpellier*), C. Broederzs (*Ludwig-Maximilians-Universität München*, Germany), N. Wingreen (Princeton University, USA)

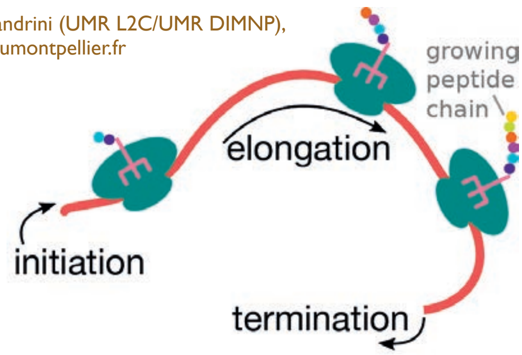


◀ ***View of bacterial partition complexes and diagram of bacterial DNA physical segregation and positioning mechanisms during cell division** (© J.Y. Bouet). Theoretical physics (phase transition theory, reaction and diffusion models, etc.) facilitate the development of controlled positioning and segregation models to overcome the lack of understanding of these mechanisms, which are important for both fundamental eukaryotic and prokaryotic biology, as well as for material physics and chemistry. © J.C. Walter*

Quantitative approaches to mRNA translation (models and experiments)

The last step of protein synthesis involves translation of the genetic code from the language of nucleotides—encoded in messenger RNA (mRNA)—to that of proteins, i.e. the building blocks of life. Despite the many technological breakthroughs in recent decades and the ever-growing quantity of available experimental data, the mechanisms underlying mRNA translation are still elusive. We quantitatively study mRNA translation via in-equilibrium and out-of-equilibrium models inspired by statistical mechanics approaches such as the exclusion process and one-dimensional archetypical traffic flow models (also known as the totally asymmetric simple exclusion process [TASEP]). We develop models and investigate them analytically and through stochastic simulation. We also propose and develop quantitative experiments aimed at studying how the determinants of an mRNA sequence affect the protein production rate of the corresponding gene. We collaborate with research groups in Montpellier and abroad. We then integrate modelling and experimental data to generate a more all-encompassing quantitative picture of this biological process. We are interested in unveiling the key factors determining translation initiation and its interplay with elongation, the role of codon usage bias, the gene length and resource competition in the translation machinery.

Contact: L. Ciandrini (UMR L2C/UMR DIMNP), luca.ciandrini@umontpellier.fr



▶ ***The mRNA translation process.** mRNA (red) is read by ribosomes (blue), which assemble the protein (growing peptide chain), linking one amino acid at a time, according to the nucleotide sequence. Our modelling frameworks incorporating experimental data are designed to identify yet unknown factors determining ribosome speeds and efficacy during translation.*

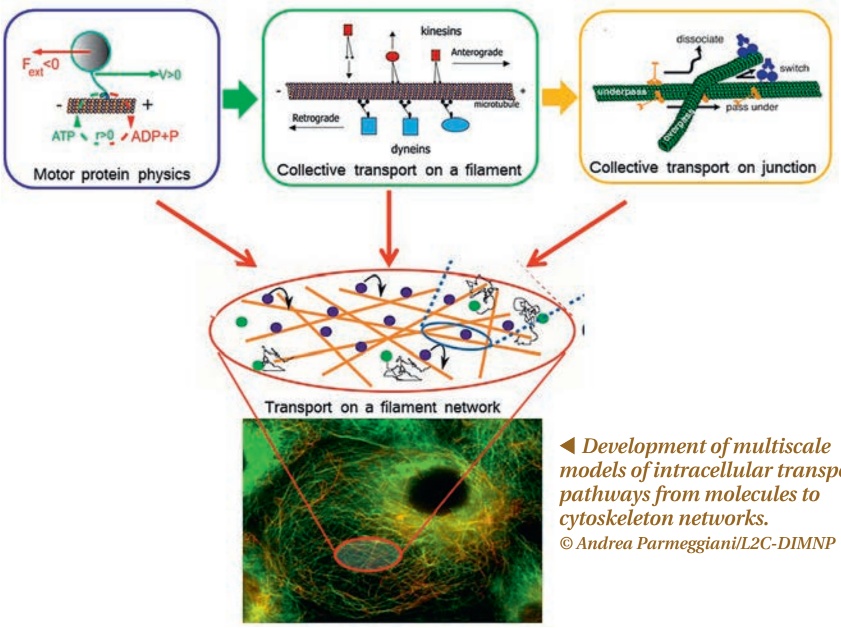
Physico-mathematical modelling of intracellular molecular transport

We have been developing over the past years, in collaboration with other research institutes*, physico-mathematical models of molecular transport in eukaryotic cells, particularly those involving cytoskeletal motor protein activity. These proteins are molecular powerhouses, surprising nanomachines that move around and produce the forces necessary for intracellular cargo transport through the energy released from ATP hydrolysis (adenosine-triphosphate)—a genuine cellular fuel. These machines use the cytoskeleton (huge protein scaffolds) and cytoplasm (intracellular medium) to move long distances intracellularly while shuttling the materials essential for all cell functions to the locations where they are needed. Metaphorically, cytoskeletal transport closely mirrors all kinds of traffic, such as that of trains, vehicles and people, as well as—in the light of the complexity of the extremely chaotic molecular world—urban evolutionary patterns of huge cities and even entire countries like France! Understanding how and why these molecular logistics work is one of the great enigmas of cell biology, with major medical implications. Indeed, deregulation of this transport can lead to serious pathologies: abnormalities in organism development, neurodegenerative diseases, cancers, etc.

The implemented multiscale approaches enable the analysis of molecular transport, from individual molecules to the entire cellular transport network. This interdisciplinary research, which also models DNA transcription and RNA translation, involves theoretical physics, biology, bioinformatics and medicine. Statistical, non-linear and stochastic physics models that have been developed help to understand and simulate cellular self-organization, intercellular communication through the formation, for example, of membrane nanotubes (genuine intercellular material transport routes), the impact of these processes on disease emergence, and the role and efficacy of current or future therapies.

Contact: A. Parmeggiani (UMR L2C/UMR DIMNP), andrea.parmeggiani@umontpellier.fr

* **Collaborators**: N. Kern, J.C. Walter, F. Geniet and J. Dorignac, J. Palmeri (UMR L2C), M.L. Vignais (Institute for Regenerative Medicine and Biotherapy, IRBM), J.P. Hugnot (Institute for Neurosciences of Montpellier, INM), B. Charlot (Institute of Electronics and Systems, IES), T. Virolle (Institute of Biology Valrose, iBV).



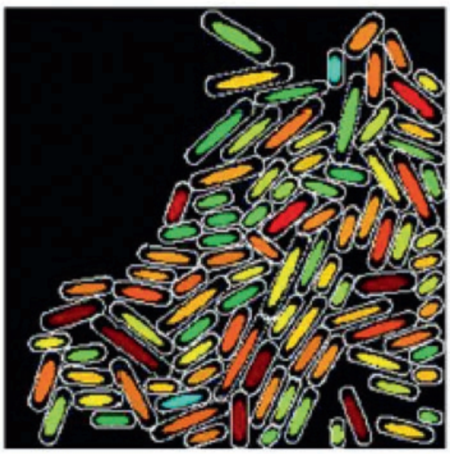
◀ *Development of multiscale models of intracellular transport pathways from molecules to cytoskeleton networks.*
© Andrea Parmeggiani/L2C-DIMNP

Stochastic dynamics of gene networks

Gene networks are essential in modern cell and molecular biology. They have a decisive role in decision making, cell differentiation and adaptation. In synthetic biology, gene circuits and networks are used to detect and process information needed for medical diagnoses, biotechnology or bioinformatics. Recent experimental results indicate that gene network functioning has a high degree of stochasticity at cellular and gene levels. Gene expression is controlled by complex molecular machinery involving DNA and DNA/protein interactions. This machinery is subject to molecular noise due to the presence/absence of regulatory protein complex components, fluctuations in chromatin organization or, more generally, intra- and inter-cellular environmental variations. Gene expression stochasticity can have major phenotypic impacts, such as the onset or relapse of infectious diseases, the adaptation of cell populations to a changing environment, resistance to pathogen treatments, etc. This intrinsic property of biological systems is a major concern in synthetic biology, where reliable and flexible biological systems are sought.

Our team develops mathematical models and methods to unravel the stochastic functioning of gene networks. In collaboration with biologists from the Center for Structural Biochemistry (CBS), the Institute of Molecular Genetics of Montpellier (IGMM) and the University of Chicago (Ecology and Evolution department), we quantify gene expression variations, e.g. at early fruitfly embryonic development stages or when central carbon metabolism changes occur during *Bacillus subtilis* bacteria adaptation to carbon source variations. This research is pivotal for gaining insight into the role of stochasticity in biological regulatory systems and could have medical and biotechnological applications.

Contacts: O. Radulescu (UMR DIMNP), ovidiu.radulescu@umontpellier.fr, L. Ciandrini (UMR DIMNP/UMR L2C), luca.ciandrini@umontpellier.fr
Collaborators: N. Declerck and J. Bonnet (Center for Structural Biochemistry, Montpellier, CBS), M. Lagha and E. Bertrand (Institute of Molecular Genetics of Montpellier, IGMM)



▲ *False colour representation of glycolytic gene expression obtained using Number & Brightness laser scanning microscopy for a population of* B. subtilis *cells subjected to a change of carbon source.*
© Ferguson et al., PNAS. *109:155 (2012). © M.L. Ferguson/CBS Montpellier, 2012*

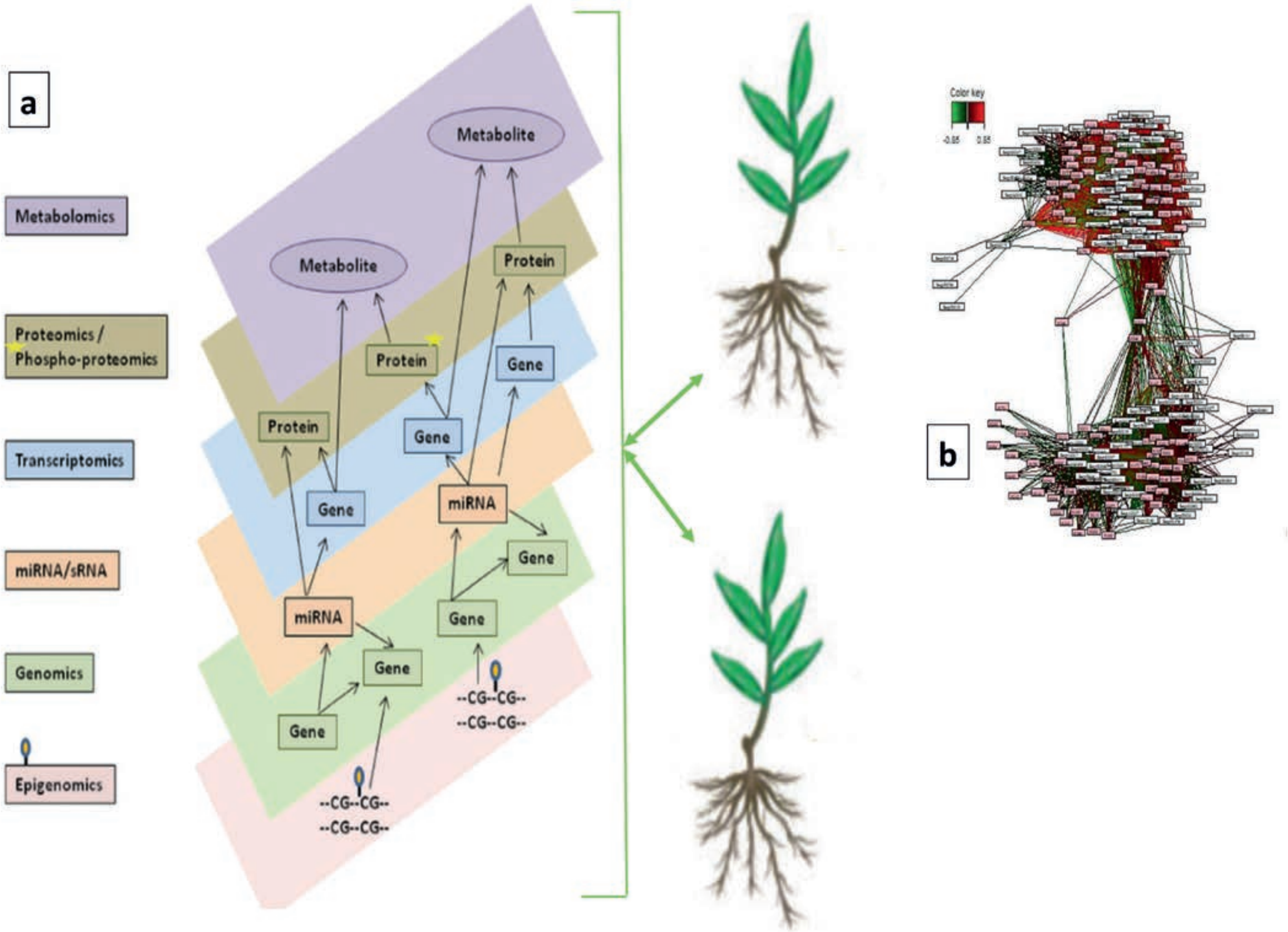
Analysis of regulatory networks of genome expression controlling stress adaptation

Gene expression is regulated by different mechanisms under genetic and epigenetic control. The first level depends on the epigenome dynamics and involves the condensation of chromatin bound to histone marks that determine the accessibility of the genomic sequence to transcription protein complexes. The second level is gene transcription regulation, which includes cytosine methylation-driven epigenetic regulation of promoters, as well as transcription activation regulation by cis- (regulatory box) and trans-regulatory elements. The third level concerns post-transcriptional regulation involving noncoding microRNAs that cleave target gene transcripts or inhibit their protein translation. Finally, post-translational modifications affect protein activity.

The BURST* team (AGAP joint research unit [UMR]) studies these mechanisms using omics data (transcriptomics, microtranscriptomics, degradome analysis and metabolomics), biology-type network analysis and validation using functional genomics approaches. These data are integrated and represented using bioinformatics tools such as Mixomics, weighted gene co-expression network analysis (WGCNA), etc. Analyses at this level generate a more comprehensive understanding of the regulation of perennial species under stress, while identifying the adaptive mechanisms involved and allele combinations that could enhance prebreeding programmes.

Contact: P. Montoro (UMR AGAP), montoro@cirad.fr

* Adaptation to abiotic stress in perennial species (BURST)



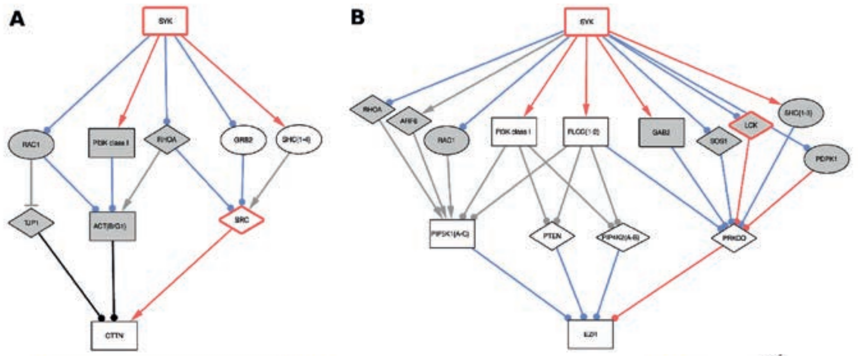
▲ *A. Integrative diagram of various levels of global genome to phenotype analyses and linkages with genetic analyses of traits of agronomic value. From Shakhawat, 2015.*

▲ *B. Integration of transcriptomics (white) and metabolomics (pink) data in eucalyptus (Favreau, in prep).*

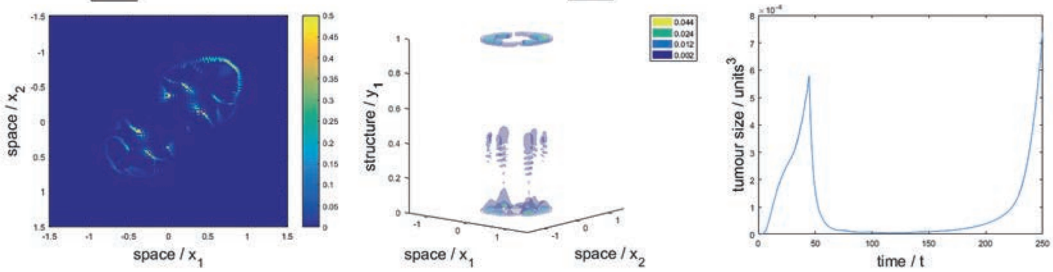
Multiscale modelling of tumour invasion

The invasive capacity of tumour cells is determined by multiple parameters, including the activation of intracellular molecular pathways controlling proliferation, migration as well as remodelling of their microenvironment by extracellular matrix remodelling enzymes. Moreover, cancer cells use the high degree of heterogeneity in individual cell behaviour to resist and sidestep therapy. Most mathematical models of tumour invasion are based on partial differential equations (PDEs) and include only one macroscopic scale. We develop new multiscale models of the invasion processes that couple PDEs with different scales and invasion front dynamics. These models take collective cell behaviour into account, e.g. growth, chemo- and hapto-tactic migration, as well as intracellular processes such as signalling and metabolic remodelling. Compared to standard PDE models, our multiscale models more accurately account for invasion front dynamics. They also predict distributions of cells not only on a spatial scale but also structurally (internal genetic and epigenetic variables), thus generating insight into resistance to treatment and related phenomena such as zonal heterogeneity. Accurate description of intracellular metabolism and signalling with patient-dependent parameters represents a major asset for the development of applications such as targeted and individualized therapies.

Contact: O. Radulescu (UMR DIMNP), ovidiu.radulescu@umontpellier.fr
Collaborators: A. Hodgkinson (UMR DIMNP), P. Coopman, G. Freiss, L. Le Cam and A. Turtoi (Institute of Cancer Research of Montpellier, IRCM)



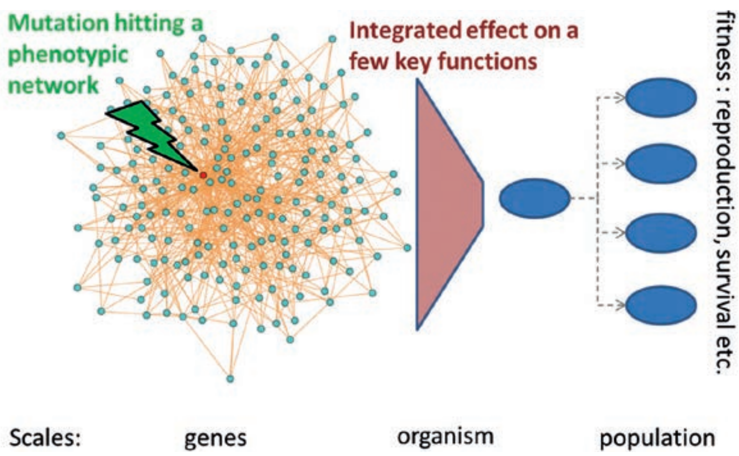
◀ *Signalling network reconstruction from phospho-proteomics data, highlighting Syk protein tyrosine kinase mechanisms of action in breast cancer.*
© From Naldi et al., *2017.* Plos Comp.Bio. *2017(13). e1005432*



◀ *Mathematical model predicted time-dependent, post-treatment, distributions in structure space explain melanoma resistance to targeted treatment. Spatial distribution of tumour cells (left). Spatiostructural distribution with a mutation dimension (centre); tumour size over a time course (right).*
© Arran Hodkinson/UMR DIMNP 2017

Modelling phenotypic evolution based on random matrix theory

The adaptation of living organisms is a dynamic phenomenon. Random mutations generated during reproduction multiply differentially—those that increase the reproduction and/or survival rate (fitness) eventually spread throughout the population. This process crucially depends on the range of random mutation effects on fitness. This information is necessary, for instance, to predict a population's capacity to adapt to environmental changes, with countless biological, agronomic and medical implications. However, a mutation is essentially a random change in DNA affecting a specific gene (or even a non-coding regulatory region) that interacts with other genes in a complex network of regulations and cascade reactions. Their integrated impacts on the entire organism's reproduction and survival is thus very hard to predict. The problem can be assessed using a probabilistic model describing (as a random variable) the effects of mutations which 'percolate' to fitness via a network of interactions that are also described by random variables (*see adjacent figure*). This generates random unspecified variables at each integration scale: genes, phenotypic traits, and then the fitness of the entire organism. Interactions between elements of the model are described by matrices whose elements are drawn into random distributions, i.e. so-called random matrices. The network complexity then becomes an asset—various laws of large numbers predict the properties of these matrices, when they are high dimensional, independently of the underlying distributions. The distribution of the effects of mutations on fitness can then be predicted in a fairly general way, since the results are as robust as the central limit theorem.



▲ *Simplified model of the genetic mutation-phenotype-selective value relationship. A mutation affects a gene that interacts with many others in various networks (metabolic, regulatory, etc.). This generates many cascading changes which 'trickle down' to a limited number of key phenotypic traits (e.g. size) for which there is an adaptive optimum. The difference between the mutant phenotype and this optimum then determines the mutant's fitness. © G. Martin*

Contact: G. Martin (UMR ISEM), guillaume.martin@umontpellier.fr

Growth models of a multicellular plant system

Unlike vertebrates, plants undergo morphogenesis throughout their lives. This ongoing production of new organs is associated with the presence of niches of non-differentiated cells in above-ground or underground stem tips, i.e. meristems. Their functioning is a dynamic process involving the regulation of physiological functions at different scales by environmental signals such as light or humidity. Understanding the developmental behaviour of plants according to their genetic specificities and in response to environmental variations is a highly complex scientific challenge. Organogenesis at the meristem level thus emanates from the interaction of intercellular (hormones, nutrients, mechanical constraints, etc.) and intracellular (transcriptional response to hormonal solicitation, etc.) signalling networks. Research into these mechanisms is based on three questions:

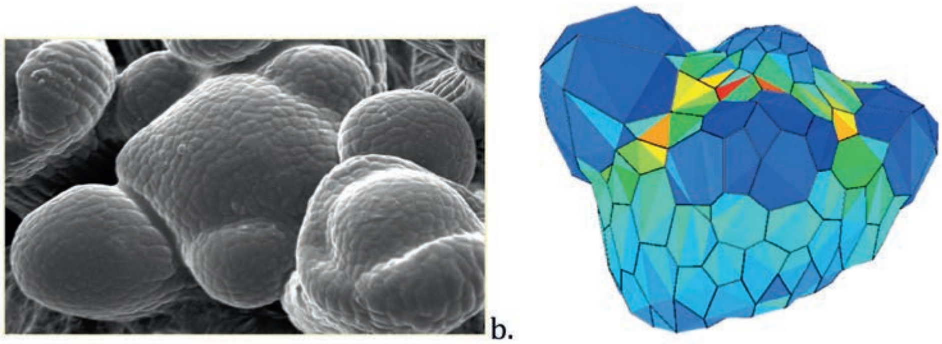
• The deformation of a material object implies the presence of mechanical stresses. How are they generated and balanced within plant tissues where each cell can be seen as an autonomous mechanical effector connected to its neighbours?

• Many varied signals are emitted and received by cells in a tissue context (diffuse molecular fields, mechanical constraints and contact interactions). How does their integration lead to consistent morphomechanical behaviour?

• Finally, how can these dynamics be shaped by external factors?

To address these questions, the Virtual Plants (INRIA) team, in collaboration with the *Laboratoire de Reproduction et Développement des Plantes* at the *École normale supérieure de Lyon*, is developing a theoretical approach supported by digital tools and quantitative observation techniques. This approach is implemented to analyse meristem behaviour and perform numerical simulations to test different operating hypotheses. TissueLab—a numerical platform for simulation and analysis of plant tissue morphogenesis—enables integration, testing, simulation and consolidation of all models and tools developed for this purpose.

Contact: C. Godin (Virtual Plants research team and project), christophe.godin@inria.fr



◀ *a.* Arabidopsis thaliana *apical meristem. The meristem gradually develops organs.*
© Jan Traas

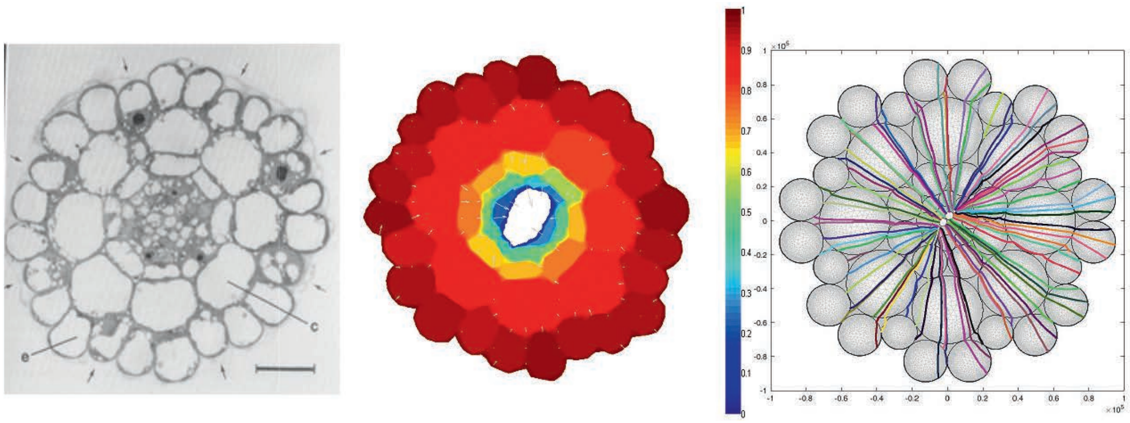
◀ *b. 3D simulation of lateral organ growth (here a numerical lateral view of a young flower).*
From Boudon et al., *2015.* Plos Comp Biol.

Modelling and testing moisture patterns in root tissues

Improving water-use efficiency is a major agricultural challenge to meet the growing nutritional needs of the world population. Understanding how water flows through plants, especially in roots, is a daunting challenge for researchers. We are developing a mathematical model of radial water transport from the soil to the conductive vessels. In a 2D root section, this model (based on partial differential equations solved by the finite elements method) displays the water potential in tissues as well as its preferential pathways (*see figure below*). These results challenge the conventional (and still taught) notion of a series of parallel water routes either through cells or cell walls.

Plant cells are surrounded by a cell wall whose stiffness, together with the water flow, result in the build-up of turgor pressure. This phenomenon is responsible for properties that are crucial for plant life, including verticality and growth in the soil. Conversely, this rigidity poses developmental problems since cells must overcome the volume constraints imposed by the wall in order to be able to expand and divide. Efficient plant development is therefore the result of a subtle interplay between the mechanical properties and the cell water content. In the future, this model will be extended to hydraulic/mechanical coupling in plant cells so as to gain insight into how tissues function under nonstationary environmental conditions or during organ development. Several developments are necessary for this—distinction between the water potential and turgor, mass conservation laws under fluctuating conditions, mechanical energy conservation laws for walls, force/deformation interactions, etc. Resolution techniques must also be adapted to deal with the multiscale and multiphysical aspects of this scientific question.

Contacts: D. Felbacq (UMR L2C), didier.felbacq@umontpellier.fr, Y. Boursiac (UMR B&PMP), yann.boursiac@inra.fr



▲ *Water in* Arabidopsis *roots. Left: radial root section viewed by light microscopy. Middle: water potential in root tissues. Right: water pathways in stationary conditions. © D. Felbacq & Y. Boursiac.*

Probabilistic models and statistical inference methods – identification of developmental patterns in plant phenotyping data

Recent advances in agronomy are a spinoff of the genomic revolution combined with technological advances that enable the acquisition of novel plant phenotyping data at various scales. New approaches are needed to characterize plant developmental processes from tissue to whole plant scales. Robotized phenotyping platforms produce high-throughput spatiotemporal plant development data and enable studies on the effects of environmental and genetic factors on plant development in a renewed context. Plant phenotyping data analysis methods are changing rapidly due to the availability of low cost big data, increased computing power and the emergence of new mathematical paradigms at the crossroads between probabilistic modelling, statistical inference and pattern recognition. Phenotyping data are intrinsically structured (spatiotemporal, multiscale), thus necessitating the development of dedicated probabilistic models and inference methods for their analysis.

This new paradigm for analysing such data is characterized by:

• Data structured in sequences, time series, tree structures, graphs, 2D and 3D images.

• Integrative models that combine response, explanatory and latent variables to model structures at different scales (e.g. development stages or growth phases). Complex dependencies between these variables, often indexed by a time series or tree structure, can be represented by probabilistic graphical models.

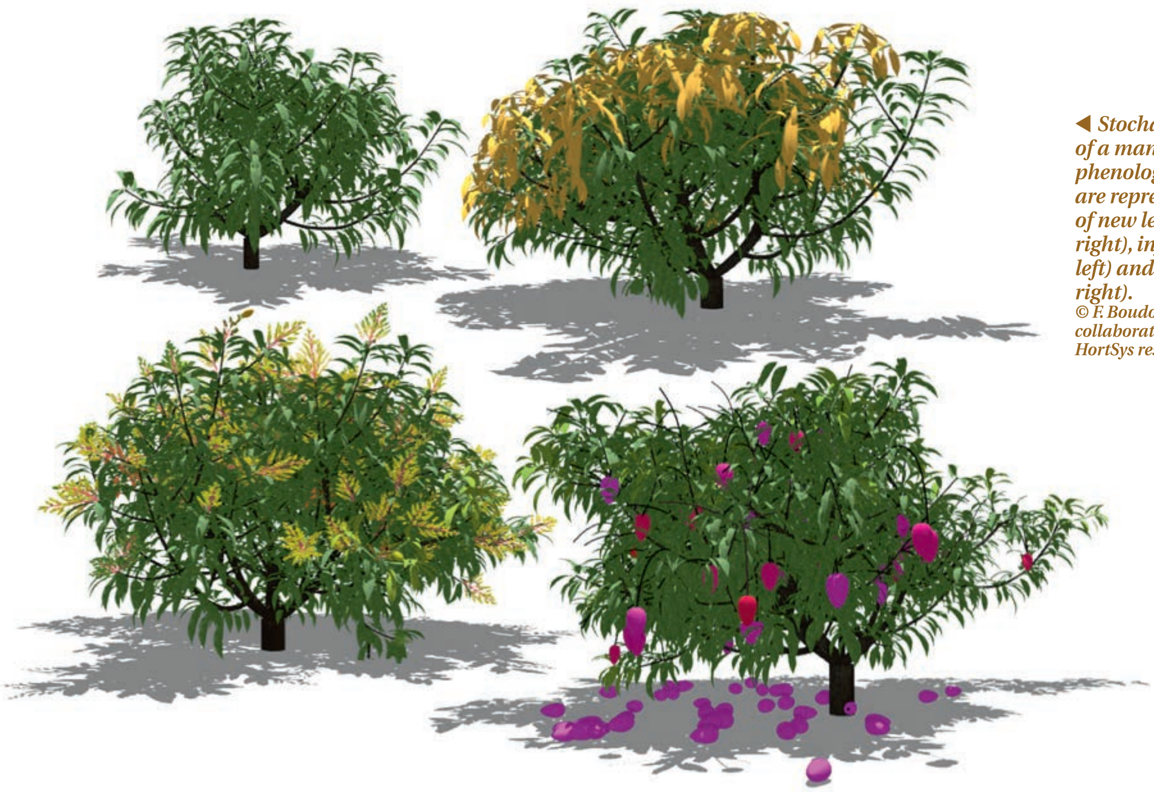
• An extended inference framework concerning not only parameter estimation but also model structure (using model selection techniques) and latent structures (e.g. segmentation into development stages or growth phases).

Contact: Y. Guédon (UMR AGAP), yann.guedon@cirad.fr

Plant structure-function models

Greater insight into how plants function and develop is needed to address societal calls for more ecological and sustainable agriculture in a global climate change setting. To this end, an approach that explicitly takes the plant structure into account to simulate the complex interactions with processes that govern plant growth has been developed in recent years—the so-called functional structural plant model (FSPM). This transdisciplinary approach at the crossroads between biology, computer science and physics is designed to incorporate plant morphology and function knowledge in the form of a dynamic 3D model. It can be utilised particularly to study the role of plant structure on different ecophysiological processes such as light interception or disease proliferation with regard to above-ground parts, as well as root/soil relationships. It therefore requires assembling the various disparate tools and models developed by the scientific community, e.g. using methods proposed by the OpenAlea platform. The Virtual Plants team (INRIA/CIRAD) is involved in the development of many tools for simulating growth and different ecophysiological processes, including mechanical ones, light capture, carbon allocation, etc. The team is also involved in the development of a number of tools for the simulation of growth and various ecophysiological processes. Moreover, it develops or collaborates in the construction of different FSPM models, representing above-ground or underground parts, and ranging from herbaceous crops (wheat, maize, sorghum) to fruit trees (mango, apple). The ongoing challenges related to these issues are to facilitate online use of these complex tools for web-distributed simulations, as well as the standardization of a number of tools for simulating ecophysiological processes. From an application perspective, future challenges include the integration of these models at different scales into crop models so as to take both genetic variability and spatial heterogeneity of simulated populations into account.

Contact: F. Boudon (UMR AGAP/Virtual Plants team-project), frederic.boudon@cirad.fr



◀ Stochastic simulation of a mango tree. Different phenological stages of growth are represented with the onset of new leafy shoots (upper right), inflorescences (lower left) and fruit growth (lower right).
© F. Boudon/CIRAD/INRIA in collaboration with the CIRAD HortSys research unit.

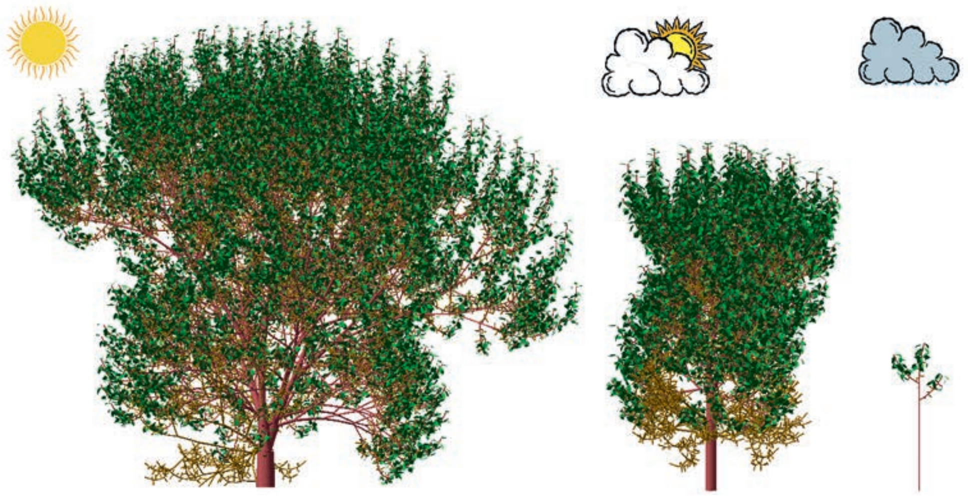
Plant growth modelling and simulation – a complex dynamic system

The structure of a plant results from a genetically determined deployment scheme whose expression is influenced by environmental conditions. It involves a dual mechanism linking development—or organogenesis, i.e. the development of new organs via terminal meristems, and growth, involving the expansion of the organs until they reach maturity. The so-called 'structural' development models provide realistic representations of plants, but do not quantify biomass, while crop models link photosynthesis produced via the leaf surface to resources (water, light), where biomass is distributed in the plant compartments in proportion to their requirements. These models generate good predictions for crops under stable environmental conditions. Structure-function models couple development and growth in a dynamic system via more or less complicated simulators.

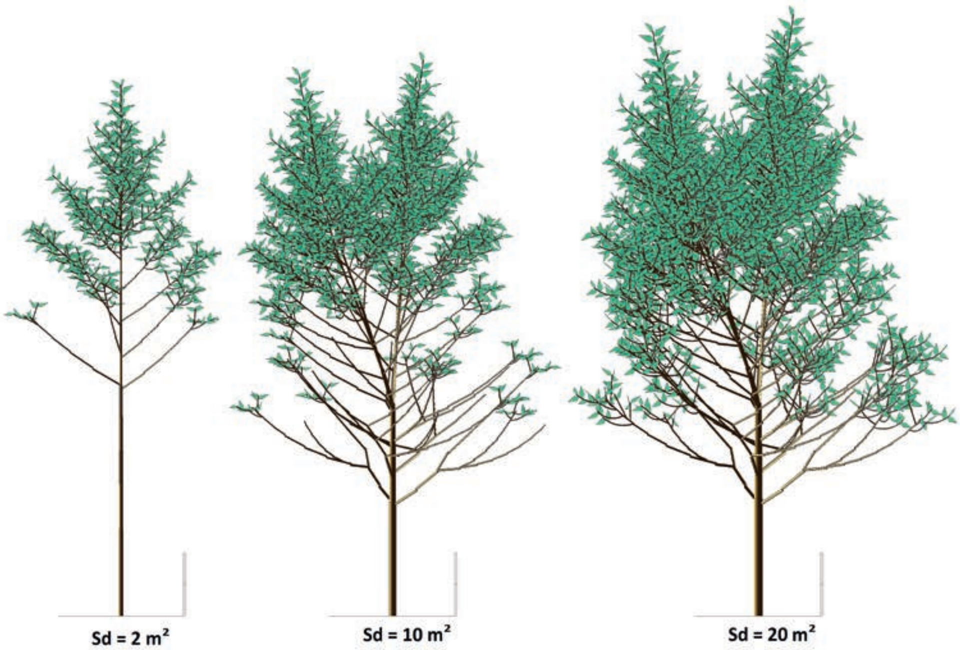
By the GreenLab approach, organogenesis is considered as stochastic, defined by laws of probabilistic functioning of meristems (growth, branching and mortality) as inferred from field observations. New sets of organs are generated with each growth cycle. The growth model is then applied—it is calculated for each set of organs according to the plant's demand and available resources. The supply/demand ratio is seen as a pressure exerted on meristems and organs by the available biomass supply, while directly affecting their functioning. By impacting the laws of probability, this ratio allows for feedback on meristem functioning and hence on the plant's architectural development. This choice, derived from the model equations, is in keeping with many plant observations: on trees, the architectures show great plasticity depending on environmental conditions; simulations illustrate known emergent properties of complex systems, such as the occurrence of pseudo-rhythmic phenomena during fruiting in some agronomic plants or the development of main branches on mature trees.

Contacts: M. Jaeger, marc.jaeger@cirad.fr and P. De Reffye, ph.dereffye@gmail.com (UMR AMAP)

For further information: http://greenlab.cirad.fr/GLUVED
www.quae.com/fr/r5053-architecture-et-croissance-des-plantes.html
https://interstices.info/jcms/c_38032/une-histoire-de-la-modelisation-des-plantes



◀ *A GreenLab model simulation of the effect of light on growth-development feedback, illustrating architectural plasticity in the same 15 year-old tree. The synthesized biomass is proportional to the radiation. Its increase boosts the supply/demand ratio value, which in turn directly affects the development intensity.* From *Mathieu* et al., *2009.* Annals of Botany. *103(8): 1173-1186.*



▲ *A GreenLab model simulation of the effect of the density on the development and architecture by growth-development feedback, illustrating the architectural plasticity. The available production area (Sd) declines as the density increases. This surface limits the production per tree and therefore the supply/demand ratio, which by feedback reduces the branching intensity and shortens the life span of the branches.* From *Hua* et al., *2011.* CASE. IEEE. *4: 185-188.*

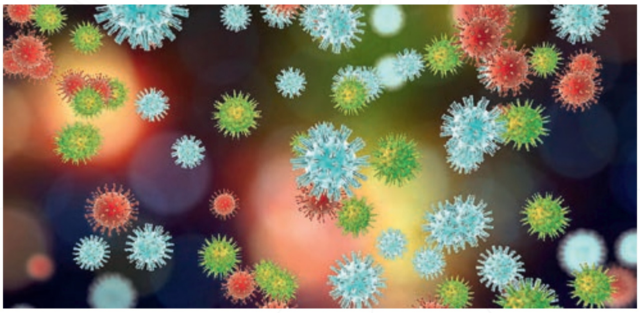
Computational Biology Institute (IBC) – development of innovative biological system research methods

Since 2012, IBC has been designing innovative bioinformatics methods to analyse, query or visualize numerical data on biological systems. These algorithms and methods contribute to the range of tools needed to conduct research projects that are based to an increasing extent on high volumes of numerical data, e.g. genomic sequences, images and biochemical structures. Several IBC research fields are involved in applying these methods for the analysis of complex systems, as illustrated by the two following examples.

In an individual infected by a single RNA virus, several haplotypes of the same virus emerge, coexist and evolve. Their genomes gradually accumulate mutations that differentiate them and enable some of the haplotypes to resist the organism's immune system or treatment. The haplotype composition and the mutations they bear influence the evolutionary dynamics as well as the disease progression, while some haplotypes bearing deleterious mutations may persist through genetic hitchhiking phenomena or via interactions between quasi-species. To be able to monitor these dynamics in terms of the virus composition during infection using high-throughput sequencing, we have designed a *de novo* genome assembly algorithm that simultaneously reconstructs the genomes of the haplotypes present and estimates their relative frequency in the sequenced sample.

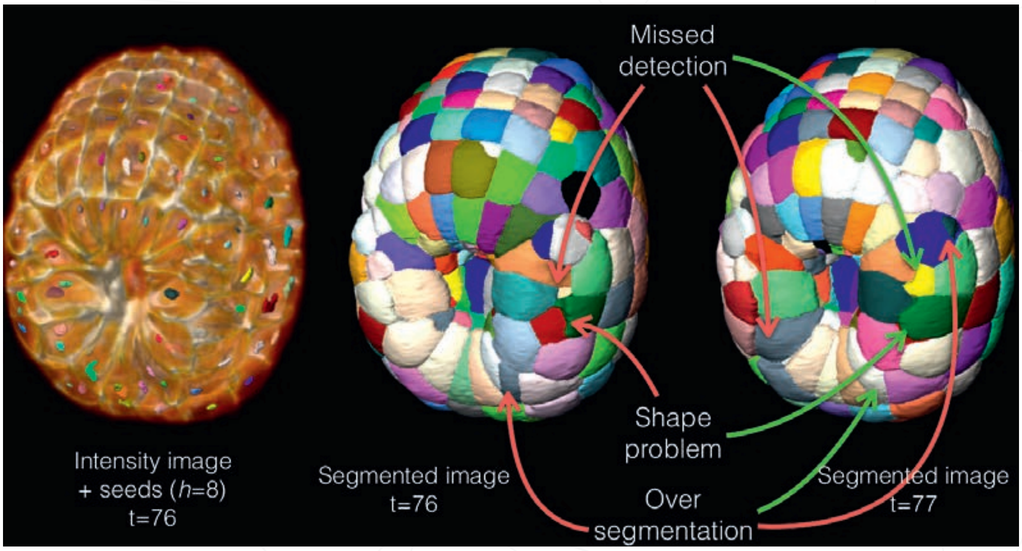
IBC has also developed a meristem modelling system for monitoring cell lines in all three spatial dimensions during plant development. This tool—fuelled by high-resolution microscopy images—segments these images to facilitate identification of each cell membrane, thereafter computing the cell line links between successive images over time. Researchers can view and monitor the relative positions of meristem cells over time—their gene expression profile and interactions affect their position within the meristem.

Institut de biologie computationnelle



▲ *Artist's image of a multitude of viruses.* © MASTERFILE

Contact: E. Rivals, rivals@lirmm.fr
For further information: www.ibc-montpellier.fr



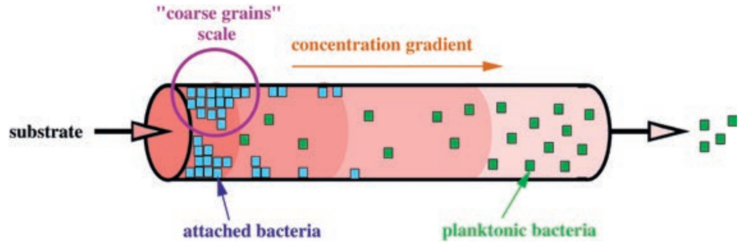
▲ *Segmentation of images into cells.* © Léo Guignard

Population dynamics

Bacterial biofilms – towards 'hybrid' modelling

Biofilms—which are found in many natural ecosystems—are assemblies of bacteria and their secreted adherent matrix. They consist of billions of microorganisms belonging to hundreds or even thousands of species, and can form various 3D structures. A biofilm is generally a complex system, i.e. composed of a very high number of individuals whose interactions depend on the spatial structure of the biofilm and the bacterial diversity. Biofilms contribute to the functioning of recent water treatment systems by improving the bacterial treatment efficiency in bioreactors. Functional biofilm models must encompass both biodiversity and spatial structure, while including realistic assumptions about the interplay between bacteria and the polymer matrix they produce. An effective macroscopic description is therefore insufficient. The models commonly used are stochastic and individual-based, i.e. each bacterium is simulated with its plethora of behaviours, which can become very time-consuming for large populations. We propose to generate reduced versions of these individual-based models through homogenization and approximations of the first moments, in order to acquire the most statistically robust properties of these computational models in terms of more synthetic mathematical models. The consideration of hybrid, stochastic or deterministic multiscale dynamics according to population size has yielded striking and generic results: a study of 'macroscopic' models obtained by scaling from pure jump models at the microscopic level has revealed areas in the state space that are sensitive to the population size. A major finding is that more individuals than expected occur within the size range of 'small populations', for which stochastic terms cannot be neglected.

Contacts: A. Lesne (UMR LPTMC), lesne@lptmc.jussieu.fr, F. Campillo (INRIA), fabien.campillo@inria.fr, A. Rapaport (UMR MISTEA), alain.rapaport@inra.fr
For further information: research carried out as part of the ANR DISCO project, https://sites.google.com/site/anrdisco

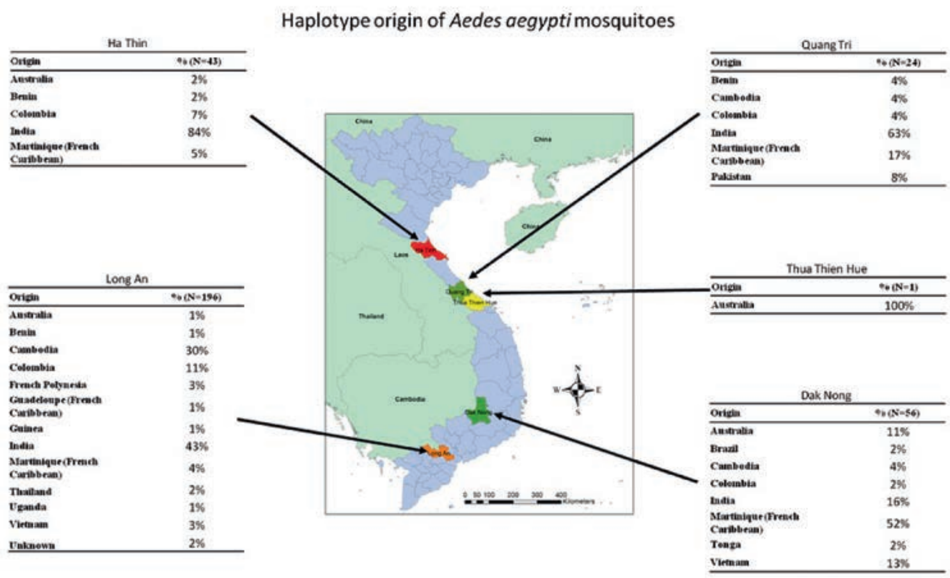


▲ *Diagram of a piston-type bioreactor.*
From Deygout et al. Ecological Modelling. *250:15 (2013).*

Eco-evolutive parameters of communicable disease emergence

The emergence or re-emergence of communicable diseases in a species or population is the outcome of increasingly complex and understood processes. However, despite theoretical advances, models fail to pre-empt these outbreaks. Data must be integrated at different biological (gene, genome, population, metapopulation), spatial (local, regional and global) and temporal (short- and long-term) scales when studying disease outbreaks. ISEM and its partners* are investigating the epidemic and evolutionary dynamics of different pathogens in host populations in an effort to get a clearer understanding and prevent the emergence of new pathogens and epidemic outbreaks. ISEM works mainly on so-called vectorial diseases (transmitted by blood-sucking arthropods). The multidisciplinary and interdisciplinary approach used is based on renowned expertise in parasite ecology, evolution and coevolution, public and veterinary health, analysis of complex biological data, etc. The dengue fever pathogen, for instance, although pivotal, is not the main determinant of the onset and maintenance of outbreaks. The vector mosquito species present in a given geographical area (mainly *Aedes aegypti* and *A. albopictus*, the Asian tiger mosquito) are equally important. Beyond the species, different lines of each species may have different disease transmission capacities (vectorial capacity) and thus influence the disease dynamics. An analysis of vector lines carried out in Vietnam between 2012 and 2014 (see *figure below*) revealed that: (i) the main vector species vary in different geographical areas, (ii) virus-carrying lines are systematically lines that have already been detected in other geographical areas (Africa, Oceania, South America or even Europe) and (iii) the total population density of a mosquito species is not a major contributory factor in outbreaks.

Contacts: L. Gavotte, laurent.gavotte@umontpellier.fr and C. Moulia, catherine.moulia@umontpellier.fr (UMR ISEM)



* CIRAD, INRIA, Universities of Barcelona and Warsaw, Gadjah Mada University and the National Institute of Health Research and Development (Indonesia), National Institute of Hygiene Epidemiology (Vietnam), *Universiti Putra Malaysia* (Malaysia), Mahidol University (Thailand).

◀ *Distribution of haplotypes of* A. aegypti *mosquito populations in Vietnam.*
© Laurent Gavotte

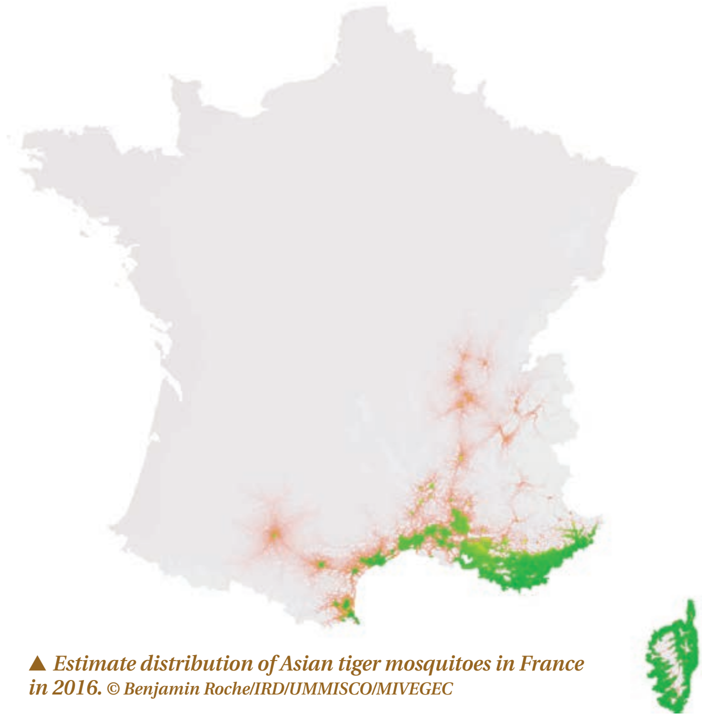
Modelling the invasion dynamics of the Asian tiger mosquito (*Aedes albopictus*) in the South of France

A new invader has been on the scene in the South of France since 2004. The Asian tiger mosquito was first detected at the French/Italian border, but has since spread throughout the entire Mediterranean region. This biological invasion is not only a nuisance due to the aggressiveness of this mosquito, it is also a potential public health bomb because of the species' virus transmission potential (e.g. chikungunya, dengue and Zika). To tackle this threat, a partnership was forged between the French *Direction Générale de la Santé*, the *Centre National d'Expertise des Vecteurs*, the regional agencies for mosquito control (EID-Méditerranée, EID-Rhône Alpes) and the MIVEGEC joint research unit (UMR) to develop a modelling framework for predicting the spread of this mosquito into mainland France. Based on national mosquito surveillance data from more than 1,300 traps provided by EID, statistical models were developed to understand the contribution of different environmental (e.g. land use, temperature, rainfall) and human (especially mobility and traffic) factors to the spread of this exotic mosquito.

The model highlighted that the dispersion of the mosquito in France was a dynamic process, with ongoing northward and westward expansion on mainland France, towards areas that are now colonized. It also demonstrated the incidental role of human transportation systems in the invasion process, by revealing a close correlation with the road network. Finally, this statistical analysis showed that the invasion process is accelerating over time, suggesting a rapid potential upsurge of mosquitoes in most major urban areas, which appear to be the preferred environment for installation of these pests. This sophisticated statistical modelling has enabled authorities to pre-empt the arrival of Asian tiger mosquitoes in areas that were not initially prepared to cope with this new health concern.

Contacts: B. Roche (UMR MIVEGEC/UMMISCO), benjamin.roche@ird.fr, F. Simard (UMR MIVEGEC), frederic.simard@ird.fr

▲ *An Asian tiger mosquito,* Aedes albopictus. *© Nil Rahola/IRD/MIVEGEC*



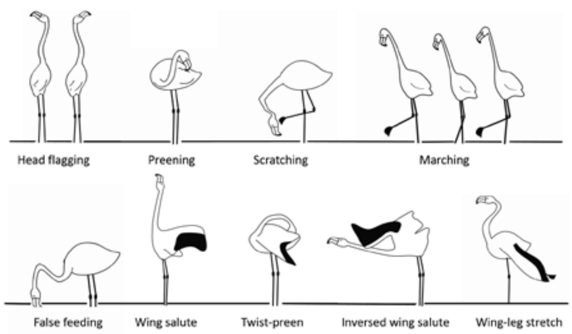
▲ *Estimate distribution of Asian tiger mosquitoes in France in 2016. © Benjamin Roche/IRD/UMMISCO/MIVEGEC*

Behaviour explains demographic patterns

Populations of evolved animal species are composed of individuals with different traits. Some may be easily identifiable, e.g. age and gender, whereas others resulting from complex genome-environment interactions may be harder to decipher. Behaviour is one of the most advanced traits. Because of its particular behavioural patterns, each individual will have specific interactions with the environment and congeners, and this behaviour will determine its demographic performance (survival, reproduction) and ultimately its selective value. However, conventional demographic studies treat individuals as being substantially the same within broad categories. On the other hand, behavioural science, i.e. ecoethology, tends to focus on short-term studies, so the impacts of the findings cannot be readily projected in demographic terms.

A recent study on Greater flamingo courtship displays revealed the crucial importance of reconciling behaviour and demographics. The complexity of the display facilitates breeding access in this species. Older birds generally have less complex displays than middle-aged birds and are therefore under-represented among breeders. However, if they manage to mate, the likelihood that they will be able to successfully rear their only chick until it is fully fledged is the same. Thus, reproductive senescence cannot be detected by just monitoring breeders in this species, despite the reality of this phenomenon. In other studies, more advanced integration of behaviour and demographics is done at the analysis level. It has in this way been found that a great tit—which is faithful to its mate of the previous year—has a much higher survival rate and also a greater chance of finding the same mate the following year, thus enhancing the pair bond while enhancing their survival. This type of combined study is very likely to become more common in future.

Contacts: R. Pradel, roger.pradel@cefe.cnrs.fr and R. Choquet (UMR CEFE), remi.choquet@cefe.cnrs.fr, A. Béchet (Tour du Valat), bechet@tourduvalat.org
For further information:
http://old.tourduvalat.org/en/actualites/publications/article_sexual_display_complexity_varies_non_linearly_age_and_predicts
https://anticaculina.wordpress.com/my-work-as-evolutionary-biologist-andzoologist/biology-pair-fidelity-and-divorce-in-monogamous-birds



▲ *Greater flamingo (*Phoenicopterus roseus*) postures.*

Environment-health – multiscale modelling of epidemiological systems

To gain insight into, model and predict the behaviour of ecoepidemiological systems associated with vector-borne diseases it is essential to consider the vectors, pathogens, reservoirs and human hosts of these pathogens, as well as interactions between these elements at different spatiotemporal scales. Multiple factors (genetic, sociodemographic, environmental, etc.) influence the properties of these elements and their interactions.

The ESPACE-DEV joint research unit (UMR) and its partners* use an interdisciplinary approach to study environment-health relationships (human vector-borne diseases in intertropical environments). The scaling concept is pivotal to the methodological considerations and is addressed in a range of ways, for example:

• Spatial distributions of Chagas disease vectors in a Brazilian area and malaria incidence rates in a village in French Guiana are studied via principal coordinate decomposition of weighted neighbourhood matrices. Advanced factor analysis methods are used to identify environmental and sociodemographic factors that could explain the spatial components and their relative importance according to the analytical scales and areas considered.

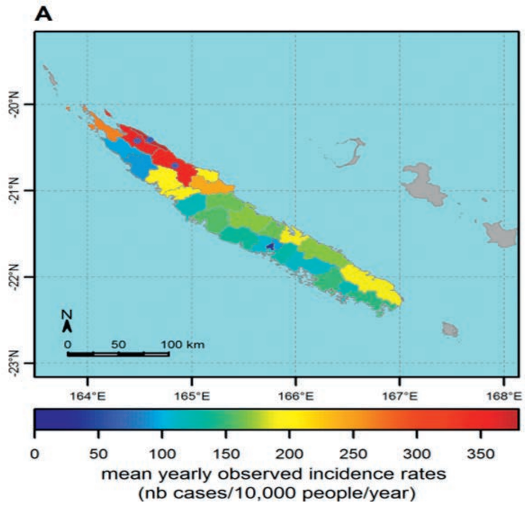
• Modelling of the spatial distribution of dengue fever at regional (South Pacific), territorial (municipalities, New Caledonia) and local (district, Nouméa) levels has demonstrated the benefits of a multiscale approach (see *Fig. 1 opposite*).

• In Réunion, spatialization of a key parameter of an *Aedes albopictus* (a dengue and chikungunya disease vector) population density prediction model makes it possible to link the outbreak hotspot scale with that of the entire island. This spatialization is based on a land-use map derived from satellite data and on mechanistic and statistical modelling (see *Fig. 2 below*).

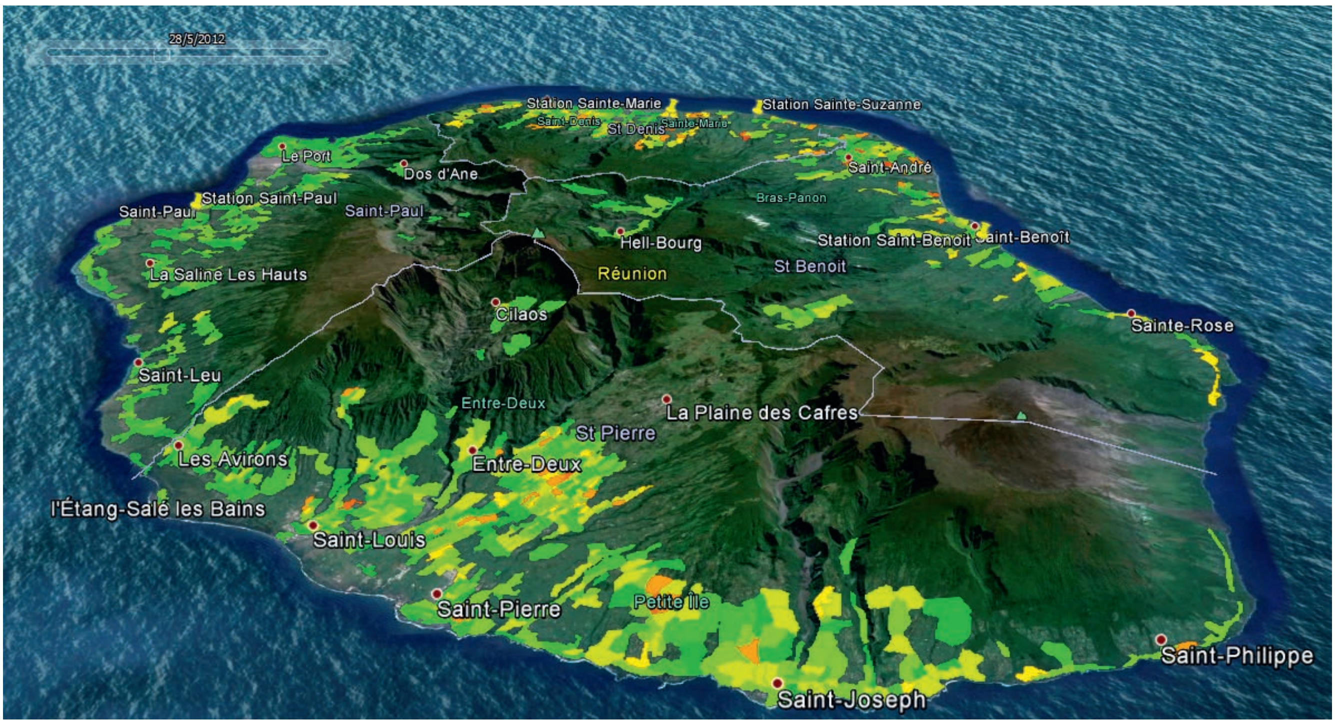
• In Indonesia, the main factors influencing chikugunya dissemination dynamics were taken into account to build a multiagent model that can be used to develop scenarios for health stakeholders. This research contributes to the development of tools for planning epidemic prevention and vector control activities at different scales.

Contacts: E. Roux, emmanuel.roux@ird.fr, M. Mangeas, morgan.mangeas@ird.fr and V. Herbreteau, vincent.herbreteau@ird.fr (UMR ESPACE-DEV)
Collaborators: N. Dessay, M. Fargette and T. Libourel (UMR ESPACE-DEV)

***Partners**:
Réunion studies: CIRAD/AGIRs, ARS-Réunion, Marie Demarchi consultant office, *Univ. Réunion*
French Guiana studies: UnB/CDS (Brazil), *Univ. Paris Descartes*, UM, UG/EpaT
New Caledonia studies: DASS-NC, SIPRES *Mairie de Nouméa, Institut Pasteur NC*
Indonesian study: UM, Center for Tropical Medicine, Faculty of Medicine, Gadjah Mada University, Sukoharjo Regency Health Center, Center of Java.



▲ *Figure 1. Spatial distribution of the dengue disease incidence in New Caledonia.*



▲ *Figure 2. Spatial distribution of* **Aedes albopictus** *population densities in Réunion.*

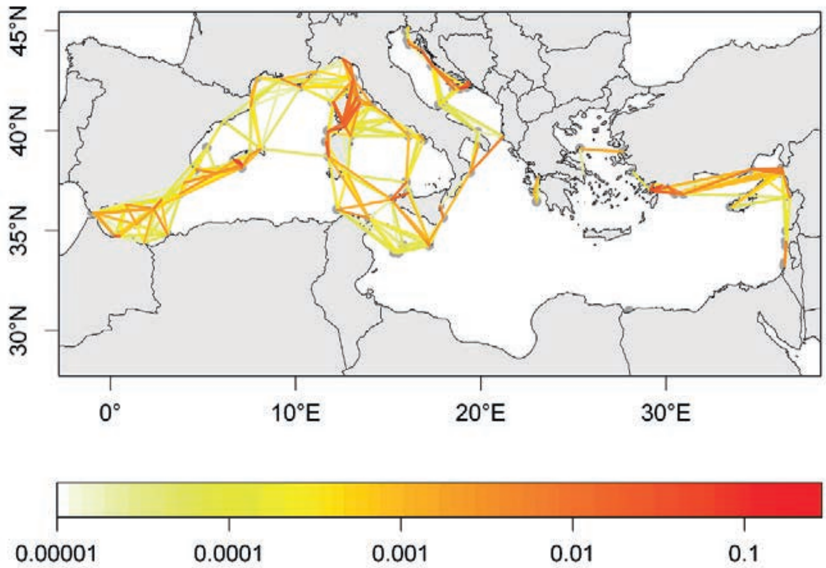
Connectivity of marine populations – individual-based modelling of grouper larval exchanges within a Mediterranean network of marine protected areas

Marine ecosystems are threatened by several factors related to human activities, including fishing, pollution, habitat degradation and climate change. One of the solutions proposed to address these threats is the development of spatialized resource management systems such as marine protected area (MPA) networks. There must be exchanges of individuals between the different MPAs if these systems are to function effectively as networks. For marine species with a sedentary adult phase, these exchanges can take place during the larval dispersal phase via marine currents. Larval dispersal is a complex process as it is determined by the many factors involved that interact at multiple spatiotemporal scales*. Dispersal of dusky grouper (*Epinephelus marginatus*) larvae within the Mediterranean MPA network was studied as part of the FishConnect project (2011-2014) funded by the Foundation for Research on Biodiversity (FRB) and the Total Foundation. We applied the individual-based Ichthyop model and found that—in the light of the mean dispersal distance of grouper larvae (120 km) and the low overall connectivity between neighbouring MPAs in the Mediterranean—this network is inefficient and fragile. The model also revealed that, under the present water warming trend, larvae will likely grow more quickly with a shorter dispersal period in the near future.

* Pineda *et al*., 2009. *Population Ecology*. 51: 17–32.

Contacts: M. Andrello (UMR CEFE), marco.andrello@gmail.com,
D. Kaplan (UMR MARBEC), david.kaplan@ird.fr,
C. Lett (UMI UMMISCO), christophe.lett@ird.fr,
S. Manel (UMR CEFE), stephanie.manel@cefe.cnrs.fr,
D. Mouillot (UMR MARBEC), david.mouillot@univ-montp2.fr

For further information:
FishConnect project: https://sites.google.com/site/projetfishconnect
Ichthyop model: www.ichthyop.org



▶ *Simulated probabilities of the connectivity (coloured segments) between Mediterranean marine protected areas (grey circles) for dusky grouper larvae. From Andrello* et al., *2013. PLoS ONE. 8. e68564. doi:10.1371/journal.pone.0068564*

Uncertainties and fisheries management – a case study on bluefin tuna

Overfishing of Atlantic and Mediterranean bluefin tuna resources has long been considered an archetypical example of overfishing and mismanagement by international agencies and national administrations. This crisis has highlighted how the uncertainties inherent to any scientific assessment can be exploited by different pressure groups to discredit the scientific advice to the detriment of economic interests. Scientific assessments are always subject to uncertainties related to: (i) our limited knowledge of the main factors controlling population dynamics, and (ii) natural variations in the environments affecting them, either directly (through mortality, growth, migration) or indirectly (through prey availability). For marine species, this situation is further complicated by the difficulty and cost of sampling, which greatly restricts monitoring capabilities. However, this crisis ended in 2009 after more than 15 years of conflict between fisheries operators, administrations, scientists and civil society, when the International Commission for the Conservation of Atlantic Tunas*, under pressure from non-governmental organizations and with rising public awareness on the issue, approved the scientific recommendations. After two decades of decline, Atlantic and Mediterranean bluefin tuna stocks have rebounded, thereby demonstrating that international fisheries management is possible when bolstered by a strong political will. However, due to the uncertainties of scientific assessments, it is not possible to accurately quantify the rate of this replenishment of tuna stocks. As some of these uncertainties are intrinsic to the fish populations, the new challenge for the scientific community is therefore to develop management models that could generate recommendations that are robust to uncertainties.

Contact: J.-M. Fromentin (UMR MARBEC), jean.marc.fromentin@ifremer.fr

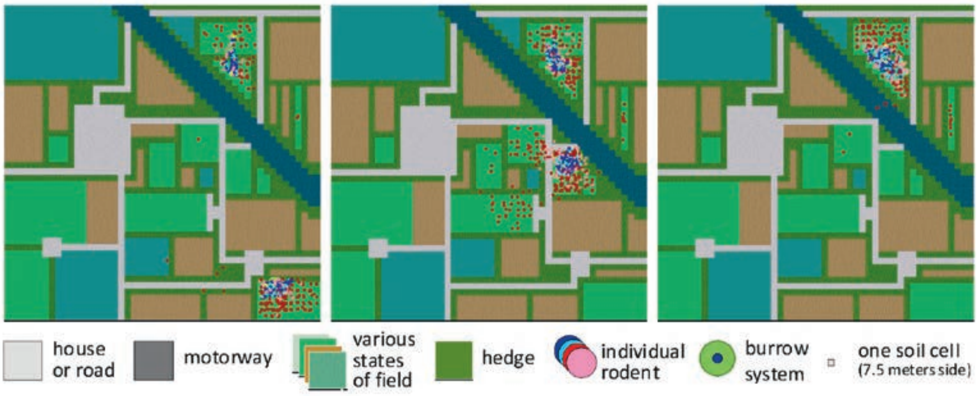
* www.iccat.int

◀ *Bluefin tuna being transferred from a fishing boat to a floating cage where the fish will be fattened for several months. © IFREMER*

Development of 'mechanically-rich' models to assess the complexity of population-environment relationships

Wild rodent management in agricultural areas requires a good overall understanding of how these populations function. Geographical, ecological, biological and ethological, etc., studies all highlight explanatory factors that differ from the legitimate observed dynamics. Simulation studies on the joint and simultaneous effects of these determinants and their interdependence may provide some insight on how these populations function. The so-called mechanically-rich modelling approach (DeAngelis and Mooij, 2003) is designed to assess such systems. This approach uses individual-centric simulators to integrate the most significant elements of known processes. The figure below shows an example of the results obtained using this type of model for studying vole populations in a heterogeneous agricultural landscape. Seasonal and sexual behaviour, genetic transmission between simulated individuals, different crop management sequences and rotations were all taken into account. Each agent is semi-autonomous and lives its lifecycle, in addition to various activities, according to its physiological status, other agents with which it interacts and landscape changes. Simulators—by accounting for this complexity—can highlight the importance of unique factors related to the complexity of the represented nature, such as sensitivity to the evolution of interactions over time (see *figure below*).

Contact: J. Le Fur (CBGP), lefur@ird.fr
For further information: DeAngelis D.L., Mooij W.M., 2003. In praise of mechanistically rich models. In: Canham, C.D., Cole, J.J., Lauenroth, W.K. (Eds.), Models in Ecosystem Science. Princeton University Press, Princeton, New Jersey, pp. 63–82

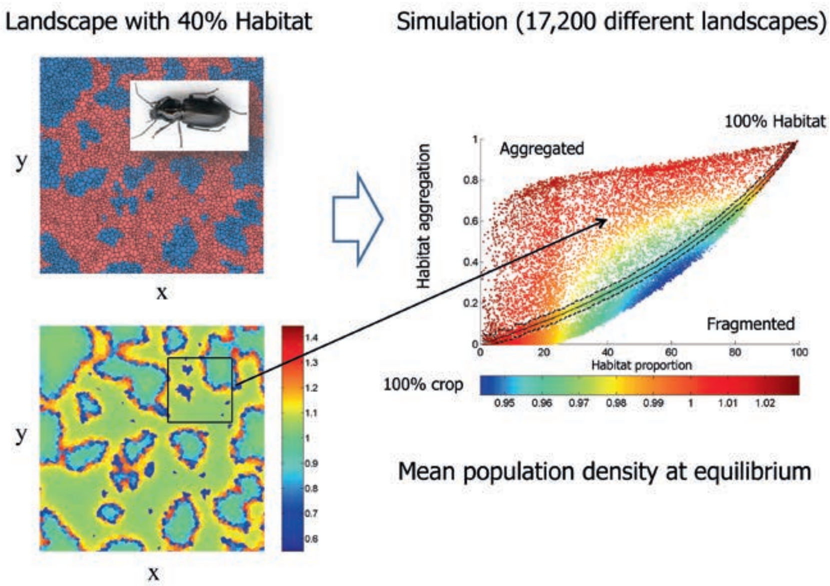


◄ *Results of daily time step simulations over a 5-year period of a common vole (*Microtus arvalis*) population in a dynamic fragmented landscape in Poitou-Charentes region (France). The three maps highlight differences between the rodent distributions obtained (with all other factors remaining unchanged) for three initially centred populations whose sizes (N0) only differed by 1/1,000. Here the simulations highlighted the sensitivity of the modelled system to individual trajectories and the interaction history.*

Regional responses of populations to a complex landscape structure

Currently, it is essential to understand the impact of agricultural landscape management decisions on the populations (heritage, harmful or more common) they support. Hence, we have developed a numerical model inferring population dynamics at the regional scale based on the (generic) behaviours of target species at local and landscape unit levels—in previous studies, this approach has also provided a tool to manage these complex agricultural systems. Specialists on these spatial ecological issues generally separate the landscape compositional properties (i.e. the main attributes of landscape units, generally the land-use proportions) and configurations (i.e. the spatial sizes, shapes and arrangements of the units). These two properties are not independent. It was long assumed that the landscape composition prevailed over and guided the regional dynamics of the hosted populations. This hypothesis was tested here by modelling diverse landscapes with perfectly controlled compositions and configurations, as well as several dynamics of local populations within and between each landscape unit. The challenge was to couple these two models to achieve the upscaling and deduce the regional response of populations. Surprisingly, this model revealed that a population's regional (landscape) response could strongly differ from its fine-scale (unit) dynamics, and could depend as much on the landscape configuration as on its composition. This regional response also largely depends on the scale at which the aggregation of non-linear local dynamics is considered, and this response is even more acute when the aggregation scale is close to that of landscape units. We hope that such coupled models will set a precedent for a better understanding of the complex ecological systems on which we depend.

Contact: C. Gaucherel (UMR AMAP), cedric.gaucherel@cirad.fr
Collaborators: P. Miguet (UMR AMAP/Chizé Centre for Biological Studies [CBEC]), V. Bretagnolle (CBEC)



◄ *Examples of functional responses of modelled populations. Based on a set of simulated landscapes (left), the population dynamics of generic insects are modelled within each landscape unit and within the landscape as a whole. Migrations between these units are taken into account depending on the landscape composition and configuration (here set at 40% and 0.6). The population is unable to completely settle in landscapes (right: low mean densities in cold colours) when they are more fragmented and when they include intermediate proportions of habitats.* © C. Gaucherel/INRA.

Population dynamics in a structured habitat

In ecology, individuals of the same species form populations that can appear and disappear as a result of colonization and extinction events. These events depend on the spatial configuration of the environment favourable for population survival (habitat) and the ability of species to move and settle within the habitat. The colonization-extinction dynamics of a set of populations in a structured habitat is addressed by metapopulation theory. This theory is applied—through non-linear dynamical equations—to study the density and structure of populations at equilibrium. The spatiotemporal behaviour of these equations is still largely unknown, although the practical needs for threatened species conservation, etc., are substantial. A growing body of data on the spatial distribution of species is now available (e.g. from the French National Inventory of Natural Heritage*). In the framework of a PhD thesis, stochastic colonization and extinction dynamics were studied on a set of islands of varying habitat size.

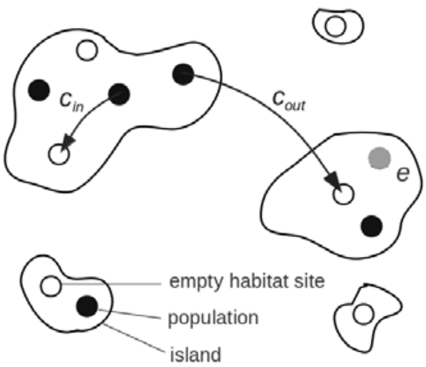
New dynamic effects were identified, including very slow extinction dynamics when the island size distributions were very heterogeneous. This phenomenon is of major practical importance because species that appear to persist in the short term may actually be undergoing very slow extinction dynamics. Two complementary activities will be the focus of future research:

• A study on the impact of temporal fluctuations in habitat quality (periodic variations or isolated catastrophic events) on the probability of colonization and extinction of populations, determining the persistence or extinction of the species.

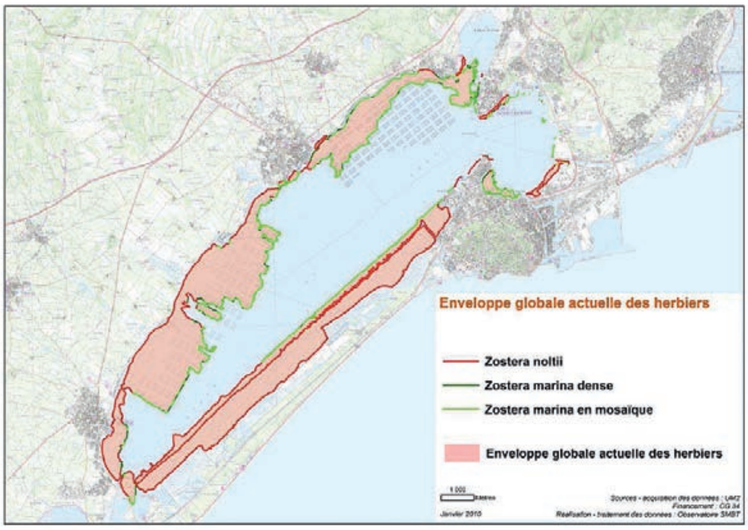
• Development of a method to assess the relevance of model predictions in actual cases by pooling spatiotemporal data—a current case study, i.e. crucial for the French Languedoc coastal zone, concerns eelgrass colonization patterns in lagoons as monitored by satellite imaging.

* National Inventory of Natural Heritage (INPN): https://inpn.mnhn.fr/accueil/presentation-inpn

Contacts: E. Pitard (UMR L2C), estelle.pitard@umontpellier.fr, F. Munoz (UMR AMAP), fmunoz@univ-grenoble-alpes.fr
For further information: http://amap.cirad.fr/fr/th3.php
https://sites.google.com/site/dybresrnsc



◀ *An example of forest habitat fragmentation—from a spatially homogeneous habitat to habitat islands of different sizes. Modelling of a fragmented habitat consisting of islands that are occupied (filled circles) or not (empty circles) by populations of a species. New sites could be colonized (arrows) via colonization within islands (C_{in} rate) or between islands (C_{out} rate), or the populations could disappear (e rate, grey circle). http://forestsforwatersheds.org*
Graphics courtesy of University of Connecticut Center for Land Use Education and Research



▲ *Map of eelgrass colonization patterns in the Thau lagoon (France) based on a field survey (source:* Syndicat Mixte de l'Etang de Thau, *January 2010).*

Impact of socioecological contexts and 'exposomes' on the health dynamics and status of human populations

The holistic approach to human population dynamics is intrinsic to biological anthropology. Human-environment interactions have long been an essential element of research in this field, as illustrated by initiatives such as the Man and the Biosphere Programme (United Nations Educational, Scientific and Cultural Organization [UNESCO]). Human biological variability is considered from two standpoints. The first is the demographic history of populations, including population size, choice of spouse, fertility, migration, bottlenecks associated with wars and diseases, etc., while the second is the adaptation of populations to their socioecological environments and health conditions—a research thrust which combines anthropobiology and epidemiology. At the population level, the dynamics associated with these adaptations can result in population (sub)structuring and/or the emergence of local adaptations. At the individual level, this adaptation to various environmental stresses, which can have a long-term physiological cost (allostatic load), is part of the broader notion of embodiment, which can be defined as, "how we, like any living organism, literally incorporate, biologically, the world in which we live, including our societal and ecological circumstances."* Assessing the impact of environments or exposure on the biological heritage of individuals and populations is currently a major epidemiology and biological anthropology challenge. Complexity analysis tools are essential when the systems studied include different scales (from DNA to metapopulations), the effects of external factors or socioecological environments, spatiotemporal dynamics (in individual or population life history terms), the emergence of biocultural traits (pathological, e.g. cancer and obesity, or not), and additional threshold effects.

Contacts: M. Gibert (UMR AMIS), morgane.gibert@univ-tlse3.fr, M. Kelly-Irving, michelle.kelly@inserm.fr, E. Rial-Sebbag, emmanuelle.rial@univ-tlse3.fr and C. Delpierre (UMR LEASP), cyrille.delpierre@inserm.fr

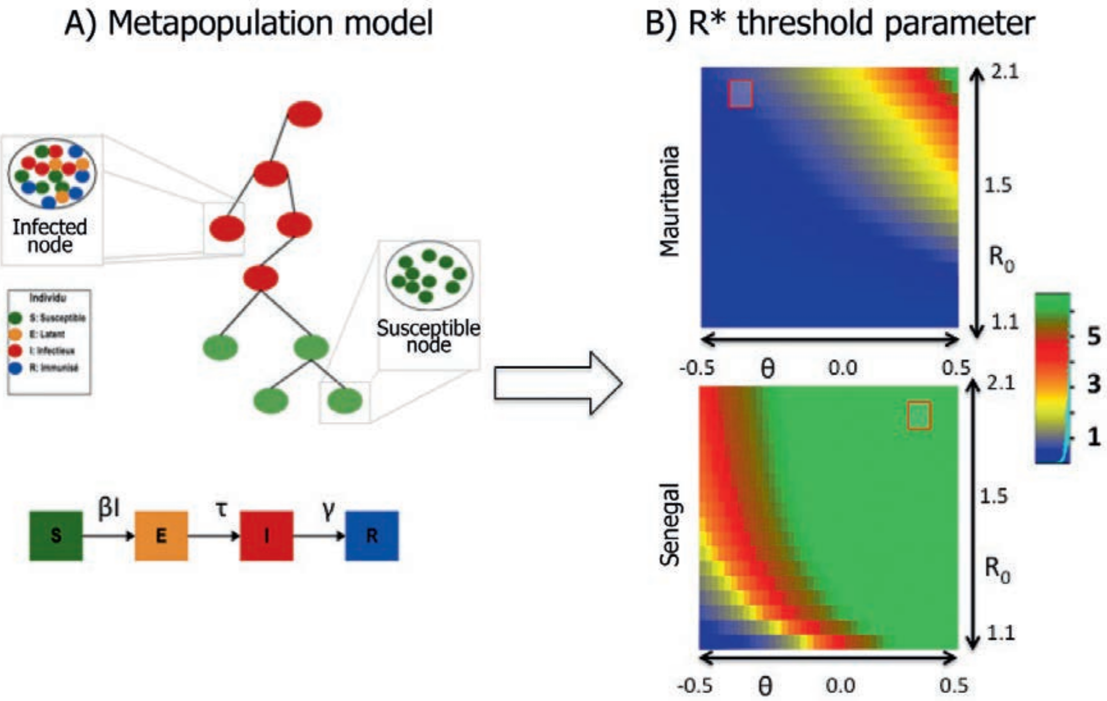
* Krieger N., 2005. Embodiment: a conceptual glossary for epidemiology. *JECH*. 59(5): 350-5.

◀ *Illustration from a Pixabay public domain image released under the Creative Commons CC0. Downloadable at: https://pixabay.com/fr/districtde-sur-arqu%C3%A9-de-lhomme-291098*

Disease mobility and transmission – the case of *peste des petits ruminants* (PPR)

The risk of an epizootic outbreak is closely linked to the frequency of cross-border livestock movements. Mobility has the dual effect of exposing animals to new pathogens, and introducing new pathogens in naive areas. PPR is a transboundary disease affecting small ruminants in West Africa. Depending on the animal age and species, infections may be more or less severe, and mortality can reach 90% in the most severe form of PPR. Metapopulation models provide an effective way to couple the disease transmission (local scale) and herd mobility (global scale) dynamics (see *Fig. A below*). In this type of model, the population is divided into subpopulations that are the nodes of the mobility network and the links represent movements. At the local level, disease transmission is described by a compartment model. The metapopulation model is described by a system of differential equations, one for each epidemiological compartment (Susceptible, Latent, Infectious, Immunized in the case of PPR) of each subpopulation, while taking the probability of transmission and the probabilities of movement in both directions between each pair of localities into account. We thus defined the threshold parameter R* indicating the risk of a pandemic (>1), or not (<1), which depends on the fraction of infected animals moved, the probability of triggering an epidemic at the local level (R0) and the network structure. Mauritania and Senegal have different volumes of traded livestock and mobility networks change around Tabaski. The risk of a PPR pandemic appears to differ in these two countries due to mobility network differences (see *Fig. B*).

Contacts: A. Apolloni, andrea.apolloni@cirad.fr,
C. Coste, caroline.coste@cirad.fr and
R. Lancelot, renaud.lancelot@cirad.fr (UMR ASTRE)



▲ *Diagram of the metapopulation model (A) and estimation of the threshold parameter R* (B).*

(A) Mobility network (top) and local transmission model (below). The compartments correspond to: Susceptible (S), i.e. not yet infected by the virus; Latent (E), i.e. infected but cannot yet transmit the disease; Infectious (I), i.e. able to infect others; and Immunized (R), i.e. already infected but can no longer infect others or be re-infected.

(B) The blue area corresponds to the set of parameters where R<1. Squares indicate areas corresponding to estimates made on the basis of serological and mobility data collected in the two countries. The θ parameter is associated with the network structure and movement distribution.*

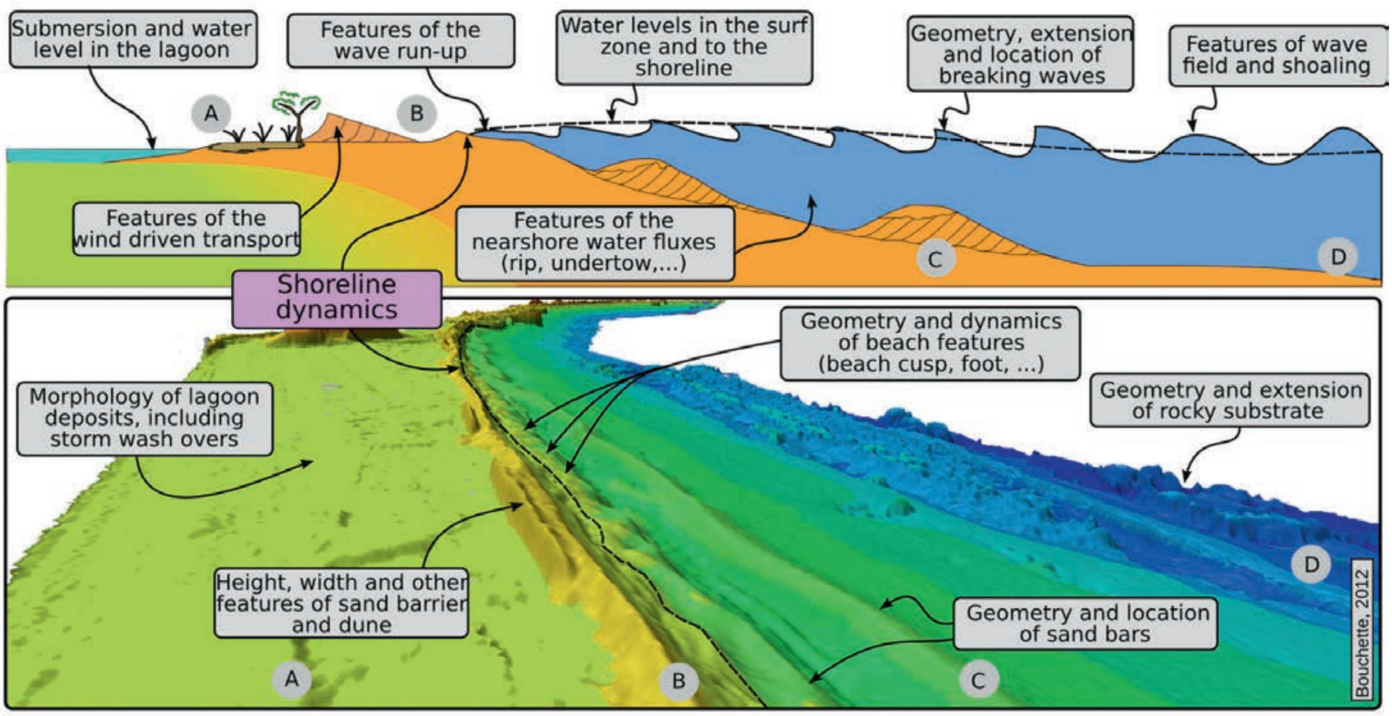
Ecosystem dynamics

Surface-current-wind-bathymetry interactions – prediction of extreme events in coastal regions

Coastal regions are the focus of intense economic activity and places where human settlements, fishing, international trade, several energy sectors and tourism also flourish. Knowledge on wave conditions in these regions is clearly a key factor in the sustainable development of these activities. Very high winds, combined with coastal currents and local bathymetric conditions, can generate particularly strong swells in coastal areas, which can in turn trigger extreme phenomena, with serious economic and human impacts. Therefore it is of paramount importance to understand and model these complex phenomena.

Our research is geared towards designing physico-mathematical models of spatiotemporal coastal swell generation in the presence of currents, high winds and at finite and variable depths, with the ultimate aim of predicting extreme scenarios so as to be able to mitigate their impacts. Theoretical modelling is based on expertise already acquired by the GLADYS* group through its research (GM joint research unit [UMR]). This group, in addition to having a huge wealth of field data that can be used to test the models developed, carries out new experiments required to enhance the models before their industrial application. This project involves a collaboration between the L2C and GM UMRs, the universities of Marseille (*Institut de Recherche sur les Phénomènes Hors Équilibre*) and Toulon (Mediterranean Institute of Oceanography), the Instituto de *Fisica Téorica* (Brazil) and the University of Qom (Iran).

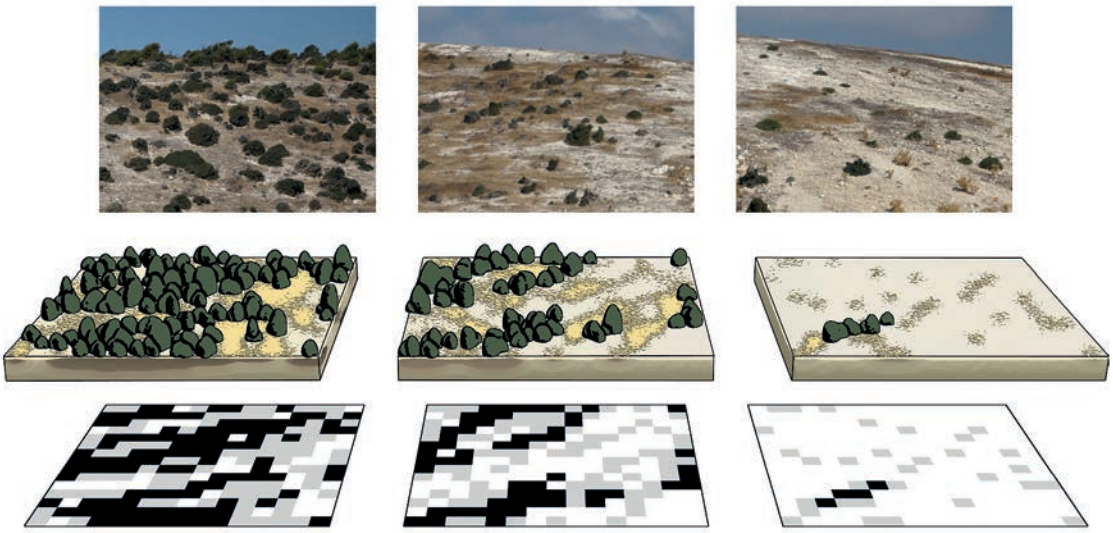
Contacts: M. Manna (UMR L2C), miguel.manna@umontpellier.fr,
F. Bouchette (UMR GM), frederic.bouchette@gmail.com / frederic.bouchette@umontpellier.fr
*** For further information on GLADYS**: www.gladys-littoral.org/en/about



Catastrophic shifts in ecosystems

Predicting ecosystem responses to disturbances is a major challenge in the current global change context. It is therefore essential to identify the mechanisms underlying ecosystem resilience to changes in the environment. Some ecosystems respond in a predictable and gradual way to steady changes in environmental conditions (e.g. climate change), while others respond suddenly, unexpectedly and often irreversibly ('catastrophic shift'). These sudden transitions—with the desertification of dryland ecosystems being a classic example (see *figure below*)—can have dramatic ecological and economic consequences. At ISEM, we are developing mathematical models to study ecological mechanisms that shape ecosystem resilience. In dryland ecosystems, for instance, some plants facilitate the recruitment and growth of other plants under their canopy. This facilitation creates a feedback loop between the ecosystem's biotic and abiotic components, thus increasing the likelihood of catastrophic transitions to desertification. Modelling these mechanisms provides essential information for implementing ecosystem management and restoration strategies. These models also help in identifying degradation indicators that could be used as early warning signals. Does an ecosystem that is nearing an undesirable transition show any distinctive symptoms? We are developing, for example, indicators of Mediterranean ecosystem degradation in the European CASCADE project, in which we design statistical tools to help anticipate any potential irreversible degradation of these ecosystems and loss of the ecosystem services they provide. Our research on ecosystem resilience contributes to improving the overall understanding of ecosystem stability. Our aim is to develop tools to anticipate and manage ecosystem responses to current and future environmental change.

Contact: S. Kéfi (UMR ISEM), sonia.kefi@umontpellier.fr
For further information on the CASCADE project: www.cascadis-project.eu



◀ *Formalization of an arid ecosystem (top) into a cellular automaton (bottom).*
© Florian Schneider

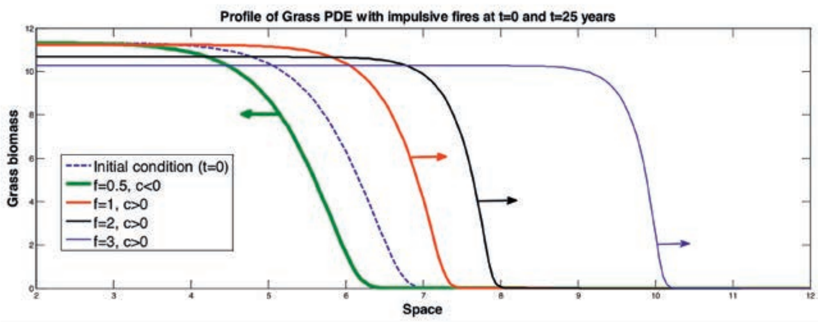
Impulsive modelling of woody-herbaceous species interactions during fires – impacts on forest-savanna dynamics

Savanna biomes are composed of a variety of vegetation features that can be observed along tropical forest-to-desert climate gradients. The underlying dynamics are the result of direct and indirect interactions between woody and herbaceous plants when fires or other disturbances occur. Empirical observations indicate that different and sometimes highly contrasting features can coexist under similar precipitation regimes, suggesting that stable alternative states or very long transitions may prevail. These fascinating issues are the focus of many modelling studies, but none of them have led to an integrated system of predictions of vegetation conditions and their possible transitions in response to climate and human-induced change. To be useful, such a system must be applicable to fractions of continents, including territories without long-term monitoring sites, which is the case throughout most of Africa.

Our research is focused on defining, studying and testing parsimonious models able to capture essential processes, while being limited to a few parameters and enabling a thorough mathematical analysis of expected trends. The savanna system was modelled using a small number of state variables expressing the biomass of the main vegetation components, i.e. grasses, woody plants, while eventually differentiating their fire-susceptible and fire-nonsusceptible fractions. Impulsive differential equations can be used to account for the sporadic nature of fires. Spatial dynamics are accounted for by using diffusion operators and/or nodes that reflect the scope of the facilitating or inhibiting forces of vegetation. This makes it possible to assess the direction in which forest-savanna edges could evolve as a function of forcing parameters, such as the fire frequency (see *figure. below*).

Contacts: P. Couteron, pierre.couteron@ird.fr,
Y. Dumont, yves.dumont@cirad.fr (UMR AMAP)

▲ *A. Variations in vegetation cover in a forest-savanna mosaic (central Cameroon, Google Earth®). Note the fringe of small woody areas around mature forest complexes, indicating a gradual extension of the latter stands.*



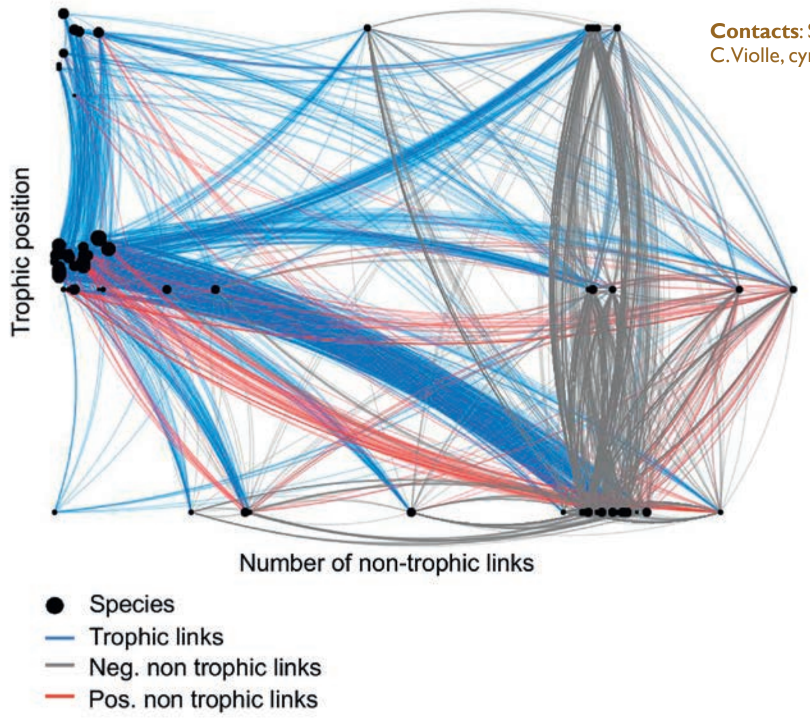
▲ *B. Predictions on the progression or retreat of the herbaceous plant component in the mosaic as a function of the fire frequency (modelled in impulsive form). In subequatorial environments, only a frequency of more than one fire a year seems to be able to curb the current forest expansion trend. From Yatat* et al.*, 2017. Ecological Complexity.*

Ecological community dynamics – from fundamental research to agroecosystem applications

Ecosystem functioning relies on the diverse relationships that link the many resident species to each other. Identifying these interactions and the role they play in ecosystem functioning is critical to improve our understanding, and eventually the accuracy of our predictions, of ecosystem resilience to disturbances, such as climate change and human use of natural resources. Interaction networks, which encompass ecosystem species and their interactions, provide an invaluable conceptual framework and toolbox for describing, visualizing and quantifying the complexity inherent to ecological communities. For example, a study of such networks for all species present in the intertidal zone of central Chile (see *figure below*) helped in assessing the role of trophic and non-trophic interactions in the resilience of these ecosystems.

Community and ecosystem ecology approaches and theories are currently applied to agroecosystems, i.e. systems that are presumably less complex but which are suspected to be functioning like natural ecosystems. Agroecological challenges, particularly related to the sustainability and resilience of agricultural production to climatic hazards, require a new outlook on these man-made ecosystems. Managing interactions between species is becoming essential. Short-term grasslands with a higher experimental diversity of species and varieties, for example, have been shown to have better production and greater resilience, under the assumption that interactions between them play a major regulatory role. New innovative and sustainable agricultural systems can be proposed by strengthening these interaction networks. Simplification of agricultural systems is actually no longer the rule, and their complexity management is increasingly approached from an overall ecological perspective, particularly from an interaction network standpoint.

Contacts: S. Kéfi, sonia.kefi@umontpellier.fr (UMR ISEM), C. Violle, cyrille.violle@cefe.cnrs.fr (UMR CEFE)



◀ ***Network of interactions between 106 species of the central Chilean intertidal area*** *Black circles indicate species, blue links are trophic interactions, grey links are negative non-trophic interactions (e.g. competition and interference) and red links are positive non-trophic interactions (e.g. facilitation). Species are ranked vertically according to their trophic levels (primary producers at the bottom and predators above) and horizontally according to the number of non-trophic links in which they are involved.*
From Kéfi et al.*, 2016.* PLOS Biol. *14, e1002527.*

Coupled modelling of water, energy and vegetation cycles on inland surfaces

Modelling of the biophysical functioning of inland surfaces is a prime tool for monitoring, management and forecasting studies on water resources and plant and agricultural productivity, under climatic and anthropogenic constraints, over a range of timeframes. The many complex processes that drive and interconnect major terrestrial material and energy cycles are taken into account, as they are crucial with respect to the climatic conditions, ecosystems and hydrosystems in a given territory. Existing interdependencies between these processes have prompted their increasingly complete integration into surface functioning models. Drawing on its expertise acquired in West African tropical regions, the TECHS* team of the HSM joint research unit (UMR) is studying water cycle dynamics in these regions and links with those of other major environmental cycles, particularly energy and carbon dynamics. The team is striving to gain insight into energy and mass exchange (H_2O, CO_2) mechanisms within the soil-vegetation-atmosphere continuum, as controlled by the physical and ecophysiological functioning of plant species and soil. The knowledge acquired is then translated for use in physically-based models that span a broad range of spatiotemporal scales from point (plant/tree) to regional and from intraday to interdecadal. Two modelling approaches are preferred, i.e. oriented towards the development of increasingly complete models in terms of processes, and/or towards strategies to couple different types of existing and reference surface models in West Africa. Applications of such tools have made it possible to obtain detailed assessments of hydrological and plant resources in an agropastoral context in the Sahel, as well as projections of the evolution of these resources under the impacts of changing climatic and anthropogenic conditions, while taking socioeconomic contexts into account in the definition of evolution and management scenarios.

Contacts: J. Demarty, jerome.demarty@ird.fr, B. Cappelaere, bernard.cappelaere@ird.fr and C. Peugeot, christophe.peugeot@ird.fr (UMR HSM)

* Eco-hydrosystem transfers team (TECHS)

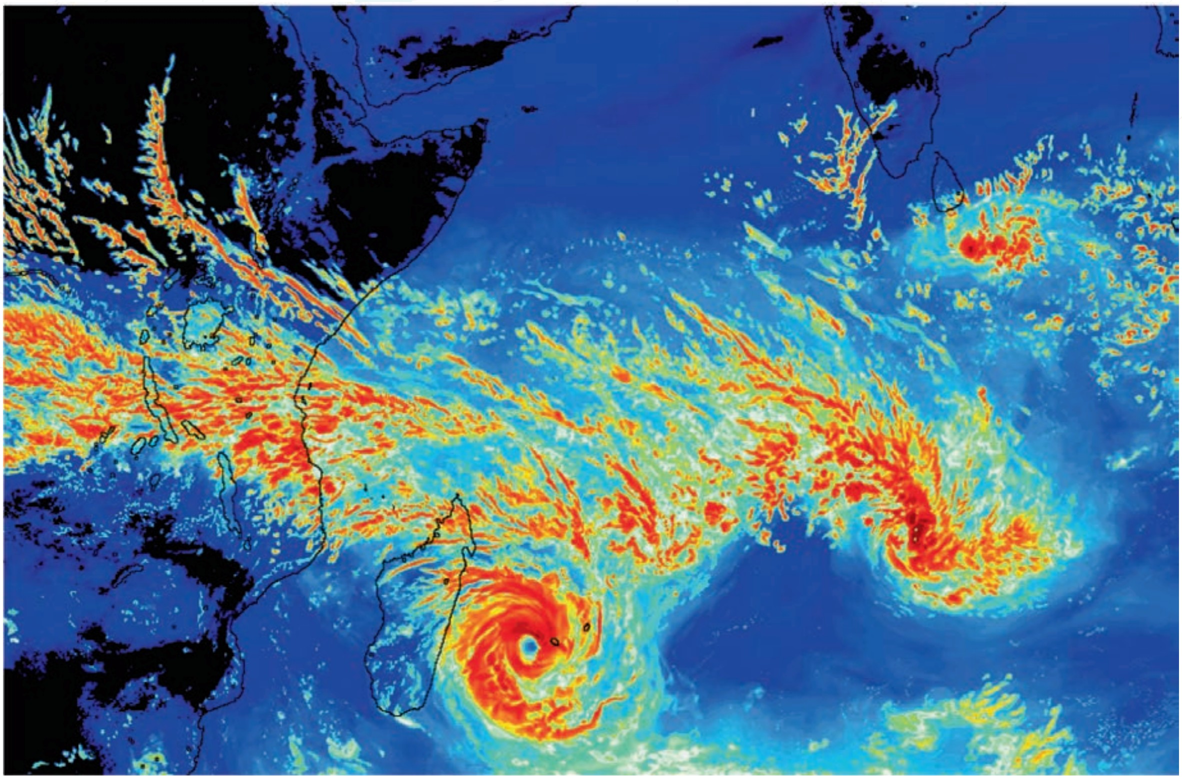
CERFACS – Ocean-atmosphere coupling in Occitanie (France)

The CERFACS climate modelling team has been working on climate and climate change since 1990. In the early 1990s, CERFACS developed a coupling software tool (OASIS) to synchronize the exchange of data (sea surface temperature, sea ice concentration, surface winds, ocean currents, radiative and turbulent ocean surface heat fluxes and precipitation) between numerical models representing different components of the Earth's climate system: atmosphere, ocean, ice pack and inland surfaces. CERFACS researchers and engineers then carried out the very first French coupled climate simulations, in partnership with *Météo-France* and the Institute Paul-Simon Laplace. OASIS is now used in many laboratories in France and abroad (Germany, Spain, UK, USA, Japan, Australia, China, etc.). It presently enables coupling of the most efficient climate models and the implementation of long-term climate experiments on parallel supercomputers (several hundred years of climatic conditions simulated in a few weeks).

CERFACS

This pioneering work on the coupling of climate models fuels many joint research studies on different topics based on observations and numerical modelling—understanding climate variability dynamics and their predictability at interannual to decadal scales, the impacts of climate change on extreme events (such as heat waves, floods, droughts and storms), European and Arctic climate patterns, ocean circulation and the climatic role of small spatial scale events (e.g. ocean eddies).

Contact: N. Monnier, monnier@cerfacs.fr
For further information:
http://cerfacs.fr
https://portal.enes.org/oasis



▲ *High resolution climate modelling of a cyclone.*

Agroecosystems, agrobiodiversity and environment – systems shaped by interactions between biological and social dynamics

The diverse range of conventional agroecosystems worldwide host substantial agrobiodiversity stemming from past and ongoing domestication processes encompassed in a landscape setting. The landscape in turn is the product (on a different scale) of combinations of ecological and dynamic environmental processes, with the history of human civilizations being one of the driving forces. Human practices hence interact with biological dynamics at several nested scales: intraspecific, interspecific and ecosystemic. Local knowledge permeates these different levels in decision-making processes and understanding the implications of knowledge is a major current research challenge.

Such agroecosystems that have not been markedly transformed by agricultural modernization, that feature scant external inputs and heterogeneous habitats and environments, can serve as models for designing sustainable agricultural systems that dovetail ecosystem and social processes. Agricultural, forestry and gathering economies coexist, alongside subsistence-oriented production and short- and long-distance trade. These productions contribute to a diversity-based economy at different spatial, ecological and social scales.

These agroecosystems may also include differentiated and relatively transformed areas, ranging from agricultural areas to domestic forests, grasslands, fallows or wetlands. Through interdisciplinary initiatives, the complementary approaches proposed by a number of Montpellier research laboratories, including CEFE, AGAP and ISEM joint research units (UMRs), as well as the Mosaïque research group (GDR), enhance insight into the genesis and evolution of agroecosystems and their agrobiodiversity, ranging from historical dynamics to contemporary situations. The disciplines involved include ethnology, ethnobiology, archaeobotany, environmental history, philosophy, political ecology, evolutionary ecology and population genetics. GDR Mosaïque, which pools 14 UMRs, including several CNRS, CIRAD and IRD laboratories in Montpellier, consolidates research on these complex systems. The photos below illustrate just part of the diverse range of socioecological systems and family farming techniques encountered, which represent complex systems whose *modus operandi* should now be analysed.

Contacts: Y. Aumeeruddy-Thomas, yildiz.aumeeruddy-thomas@cefe.cnrs.fr and D. McKey, Doyle.mckey@cefe.cnrs.fr (UMR CEFE)
For further information:
www.cefe.cnrs.fr/fr/recherche/ines/ibc/grd-3353-mosaique-2

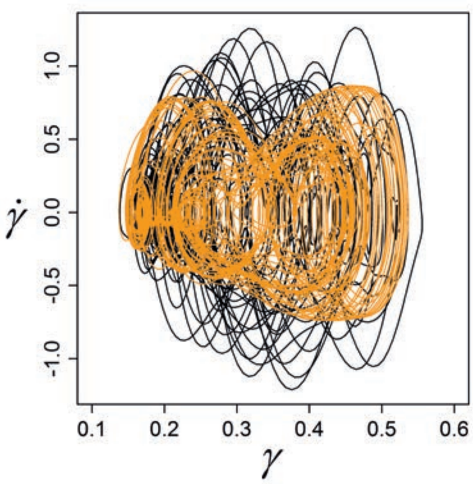
▲ ***Bangweulu floodplain in Zambia.*** *Farmers build up raised fields so that their crops will have well-drained patches of soil to grow (left). In the flood season, the basin is flooded to 1 m depth. In the same environment, farmers also take advantage of mounds already formed by termites and transform them into raised well-drained fertile patches (right). It is essential to gain insight into the interactions between human and non-human 'soil engineers' to be able to fully grasp the underpinnings of the agricultural system. © Doyle McKey*

▲ ***Olive groves combining oleasters and olive trees (Rif region, northern Morocco).*** *This system incorporates a heterogeneous combination of wild rootstocks (or plants that have grown spontaneously from seeds) and varieties cultivated through grafting. This farming system provides the basis for an agroecosystem with a wealth of interspecific biodiversity associated with high cereal, legume and wildlife diversity. ©Yildiz Aumeeruddy-Thomas*

Formulating equations from observations – application to the classification of agricultural cover and epidemiology

Approaches that enable direct formulation of laws on the basis of observations are useful for dealing with the complexity of the real world. Complex systems science can provide new impetus at this level, which is the aim of the GPoM* modelling platform developed at CESBIO—to obtain equations that mirror the laws that govern dynamics based directly on a series of observational measurements. The point is no longer to build models from preexisting knowledge, but rather to formulate equations from observations in order to interpret dynamic behaviours or interactions between observed variables. These tools, applied to spatial remote sensing monitoring of cereal crops in northern Morocco, have yielded models with a predictability range of 48 to 60 days. Most of them showed specific chaotic behaviour that had only previously been observed in very exceptional theoretical cases, while also revealing the high susceptibility of crops to minor disturbances as well as the fact that the farming practices were well adapted to semiarid conditions. Tests in southern India highlighted that these tools could distinguish the dynamic behaviours of different crop species, which led us to propose a new classification approach. These generic tools have been applied to other themes, particularly epidemiology. The approach thus generated a new model linking the Bombay bubonic plague epidemic (1896-1911) to epizootic diseases in rats, while each term could be interpreted, which was unexpected. A model for the Ebola disease epidemic in West Africa (2013-2016), highlighting four distinct epidemiological situations, was also developed.

Contact: S. Mangiarotti (UMR CESBIO), sylvain.mangiarotti@ird.fr
***For further information on generalized polynomial modelling (GPoM)**:
https://cran.r-project.org/web/packages/GPoM



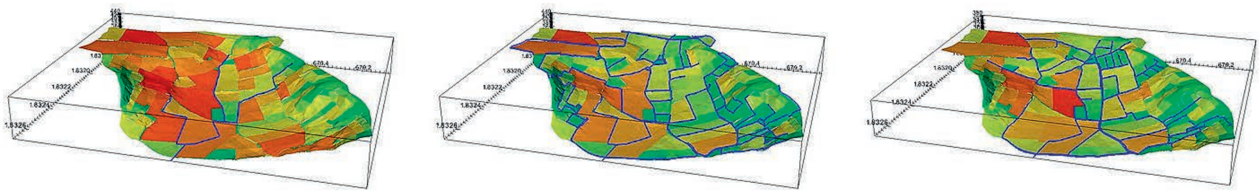
◀ ***Cereal crop dynamics represented by a phase portrait (NDVI, dNDVI/dt) in a semiarid region. AVHRR (black) and model (orange) data.*** *© Flavie Le Jean/CESBIO*

OpenFLUID Plateform – spatial modelling of complex landscape functioning

Understanding how cultivated landscapes work is a major environmental management challenge, particularly in terms of integrating agriculture into a sustainable development and quality approach. Such landscapes embody many geographical features, biophysical and socioeconomic processes, whose dynamics are spatially distributed, with strong interactions, even feedback, between them. A landscape system is therefore highly complex, and such systems are studied over large spatiotemporal areas mainly via modelling. Tools are essential to gain insight into such features. Development of the OpenFLUID platform has therefore been under way since 2005 for the spatial modelling of complex landscapes.

OpenFLUID proposes a spatiotemporal landscape modelling framework based on: (i) a representation of spatial organization in the form of space graphs, and (ii) a system for coupling dynamic models, plugged into the platform on request. The space graph representation obtained from geographical data includes landscape features (graph nodes: plot, river section, road section, underground, atmosphere, etc.), and relationships between these features (arcs on the graph that link the nodes). The coupled models use this space graph to simulate the landscape's spatiotemporal dynamics. OpenFLUID—with advanced nested graph and variable time step coupling features—allows the use of multiscale modelling approaches. The OpenFLUID platform is a complete software environment built around a modelling and simulation framework: model development, capitalization and sharing, application preparation, simulations and processing of the results. The platform also offers various bindings and interconnections with programming languages and third-party tools, including the R environment to address, for example, multisimulation research needs.

Contact: J.-C. Fabre (UMR LISAH), jean-christophe.fabre@inra.fr
For further information: www.openfluid-project.org



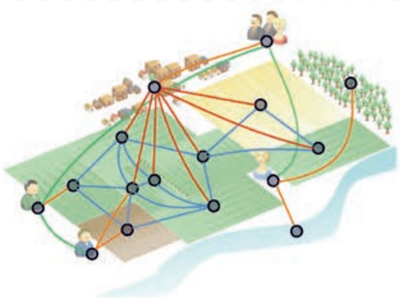
▲ *Example of multisimulations to determine the optimum density and spatial organization of a hydrographic network so as to limit erosion hazards in agricultural plots connected to this network.*
© F. Levavasseur (simulation results)/J.C. Fabre (graphic layout)

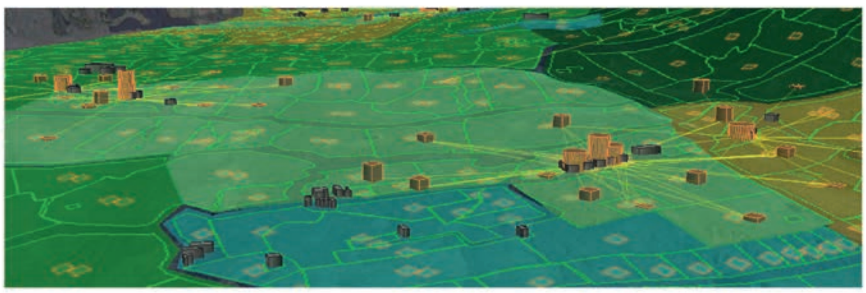
Ocelet modelling platform – simulating spatial dynamics *via* interaction graphs

The Ocelet platform is used in different disciplines to build simulation models for studying phenomena that are expressed spatially in territories. Among the other tools and approaches designed for this purpose, Ocelet stands out by the use of the interaction graph as the basic concept underlying the model building process. Graphs are simply sets of nodes, some of which are connected by arcs. The interaction graph is defined as a graph where the arcs are able to hold interaction functions. Any system to be modelled is thus viewed as a set of interconnected entities, while the execution of interaction functions leads to changes in the related entities thus prompting the system to evolve. Note that this same concept enables a unified representation of spatial entities in vector and raster formats for their joint use in models.

The Ocelet software environment and its dedicated modelling language offer a limited number of formally defined concepts that are essential for modellers. The user interface includes various functions for model creation and maintenance, Ocelet source editing, compilation, simulation launching, display and exportation of simulation results, particularly in the form of animated maps. The Ocelet modelling language enables users to model—with considerable freedom of expression—a segment of the concerned territory and the underlying processes in order to simulate its evolution over time. Models have been developed in various fields, e.g. coastal dynamics of mangrove ecosystems, mosquito population dynamics to support vector control, prospective simulation of urban sprawl scenarios, and agrarian dynamics in a cotton cropping area in Burkina Faso. The software and user manual are available online at the Ocelet website.

Contacts: P. Degenne, pascal.degenne@cirad.fr and D. Lo Seen, danny.lo_seen@cirad.fr (UMR TETIS)
For further information: www.ocelet.fr





▲ *Interaction graphs and agricultural biomass transfer modelling in Réunion.* *P. Degenne, 2018, GABiR project.*

Territorial management

Modelling societies and their territories – the importance of social science

An agent-based platform is a simplified description of reality built using a systemic approach whose development has been heralded over the past two decades. This involves the formalization of a high number of entities called agents, each representing a social unit, individual, family or other community, and with a certain degree of autonomy in a given context. The latter can include all links between these agents, a biophysical setting or a combination of both. All interactions between these entities create emergence dynamics—which represents a major contribution of these models—revealing non-linear social dynamics, which are not necessarily predictable, while accounting for their weight in terms of impacts on the environmental and social contexts. These models are often used in the agroenvironmental field to reflect the impact of human activities over an area. Here it is important to differentiate the research scope and subject. While research subjects are often focused on studying human dynamics and their impacts, the research scope often mostly concerns the territory, thus creating a fundamental bias, i.e. only human dynamics directly related to the territory are integrated. However, many social dynamics are not derived from the local territory. For instance, the demographic dynamics, particularly with regard to the inheritance transmission of farms in France, may be vital. These are decisive in the land-use dynamics over a generation, but also in the agricultural and environmental strategies of the present generation—farmers do not reinvest when they know that the farm will not be revived. More generally, the integration of environmental dynamics is progressing well in multiagent models through explicit and formalized coupling via geographical information tools, e.g. through dedicated platforms such as GAMA (*see p. 50*), but there is still a need to incorporate the human sciences, beyond the economic aspects.

Contacts: M. Saqalli (UMR GEODE), Mehdi.saqalli@univ-tlse2.fr, M. Belém (WASCAL), belem.m@wascal.org, B. Gaudou (SMAC/IRIT team), benoit.gaudou@ut-capitole.fr
Collaborators: M. Saenz (*Programa de Manejo del Agua y del Suelo/Universidad de Cuenca,* Ecuador), M. Paegelow & N. Maestripieri (UMR GEODE)

▲ *Use of qualitative socioeconomic survey tools to incorporate the perceptions of local actors (spatial perceptions, resources, risks, etc.) into the definition of the beliefs of agents to be modelled, according to belief-desire-intention (BDI) type architectures and scenario-based formalization tools via workshops with experts on the dynamics and/or territory targeted by the model. © GEODE*

Modelling assessment of strategies for reducing herbicide usage in wine-growing catchments

Reducing the risk of herbicide contamination of surface and groundwater is a major issue in the Mediterranean wine-growing region due to the considerable risks associated with the high rate of surface runoff and herbicide use. The SP3A project has developed a method for evaluating prospective soil maintenance strategies proposed by a group of experts to reduce herbicide-contaminated runoff while preserving production. This method is based on a chain of models developed on the OpenFLUID (*see p. 45*) and DIESE* modelling platforms, which can simulate, in different climatic settings, technical soil maintenance sequences, soil surface dynamics, pollutant runoff flows, water and nitrogen stress in vineyards and their impact on grape yields. Multidisciplinary modelling couples representations of vineyard work sites, hydrological flows at the catchment scale and vine growth. It provides a quantified basis for discussion on how practices could be changed. In the presented example, the model assessment was consistent with the wine growers' opinion on the need to be more flexible in the definition of herbicide usage reduction strategies. It demonstrates that a certain degree of flexibility is: (i) necessary to meet production objectives, and (ii) possible without drastically increasing the runoff contamination level. However, it also indicates that the ultimate goal should be to completely abandon herbicides in order to safeguard the quality of water bodies fed by runoff. The modelling approach alone is of course not sufficient to formulate strategies that will meet production and environmental objectives while being tailored to local conditions of an area, whereas it could be effectively included in a stakeholder co-construction process.


© LISAH

Contacts: A. Biarnès, anne.biarnes@ird.fr and M. Voltz, marc.voltz@inra.fr (UMR LISAH)
Collaborators: P. Andrieux (UMR LISAH), J.M. Barbier (Tropical Agrosystems UR, ASTRO), A. Bonnefoy (UMR LISAH), C. Compagnone (*Centre d'Économie et de Sociologie Appliquées à l'Agriculture et aux Espaces Ruraux*, UMR CEASER), X. Delpuech (French Institute for Vine and Wine, IFV), C. Gary & A. Metay (UMR SYSTEM), J.-P. Rellier (UR INRA-MIAT)

* For further information on the DIESE platform (DIscrete Event Simulation Environment): https://carlit.toulouse.inra.fr/diese

Earth-mound landscapes in seasonally flooded savannas in Africa and South America

Earth-mound landscapes feature exposed earth islets that are regularly spaced in a seasonally flooded matrix. As well-drained soil is a vital resource, these islets benefit those who build them, i.e. people (agricultural raised fields) and 'soil engineers' (earthworms, termites, etc.). The emergence of these landscapes, irrespective of their origin, transforms the functioning of the ecosystem. Several factors underlie their complexity.

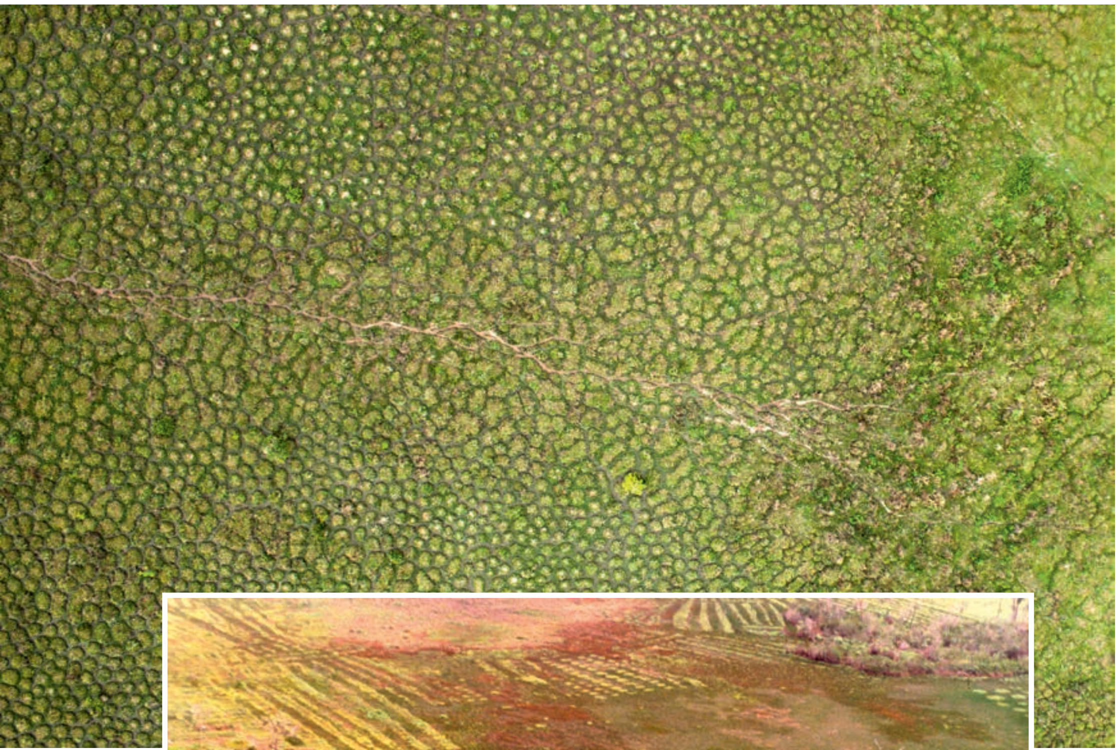
First, they are formed by interactions between sociocultural and natural processes—necessitating a transdisciplinary approach to study them.

Second, each process produces a type of spatial order that can be planned (applied by a farmer building a plot of raised fields) or can emerge spontaneously from the collective actions of individuals in a society (arrangement of structures built by different farmers), or from natural self-organizing processes (Turing mechanisms—short-scale facilitation, larger-scale inhibition—due to soil fauna activity). The dynamics are dominated by feedbacks and are therefore highly non-linear, regardless of whether the emerging order is spontaneous (social processes) or the result of self-organization (biological processes).

Third, these order-generating mechanisms interact, thus producing new feedbacks. In the coastal savanna regions of French Guiana, soil engineers maintain the vestiges of abandoned raised fields, thus curbing erosion. But these organisms would not be able to build mounds themselves. The construction and subsequent abandonment of raised fields has propelled the system into an alternative stable state. Elsewhere, in the larger and geologically older Orinoco Llanos savanna areas, soil engineers have had enough time and space to develop specific adaptations to flooding by building their own mounds.

Fourth, these landscapes may be likened to palimpsests, where social and biological processes have interacted at different times in the past and continue to do so, creating landscapes each with its own history and unique ecological heritage. Studying such complex systems has required collaborations between researchers from many disciplines: ecologists, soil scientists, geographers, archaeologists, archaeobotanists, agronomists, ethnobiologists and remote sensing specialists.

Contact: D. McKey (UMR CEFE), doyle.mckey@cefe.cnrs.fr
For further information:
http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0154269
http://www.pnas.org/content/107/17/7823.short
https://ethnoecologie.revues.org/2193
https://www.youtube.com/watch?v=7K58jjEmeHo
https://www.youtube.com/watch?v=PXeJcWcfS9I
https://mycore.core-cloud.net/index.php/s/e01a65c5769726d35c4f005a13c46502
Collaborations: with Eco&Sols and TETIS joint research units [UMRs], *Avion Jaune* and YellowScan companies and other laboratories in France and abroad (UK, Spain, USA, Luxembourg, Bolivia, Colombia, Republic of the Congo, Zambia).



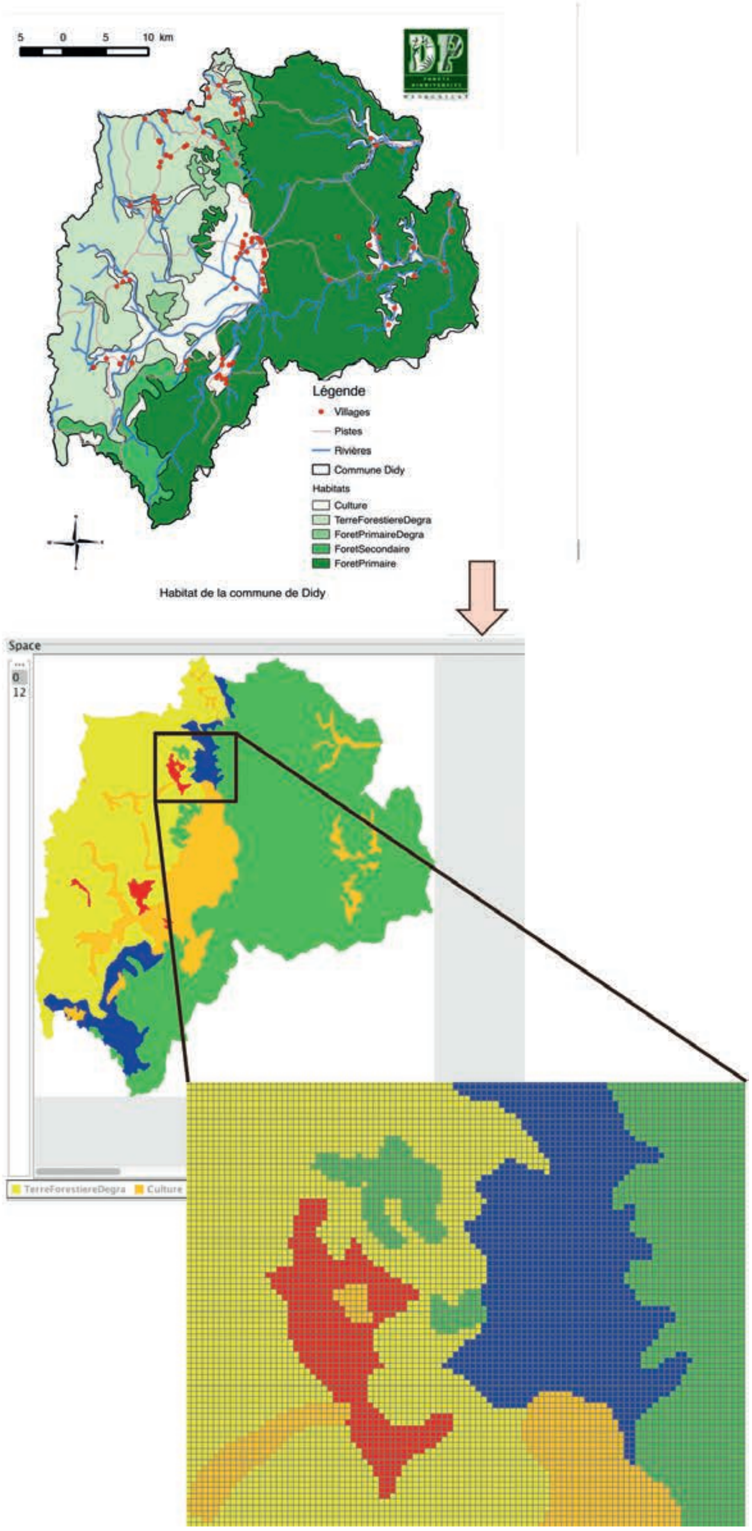
◀ *The* surales*, an earth-mound landscape of natural origin. Aerial Pixy™ drone photograph of a* surales *landscape in the Orinoco Llanos of Colombia.* Surales *mounds are formed by earthworms. The mound shapes and sizes vary over ecological gradients (here, slight variation in elevation) as predicted by the spatial self-organization theory. Photograph © Delphine Renard (post-doc at CEFE).*

◀ *Aerial photograph of vestiges of pre-Columbian raised fields in coastal savanna regions in French Guiana. These human-constructed mounds, which have been abandoned for at least 500 years, have since been 're-engineered' by earthworms, social insects and plant roots. Photo © Stéphen Rostain, UMR 8096,* Archéologie des Amériques.

Impact of decentralized forest management programmes on socioecosystem sustainability in a legal pluralism context

In a situation marked by the rapid disappearance of primary forests in Madagascar, the State has set up a decentralized programme generally for the management of natural resources, and more specifically for forest resources, which have been assigned to local communities (COBAs). The latter are therefore in charge of proposing management plans (zoning, quotas, permits, etc.) that ensure the ecological, economic and social sustainability of their region. A monitoring and evaluation protocol applied to 18 COBAs in Didy municipality (Alaotra Mangoro region), as well as a simulation model, were jointly developed to assess the impact of these plans on the socioecosystem sustainability. Impact assessment is based on an understanding of the ecological dynamics (including population and land-use dynamics), socioeconomic dynamics (including the distribution and allocation of income from forest resources and other income-generating activities) and legal-institutional dynamics (observance of rights, COBA obligations and stakeholder involvement in the decentralized management process). Many disciplines are therefore necessary to get an overall understanding of the socioecosystem within the area of the concerned local community. The effectiveness of management plans on the behaviour of populations also depends on the opportunistic exploitation of a set of regulations derived from State laws, customs and practices. All disciplines called upon as well as regulations at different levels (park and forest administration, customary authorities, etc.) represent viewpoints on the socioecosystem that need to be identified, formalized and injected into an integrated simulation model. Several scenarios were simulated to assess the respective advantages and disadvantages of different management models, from traditional management to decentralized management for protection and/or exploitation, including concessions.

Contacts: S. Aubert, sigrid.aubert@cirad.fr and
J.-P. Müller, jean-pierre.muller@cirad.fr (UPR GREEN)
For further information: COGESFOR project, www.cogesformada.org



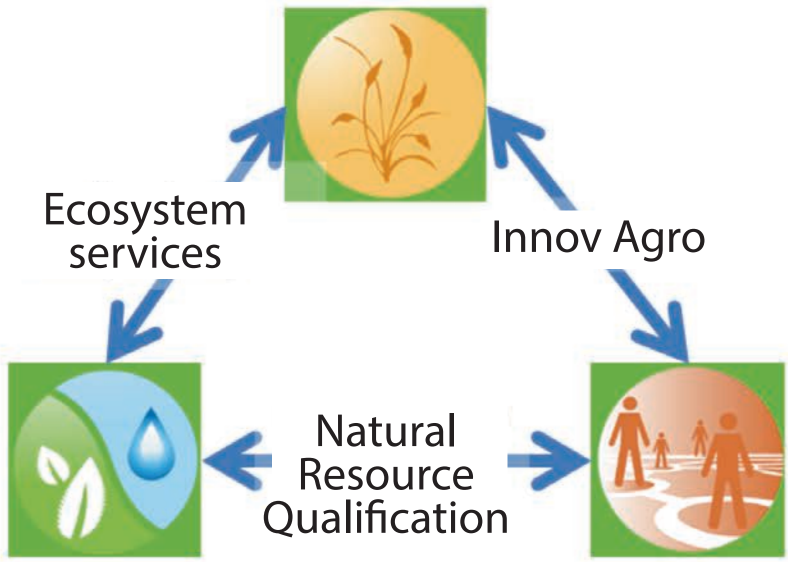
▲ *From the mapping of a municipality to the simulation of practices and their regulations.*

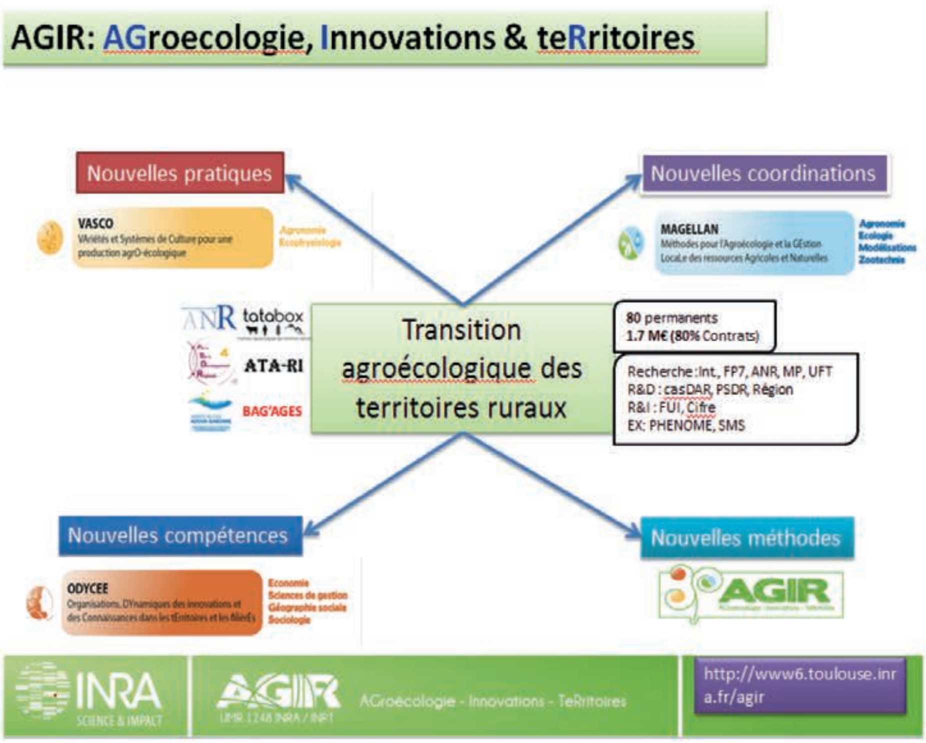
Studies on agroecosystem complexity and transition processes

The interdisciplinary scientific project of the AGIR joint research unit [UMR] aims to generate knowledge, methods and systems to develop diversified agroecosystems adapted to address global challenges via innovations and changes in natural resource management methods. Agroecology refers to agriculture that mobilizes ecosystem service levers through biological regulation to reduce reliance on synthetic inputs. Knowledge on biophysical and ecological processes, sets of stakeholders and agroecosystems, including analysis of changes (technical, organizational and institutional) in production systems, sectors and territories is required to be able to develop such agroecological systems while monitoring transitions to new systems at the territorial level.

Contacts: J.-E. Bergez, jacques-eric.bergez@inra.fr
and D. Galliano, danielle.galliano@inra.fr (UMR AGIR)

Territorial agroecosystems can be seen as complex adaptively managed systems that make effective use of natural (e.g. biodiversity, water), structural (e.g. farms, cooperatives) and cognitive (e.g. farmers' groups) resources. These systems are prone to many uncertainties (e.g. climate, prices, regulations) that force stakeholders to make relatively risky choices, while above all obliging them to have an adaptive system management strategy. Some change models are essentially based on *ad hoc* or incremental innovations, but others call for a more radical overhaul of agricultural and food systems. Major restructuring of the forms of between-stakeholder coordination may be necessary. Incomplete knowledge—concerning ecological processes, the difficulty of predicting the effects of practices or between-stakeholder relationships when implementing these practices—may also give rise to new forms of rationale for agricultural stakeholders. Researchers' contributions to innovation must be revised to take these uncertainties into account. Moreover, closer integration of existing and future links between socioecological and sociotechnical systems is needed to address the marked 'greening' trend in agriculture.





PASHAMAMA-MONOIL model – impacts oil development activities in Ecuador

The northern Oriente region (Ecuadorian Amazon) has been colonized since the 1970s due to the combined effect of a significant state incentive for colonization by Andean inhabitants and oil development, which has led to the building of new roads and pollution. The PASHAMAMA-MONOIL model is designed to assess the combined impacts of these dynamics on both the environment and the human population by simulating population growth patterns, mostly immigration-driven, and oil pollution exposure over time. This model, which was built on the GAMA modelling platform (see below), is agent-based and spatialized. It serves as a basis for retrospective/prospective studies:

- a retrospective study of past dynamics (demographic, environmental and contamination)
- a prospective study (scenarios) according to future policies, oil or agricultural commodity prices, demographics, etc.

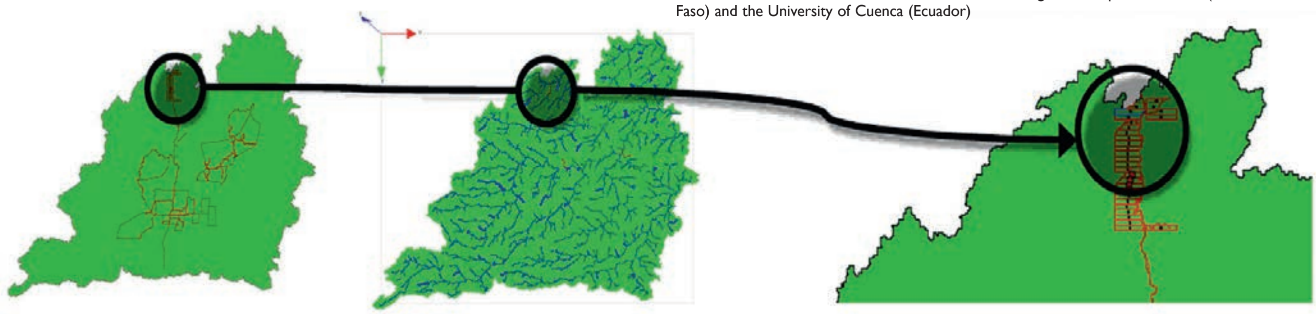
The model was developed by the IRIT and GEODE joint research units (UMRs) and their partners* in three study areas: Pacayacu, Joya de Los Sachas and Dayuma. It couples two main dynamics:

- Oil companies are building roads, pipelines and other infrastructure. These cause leaks, breakages and other accidents that result in the leaching of local oil pollution into waterways, then affecting surrounding soils, farms and people.
- Colonizers from the Andes, the coastal region and southern Amazon settled on agricultural concessions that they chose to be as close as possible to roads, and they then produced food and cash crops there.

Spatial, oil infrastructure and road data were from the Ecuadorian Ministry of Environment as well as local governments, while demographic data was from the National Ecuadorian Census Institute. The categorization of farmers was based on agricultural, anthropological and economic surveys carried out from 2014 to 2016.

Contacts: B. Gaudou (UMR IRIT), benoit.gaudou@ut-capitole.fr, M. Belém (WASCAL), mahamadou.belem@gmail.com, M. Saenz (University of Cuenca), msaenz47@gmail.com, M. Paegelow, paegelow@univ-tlse2.fr, N. Maestripieri, maestripieri@univ-tlse2.fr, M. Saqalli, mehdi.saqalli@univ-tlse2.fr and L. Houssou, Jaderne@gmail.com (UMR GEODE)

* West African Science Service Center on Climate Change and Adapted Land Use (WASCAL, Burkina Faso) and the University of Cuenca (Ecuador)



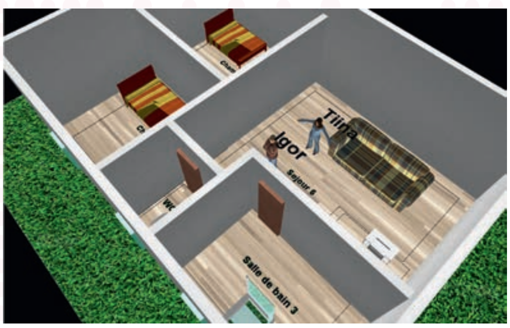
▲ *Example of an oil spill causing pollution at the Dayuma site (Ecuador) and impacting colonized areas.*
© L. Houssou & M. Saqalli

GAMA – an open-source complex system agent-based modelling and simulation platform

Agent-based modelling is becoming increasingly attractive for complex systems research. This approach consists of studying a system by modelling its components in the form of autonomous computational entities called agents, with their own specific characteristics and behaviours. The agent concept, which derives from the artificial intelligence field, is versatile—an agent can represent different types and levels of entities, e.g. a human being, house, social group or city. An agent-based model can deliver relevant information on the dynamics of the system it represents through agent-interaction. It can also serve as a virtual laboratory to test and predict the impact of new policies. Finally, it may be used as a discussion medium in participatory modelling and simulation processes. Agent-based model construction requires extensive computer programming because all agents and their behaviors must be described via algorithms. The GAMA open-source platform, which has been under development since 2007 by a consortium of research teams under the leadership of the UMMISCO international joint research unit (IMU), aims to help modellers carry out this work. GAMA is a generic platform (adapted to any type of application), which allows model content building using GAML, an easy-access modelling language. GAMA has enjoyed significant growth in recent years because of its capacity to build and simulate large-scale models, including hundreds of thousands of agents and detailed geographic data. It also has advanced 3D visualization tools as well as tools devoted to the construction of serious games. This platform is now used in many research projects tackling issues as varied as epidemiology, land-use change, natural or technological risks, natural resource management and urban mobility.

Contacts: P. Taillandier (UR MIAT), patrick.taillandier@inra.fr, B. Gaudou (UMR IRIT), benoit.gaudou@ut-capitole.fr, A. Drogoul (UMI UMMISCO), alexis.drogoul@ird.fr
For further information: http://gama-platform.org

▲ *Screenshot of a road traffic simulation for the French city of Rouen generated using GAMA.*

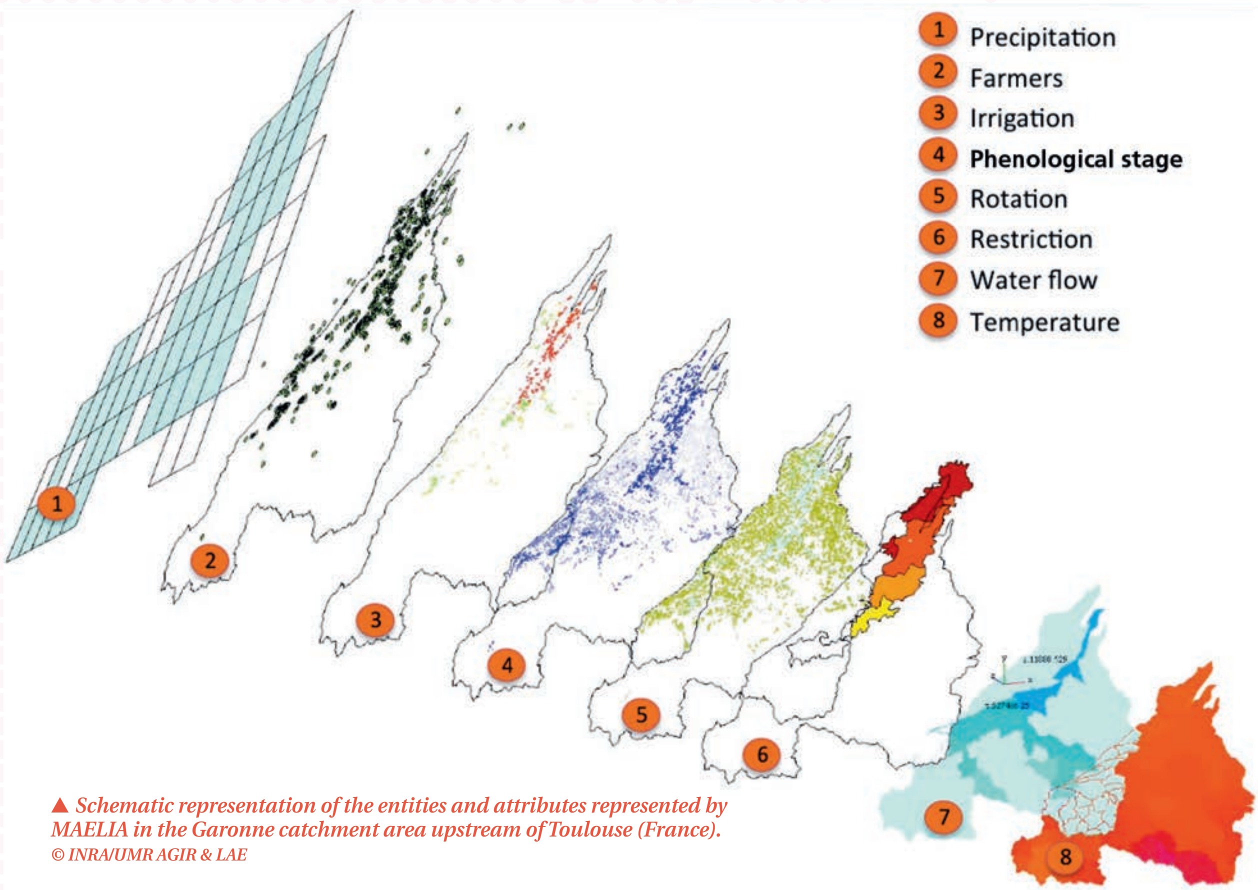


◀ *Screenshot of a simulation concerning indoor air quality generated using GAMA.*

MAELIA multiagent platform – modelling and simulation of socioagroecosystems

Designing sustainable natural resource management strategies within rural territories in an uncertain global change context is a major challenge in the Global North and South. MAELIA is a multiagent modelling and simulation platform for assessing—at the territorial level—environmental, economic and social impacts of scenarios of combined changes regarding natural resource management, agricultural activities and global change (demography, markets and agricultural policies, land-use dynamics and climate change). MAELIA provides a unique way of representing functioning of and interactions between the four major subsystems of a 'social-ecological system': (i) ecosystems, (ii) systems of resources generated by these ecosystems, (iii) activities of users of those resources, and (iv) systems of governance of user-resource interactions. MAELIA can currently be used to model and simulate—at fine spatial and temporal resolution—interactions between agricultural activities (choice of crop rotation, management of cropping systems within each farming system), hydrological aspects of various water resources (based on SWAT® formalisms) and water resource management (dam releases, water use restrictions). More generally, MAELIA provides a software architecture developed under GAMA® to represent interactions between agricultural activities, agricultural landscape dynamics and natural resource management at the territorial level. Projects designed to extend MAELIA's functionalities are addressing issues related to interactions between field crop and livestock farming systems, biogeochemical cycles, biological regulations, territorial management of organic waste products and agroforestry and agroecological systems. The MAELIA development contributors' club currently includes research laboratories (INRA, CNRS, universities, CIRAD), ARVALIS, the *Compagnie d'Aménagement des Coteaux de Gascogne* and the *Association pour la Relance Agronomique en Alsace*.

Contacts: O. Therond (Agronomy and Environment Laboratory, UMR LAE), olivier.therond@inra.fr, J. Villerd (UMR LAE), jean.villerd@inra.fr, P. Taillandier (UR MIAT), patrick.taillandier@gmail.com, B. Gaudou (UMR IRIT), benoit.gaudou@ut-capitole.fr
Collaborators: C. Murgue (*Compagnie d'Aménagement des Coteaux de Gascogne*, CACG), B. Lacroix (ARVALIS *Institut du Végétal*), D. Leenhardt (UMR AGIR)
For further information: http://maelia-platform.inra.fr



▲ *Schematic representation of the entities and attributes represented by MAELIA in the Garonne catchment area upstream of Toulouse (France).*
© INRA/UMR AGIR & LAE

Simulation models for analysing the impact of seed exchange and farmers' practices on agrobiodiversity dynamics

The sustained high genetic diversity of crops has enabled human populations to survive and adapt to adverse climatic conditions over the centuries. This varietal diversity—upheld by seed management practices—now helps farmers cope with global change. Farmers' seed systems facilitate the preservation and circulation of a diverse range of local and research-derived varieties, thus facilitating seed supplies to farms in addition to the national supply. The IMAS project focused on the enhancement and maintenance of agrobiodiversity in developing countries through the identification of new forms of varietal diversity management via the interplay, at different scales, between farmer, commercial and institutional seed systems. The approach was based on the co-construction of innovative tools (multiagent models) that could incorporate the viewpoints of the different stakeholders, simulate the dynamics of biodiversity management in order to analyse the impacts of future developments, while supporting participatory action research. An iterative approach, with an ongoing dialogue with the actors (farmers and researchers), made it possible to compare their perception of the system—at the considered system scales—and to work on the construction and appropriation of shared representations. The seed system is thus considered as a complex system characterized by the many:

- functions related to seeds: agricultural production, conservation, selection, dissemination
- scales and timeframes: from the plot to the international public policy framework
- stakeholders and standpoints: farmers, government organizations, non-governmental organizations, researchers, etc.

IMAS has been extended via the Dynaversity and CoEx projects in which network analysis methods are implemented to study interactions between farmer seed systems and certified seed chains. The aim is to offer innovative modes of governance that are better adapted to the day-to-day reality of farmers' crop diversity management practices.

Contacts: D. Bazile (CIRAD DGD-RS/UPR GREEN), didier.bazile@cirad.fr, V. Labeyrie, vanesse.labeyrie@cirad.fr and J.-P. Müller, jean-pierre.muller@cirad.fr (UPR GREEN)
For further information on IMAS (Impact of seed access conditions on genetic resource diversity in agriculture): http://imas.agropolis.fr/index.html
CoEx project: https://umr-agap.cirad.fr/projets-de-recherche/coex

◀ *A quinoa seed system simulation workshop based on a role-playing game in Chile. IMAS project, December 2011. © D. Bazile*

Ecosystem services and territorial management

The definition of the ecosystem services concept provides a framework for operational analysis of relationships between sociosystems and ecosystems based on the benefits that socioeconomic stakeholders derive from ecosystem functioning. It broadens the issues, and thereby the disciplines involved, in addressing the needs and terms of ecosystem conservation policies, but also other territorial management related areas. In addition to monetary appraisals, which are widely discussed by advocates of the intrinsic value of nature, the recognition of ecosystem services provides a framework for a functional approach to ecosystem analysis at the territorial level, and for multicriteria approaches to account for the many diverse impacts and interactions. The mapping of services and their interactions through the service package concept makes it possible to leverage the landscape concept as a spatial integrator of some services and to guide land-use planning initiatives that underlie territorial development policies. The identification of services and how they are perceived by stakeholders and populations facilitates joint collective formulation of service conservation or heritage enhancement objectives at the territorial scale. This new reference framework therefore contributes to strengthening territorial governance systems and identifying support needs to strengthen knowledge and recognition of ecological processes, and thereby the social learning necessary to embrace new pro-environmental values. In this regard, ecosystem services are no longer just a benchmark studied by researchers, but also a collective action mediation tool within a consultation and territorial governance framework. The research carried out by CEE-M in this field is focused on both (monetary) assessment methods and the prioritization of services in support of public decision-making at national, regional or local levels.

Contacts: H. Rey-Valette, helene.rey-valette@univ-montp1.fr and J.-M. Salles, jean-michel.salles@supagro.inra.fr (UMR CEE-M)

Laboratory of Computer and Production Engineering – simulation modelling and assessment of complex system behaviour

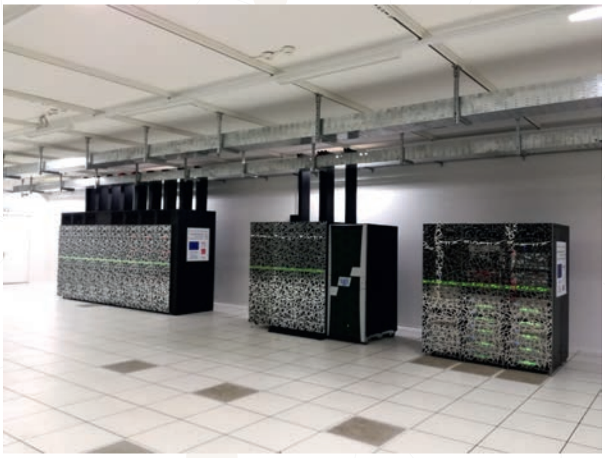
The systems engineering approach is aimed at rigorously conducting and managing the design, implementation and integration of reputedly complex systems. Driven by system thinking and system science fundamentals, it focuses on the deployment of a model-based approach (model-based system engineering [MBSE]) among other principles. The LGI2P Interoperable System & Organization Engineering (ISOE) team conceptualizes and develops methods for multiview and multiparadigm modelling and assessment of complex system capacities and properties. Here 'method' refers to the definition of concepts (MBSE and the domain in which the target system is located), domain-specific modelling languages [DSML], a dedicated operational approach for using the method, support tools and an experiment-based repository. These methods are geared towards supporting and guiding a collective of multidomain stakeholders collaboratively involved in various activities. Here 'engineering' is focused on needs and demands, architecture, verification, validation and assessment of values, capacities and properties (functional and non-functional) expected by the stakeholders. This also entails ensuring the traceability of relationships and constraints (allocation, decomposition, structuring and architectural choice decisions) between the components of the system of interest (requirements, values, capacities and expected properties) and alternatives to engineering-generated architectural solutions (values, capacities and properties provided under operational conditions). The application domains prioritize technical and sociotechnical systems, including critical infrastructure (e.g. transport, energy and water), with a focus on non-functional safety, security, resilience, interoperability and performance features.

Contacts: J. Montmain (LGI2P), jacky.montmain@mines-ales.fr,
V. Chapurlat (ISOE team), vincent.chapurlat@mines-ales.fr
For further information: http://lgi2p.mines-ales.fr

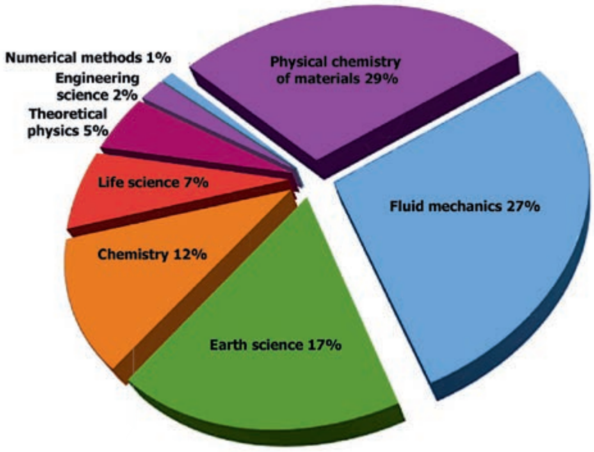
CALMIP – supercomputing in Occitanie region (France)

This computing mesocenter was founded in 1994 and became a joint service unit (UMS) of the French National Centre for Scientific Research (CNRS) in 2014. Hosted within the Clément Ader Institute on the Toulouse Montaudran Aerospace campus, the Computations in Midi-Pyrénées - Computing Mesocenter (CALMIP) is an integral part of the supercomputing platform it shares with *Météo-France*, and thus benefits from a first-rate technological environment. CALMIP —supported by Occitanie Region and its affiliated educational and research institutions—upgrades its computational fleet every 4 years. Currently in production, the EOS supercomputer was ranked 183rd in the TOP 500 when it was commissioned in 2014. A team of six engineers operates the supercomputer on a daily basis and provides technical and scientific support to users—250 scientific projects in 2016 from 45 laboratories. CALMIP is deeply rooted in the academic community and provides the necessary computing capacity to researchers from a broad range of backgrounds, e.g. materials, fluid mechanics, earth science, chemistry and life science. Since 2008, CALMIP has been providing up to 10% of its computing power to the VSE-SME community.

Contact: J.-L. Estivalèzes, jean-luc.estivalezes@imft.fr
For further information: www.calmip.univ-toulouse.fr



▲ *Computation and data storage system.* © J.L. Estivalèzes/CALMIP



▲ *Distribution of computation hours by scientific theme.*

▲ ***Interactive simulation in the city of George, South Africa.***
© Ch. Fabricius

Different applications of the complex systems approach

Complex systems prevail in many private, professional, collective and public action spheres. The research examples presented in this *Dossier* reflect the development of specific methods to gain greater insight into the system complexity. This chapter discusses various ways these approaches can be applied. They can increase the representation capacity by offering tools to enhance visualization of the state of a system and its different dynamics. One of the challenges facing complex system managers once they have these tools at hand is to reconcile the different alternatives available to manage their systems in accordance with their baseline objectives. Some approaches provide tools to underpin such decisions in complex and often uncertain situations. They add an appraisal dimension to the system status visibility. This often involves a multicriteria evaluation, in accordance with the many different viewpoints, since the complexity is not solely nested in the structure of the system to be managed. However, the manager is seldom alone, especially when it comes to public action. All of the system parameters are hard to control simultaneously, and managers often have to accommodate a diverse range of stakeholders—each with their own vision and drivers while directly or indirectly having a legitimate right to intervene in the system. This chapter also proposes methods to facilitate the shift from collective to concerted action. Finally, 'complex system thinking' gives rise to new decision-making models that place interactions at the core of the different components of the system to be managed in order to rely on, benefit from and no longer try to restrict them.

The first section is devoted to the use of complex systems observatories, which feature ongoing acquisition and processing of indicators over a broad geographical area with a diverse range of observable factors. Once these data are processed, alerts can be generated by linking indicators that are *a priori* distant in time, space or with regard to the themes in question. This section highlights the added value of tapping the potential of satellite-based images to feed these observatories with data and shape them into potential decision support tools. Processing such high volumes of data is dynamic and necessitates the development of specific models to explain the implications of policy choices on the different facets of complex systems.

The second section discusses multicriteria decision support for more targeted issues involving analysis and weighting of a variety of interdependent criteria. The first level of decision support concerns the empowerment of actors in a given territory to help gain a clearer understanding of the interplay between the various facets of the territory while assessing responses to operational choices in different settings. More conventionally, decision support compares alternatives. Focusing on the complexity—particularly on the links between criteria and beyond prioritizing preferences—sheds light on how a choice made for one objective can alter the scope for achieving another objective, which lies beyond the initial field of interest and vision.

Decision-making assistance requests come from many domains: fisheries, quantitative water management, health, etc. The time factor must be taken into account to ensure relevant comparisons, particularly through diachronic analyses. Interdependencies develop with delayed effects or via build-ups that become noteworthy only when the timeframes are sufficiently long. Prospective territorial research thus strives to develop plausible varied narratives on system changes over relatively long periods (in relation to typical management times), thus fostering necessary debate on these options.

The third section focuses on social aspects of participation and consultation. The examples presented explicitly showcase the diversity of actors involved in system management. This no longer involves providing decision support to just a single ideal decision maker, but rather to a collective whose members may not necessarily have links with specific institutions governing their interactions with regard to contributions to the managed system. A first approach involves the participation of stakeholders in the modelled processes with different levels of commitment depending on the target objectives. Examples are given on social change, water and land management, and health. They refer to a common initial epistemological framework and are based on a diverse set of tools: simulation models, role-playing games, *ad hoc* workshops, etc. The extent of uncertainty is of paramount importance and the proposed methods illustrate different ways of taking this factor into account. The challenge is sometimes to boost actors' awareness of the uncertainties and their impacts rather than striving to reduce them. Finally, the methods presented place the spotlight on interactions between research and society—the complex nature of systems cannot be solely explained by academic knowledge, but the overall understanding can be enhanced by considering complementary forms of knowledge, particularly forms based on practical experience, and by regularly testing each form of knowledge against others.

The last section showcases new models to support decision making in complex situations. The examples presented explore the synergy between very different types of modelling with regard to the mathematical formalism (analytical, probabilistic, Bayesian, etc.) and computer simulation tools applied. They illustrate some major challenges in the agroecology field to find tradeoffs between ecosystem and water management services for predicting flash flood risks and decontaminating ever more threatened resources.

Olivier Barreteau (UMR G-EAU)
and Claude Monteil (UMR DYNAFOR)

Different applications of the complex systems approach

The research units and teams conducting activities on one (or several) themes mentioned in this chapter are listed in the following chart. Dark green areas indicate a theme that is the main focus of the research team, while pale green areas represent other themes in which it is also involved. The location of an article is indicated by the page number.

3.1. Use of observatories
3.2. Multicriteria decision support
3.3. Participation and consultation
3.4. New decision-support models

Research units and teams** - Different applications of the complex systems approach	3.1	3.2	3.3	3.4
AGIR • *Agroecologies - Innovations - Ruralities*				
Agro • *Agronomy and Sustainable Development*				
AMAP • *Botany and Computational Plant Architecture*				
ASTRE • *Animals, Health, Territories, Risks & Ecosystems*	p. 57	p. 62	p. 65	
CEE-M • *Center for Environmental Economics – Montpellier*				
CeMEB • *Mediterranean Centre for Environment and Biodiversity*				
CERTOP • Centre d'Étude et de Recherche Travail Organisation Pouvoir			p. 67	
CINES • *National Computing Center for Higher Education*				
DIMNP • Dynamique des Interactions Membranaires Normales et Pathologiques				
DYNAFOR • *Dynamics and Ecology of Agriforestry Landscapes*			p. 66	
ESPACE-DEV • *Space for Development*	p. 57/58/59			
G-EAU • *Water Resource Management, Actors and Uses*		p. 63	p. 64/65	
GEODE • *Environmental Geography*		p. 61		
GEOSUD • *GEOinformation for SUstainable Development*				
GRED • *Governance, Risk, Environment, Development*		p. 62		
GREEN • *Management of Renewable Resources and Environment*			p. 64/67	
HSM • *HydroSciences Montpellier*				
IMFT • Institut de Mécanique des Fluides de Toulouse				p. 69
IRIT • *Toulouse Institute of Computer Science Research*	p. 57			
ITAP • *Information-Technologies-Environmental Analysis-Agricultural Processes*				
L2C • Laboratoire Charles Coulomb				
LBE • *Laboratory of Environmental Biotechnology*				p. 68
LGI2P • Laboratoire de Génie Informatique et d'Ingénierie de Production		p. 60		
LGP • Laboratoire Génie de Production				p. 69
LISST • *Interdisciplinary Laboratory Solidarities, Societies and Territories*				
MIAT • *Applied Mathematics and Informatics Toulouse*				p. 68
MISTEA • *Mathematics, Computer Science and Statistics for Environment and Agronomy*				p. 68
MIVEGEC • *Genetics and Evolution of Infectious Diseases*				
NUMEV • *Digital and Hardware Solutions and Modelling for the Environment and Life Sciences*				
OREME • *Observatory for Research on the Mediterranean Environment*				
SMS • *Structuring of Social Worlds*				
SYSTEM • *Tropical and Mediterranean Cropping System Functioning and Management*				
TETIS • *Spatial Information and Analysis for Territories and Ecosystems*	p. 57	p. 60		
TULIP • *Towards a Unified Theory of Biotic Interactions: Role of Environmental Perturbations*				
Virtual Plants project team • *French Institute for Research in Computer Science and Automation*				
XSYS • *Toulouse Institute for Complex Systems Studies*				
#DigitAg • *Digital Agriculture Convergence Lab*				

**See the detailed chart on page 72 listing all of the research units and teams in Occitanie and all of the themes covered in this *Dossier*.

Use of observatories

Complex multicontext information systems for alert management

Many complex information system (IS) studies are focused on surveillance and crisis management. Beyond the ISO 27000 standards that formalize the information security management system concept, how do we take alerts into account—under different contexts (software, ecological, environmental, epidemiological, industrial, etc.) and criticality levels—to detect transitions from nominal to accidental system operation? Addressing issues related to paradigm shifts between normal use and crisis management requires that the proposed models include a generic dimension to be able to describe how such shifts in use occur—feedback or alert mechanism, decision making and change of governance type? What is the involvement in information monitoring, IS and its interfaces in decision making, monitoring and alert processes? Phenomena of (false) alarms, fakes, buzzes, spams and social network rumours reposition issues of information quality and trust in systems devoted to the dissemination of all kinds of alerts/alarms and decision support systems. The models below are based on different facets:

- Management of control and monitoring activities
- Management of alerts and abnormal events
- Dynamics and integration of crisis management in IS
- Dynamic reconfiguration of complex environments
- Adaptation of management of the security of infrastructures, connected cities, cybersecurity, crisis management, etc.
- IT sustainability: business continuity plan/IT continuity plan
- Status and maintenance of alert dissemination vectors during crises

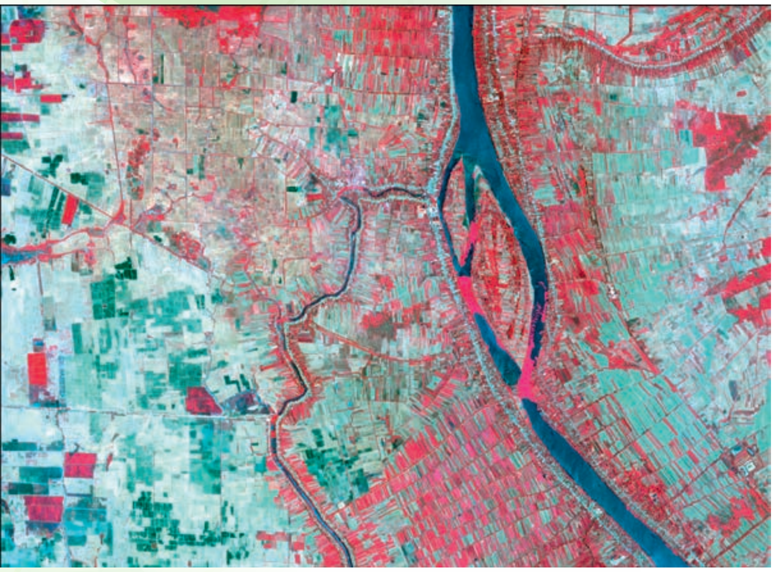
Contacts: F. Sedes (UMR IRIT), florence.sedes@irit.fr, T. Libourel (UMR ESPACE-DEV), therese.libourel@umontpellier.fr, A. Miralles (UMR TETIS), andre.miralles@teledetection.fr

Satellite images for vector-borne disease transmission risk mapping

Vector-borne diseases are infectious diseases that are transmitted between vertebrate hosts by blood-sucking arthropod vectors (flies, mosquitoes, etc.). Many remote sensing and spatial modelling applications have been developed in recent decades to gain greater insight into these complex systems, including the development of predictive tools that may be used by health stakeholders to more effectively target surveillance and monitoring. Satellite imagery-derived information—measured at daily to yearly frequencies—provides indirect indicators of the presence or abundance of vectors or hosts associated with disease transmission in relation to the surface temperature, land-use patterns, the presence of water areas and vegetation. Complementary modelling approaches are also used to integrate this information into risk prediction systems.

Statistical models based on observational data highlight links between environmental indicators and entomological or epidemiological data. Several studies have confirmed the value of this approach, e.g. for mapping animal trypanosomiasis, West Nile fever and Rift Valley fever risks. Moreover, knowledge-based models (transmission cycle, vector and host ecology) can assimilate remote sensing data, including population dynamics models for dynamic mapping of densities of mosquito vectors of dengue, chikungunya and Rift Valley fever. The advent of programming languages dedicated to spatial dynamics modelling, while allowing real-time assimilation of series of satellite image data, fosters this development (e.g. see the Ocelet modelling platform outlined on p. 45). The ever-increasing availability and accessibility of satellite and airborne imagery data, in conjunction with the development of techniques such as telemetry, has given rise to new research opportunities requiring a strong interdisciplinary approach between ecologists, epidemiologists, entomologists, geographers, modellers and remote-sensing specialists.

Contacts: A. Tran (UMR TETIS/UMR ASTRE), annelise.tran@cirad.fr, P. Degenne (UMR TETIS), pascal.degenne@cirad.fr, L. Guerrini (UMR ASTRE), laure.guerrini@cirad.fr
For further information: Theia Land Data Centre, Health & Wellbeing theme: https://www.theia-land.fr/en/themes/health-0



▲ *SPOT-6 image, Cambodia. High-resolution spatial images enable mapping of different land cover types that provide favorable habitats for different mosquito species or other vectors and reservoirs.*
© Airbus DS 2016, reproduced by CIRAD in compliance with the Airbus DS licence

▲ *Tsetse fly* **Glossina palpalis gambiensis.** *© O. Esnault/CIRAD*

▲ *Capturing mosquito vectors, Senegal. © A. Tran/CIRAD*

Scientific observatory for decision support

Several monitoring and decision support experiments (ROSELT/OSS*, Health Observatory in Indonesia, GEOSUD) have fostered collective debate on the 'observatory' topic. The OSAGE scientific observatory on society-environment interactions in support of land managers is a scientific research instrument that helps gain insight into and document —over time—processes involved in socially-relevant issues, while facilitating between-stakeholder discussion and negotiation, and ultimately informing land managers in advance to help them make appropriate decisions. This is an operative, artificial (developed by and for humans) and integrated system combining three components (*see below*):

• The scientific component draws on baseline knowledge, pinpoints the data to be mobilized or acquired, collects data, produces information, while enhancing baseline knowledge on the underlying systemic functioning and dynamics through iterative loops. It undertakes spatiotemporal monitoring and ensures the scientific quality and relevance of the activities.

• The technical component provides services to acquire, store, process, manage, share, exchange and disseminate data, information and knowledge. It ensures the robustness, replicability and maintenance of the services provided.

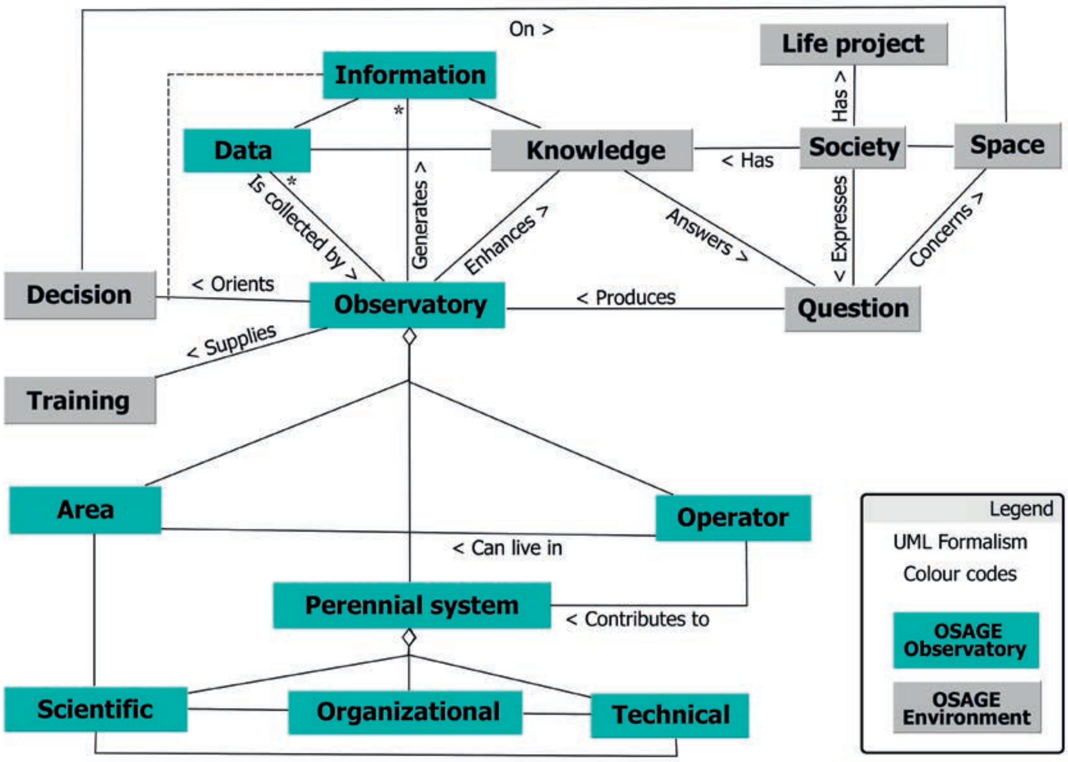
• The organisational component oversees observatory governance, with roles attributed to identified and mobilized stakeholders (operators) to consolidate the observatory's scientific, technical and administrative dimensions. It sets the rules for sharing and disseminating data and information while maintaining its operability and sustainability.

The scope of the observatory is set to represent the area related to the issue at hand. The observatory, like any system, can be elementary (a group of operators, a zone), or complex (several groups of operators, several zones**) to address the same issue, depending on the scale considered.

Contacts: M. Loireau, maud.loireau@ird.fr, M. Fargette, mireille.fargette@ird.fr, T. Libourel, therese.libourel@umontpellier.fr and J.-C. Desconnets, jean-christophe.desconnets@ird.fr (UMR ESPACE-DEV)

* Long-term Environmental Monitoring in a Circum-Saharan Network (Sahara and Sahel Observatory)
** This concerns a network of observatories.

▲ *Over 20 years of protection of the Dantiandou Observatory site. National environmental monitoring system in Niger.* © Maud Loireau, 2010



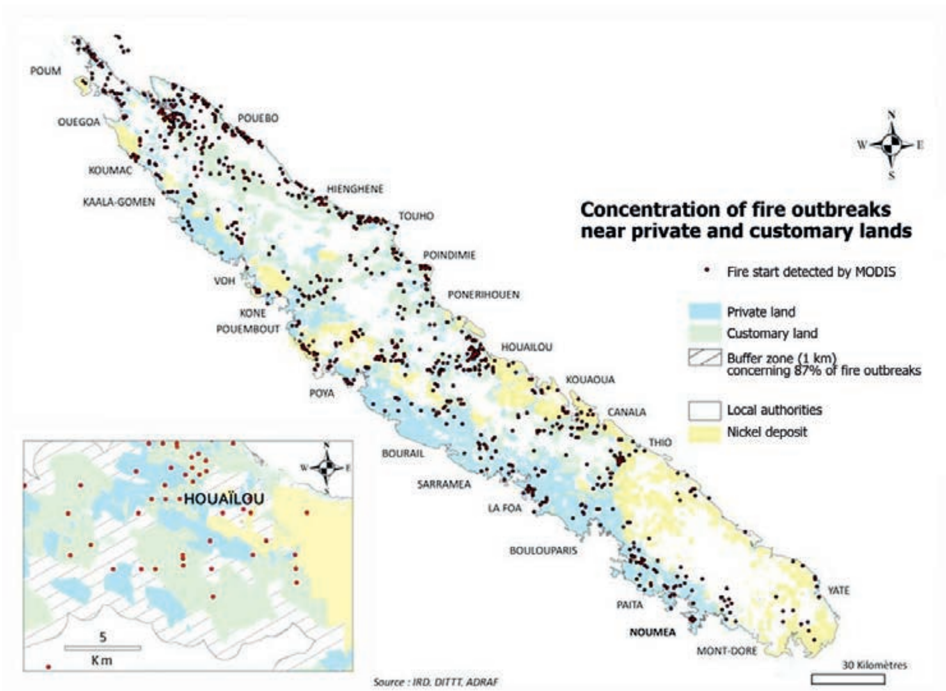
▲ *General structure of the* Observatoire Scientifique en Appui aux Gestionnaires de territoires *(scientific observatory in support of land managers; OSAGE) – UML formalism.* Adapted from Loireau et al.

Modelling fires and their impacts on biodiversity

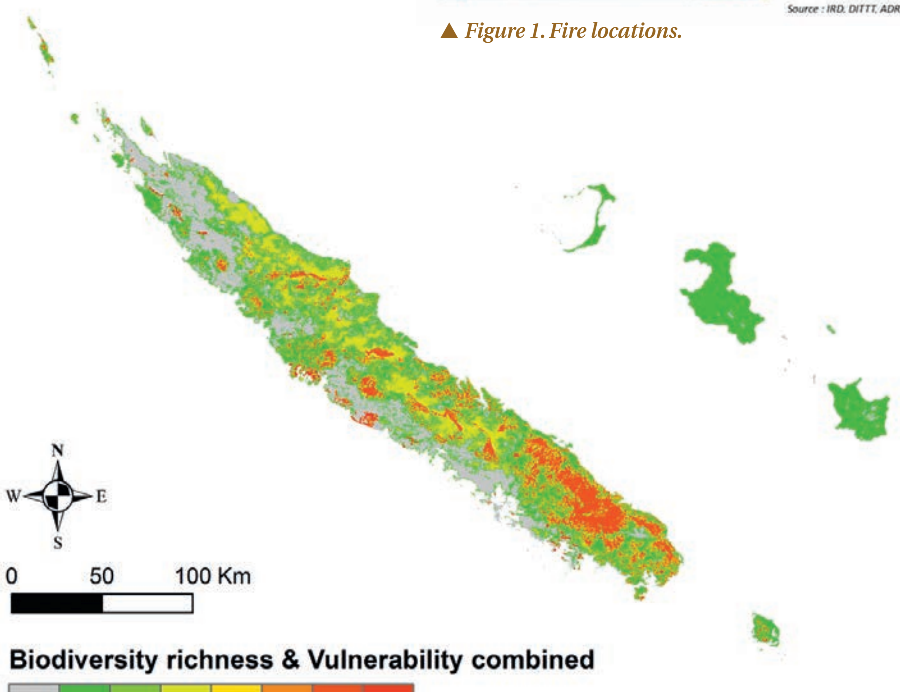
One of the main results of the Fires and Biodiversity project was the development of a spatially explicit model of fire risk in New Caledonia. It incorporates a Bayesian statistical approach using the history of fires (locations and areas) that occurred during the 2000-2010 period obtained using remote sensing (*see Fig. 1*), as well as a mechanical approach to fire behaviour. This model uses all knowledge accrued in the various project disciplines (biology, botany, meteorology, mathematics, remote sensing, etc.) and combines them within a Bayesian network to produce dynamic fire risk and impact maps. It provides—in probability form—a daily estimate of the fire risk at any point on *Grande Terre* island (on a 300 m x 300 m grid).

Contacts: M. Mangeas, morgan.mangeas@ird.fr
and M. Despinoy, marc.despinoy@ird.fr (UMR ESPACE-DEV)

This model first calculates the fire outbreak probability based on weather conditions, the water stress status of standing vegetation, distances to roads and tribes. The second probability—calculated using a fire modelling system developed in the United States (FlamMap)—provides an estimate of fire spreading patterns from potential fire source sites over a 6 h period to represent a worst-case scenario of a fire that would last an entire afternoon with simulated propagation rates at any point and per weather type. The third probability is related to the severity of an immediate fire and is calculated for the impacted area—it compares the simulated intensities according to the weather conditions and ecosystem type. The fourth probability estimates the biodiversity implications (*see Fig. 2*) by integrating the recorded biodiversity and its type (especially its endemism). Fire stakeholders/decision makers in New Caledonia currently have access to this model via a dedicated website, and it is intended to be tailored/transformed into an operational surveillance system to forestall biodiversity loss.



▲ *Figure 1. Fire locations.*



◀ *Figure 2. Fire vulnerability of biodiversity.*
© UMR ESPACE-DEV

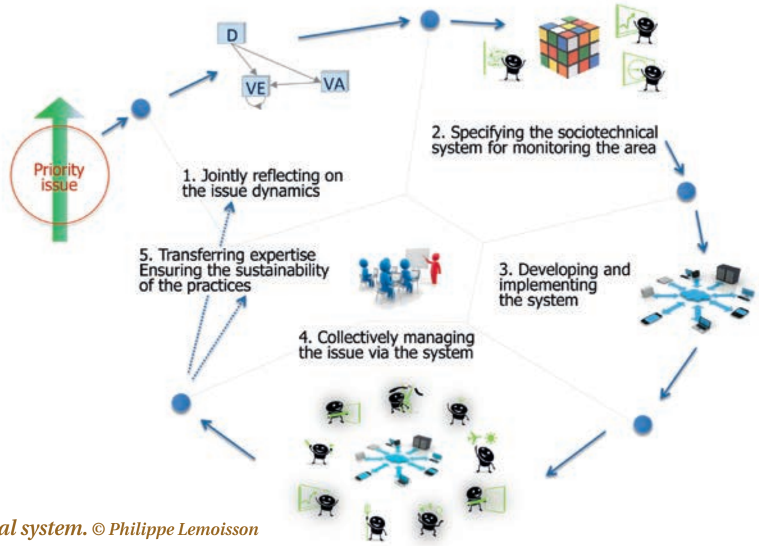
Multicriteria decision support

Thau Bassin observatory – supervised learning amongst Thau stakeholders

Stakeholders in the Thau region (Hérault, France) have—since the mid-2000s—been stepping up efforts to safeguard the quality of the environment and develop the region by streamlining the sectoral governance imposed by each public policy (development, water and environment). In 2005, a regional engineering team was set up, i.e. the *Syndicat Mixte du Bassin de Thau* (SMBT). Then from 2005 to 2014, long-term planning documents (territorial coherence plan, water development and management plan, Natura 2000) were drawn up in a coordinated manner, while an ambitious action programme (2012-2018 integrated management contract) was launched and innovative environmental monitoring systems (preventive *malaïgue* shellfish disease monitoring, VigiThau and Thau Observatory) were also developed. Among these initiatives, the Thau Bassin Observatory monitors actions carried out under the integrated management contract. A web application jointly designed by SMBT and UMR TETIS is being developed—its core component is a multimodal interface for visualizing indicators (thematic maps, time-series diagrams, objective tracking, etc.).

When viewed as a product, the Observatory provides data, maps and technical documents to stakeholders and parties involved in the collective action (elected officials, technicians, economic stakeholders, associations and citizens). When viewed as the process illustrated in the adjacent figure, the Observatory oversees the learning process among the same local stakeholders. In phase 1, joint brainstorming on the dynamics involved will help define the monitoring system. Once the system is deployed, it becomes a collective action support, thus promoting the transfer of skills and the sustainability of the practices. At the end of the pilot learning period, the knowledge acquired is used collectively to enhance the overall understanding of the complex 'territorial' system and allow for a new iteration.

Contact: P. Lemoisson (UMR TETIS), philippe.lemoisson@cirad.fr



▶ *Collective learning and action on the territorial system.* © *Philippe Lemoisson*

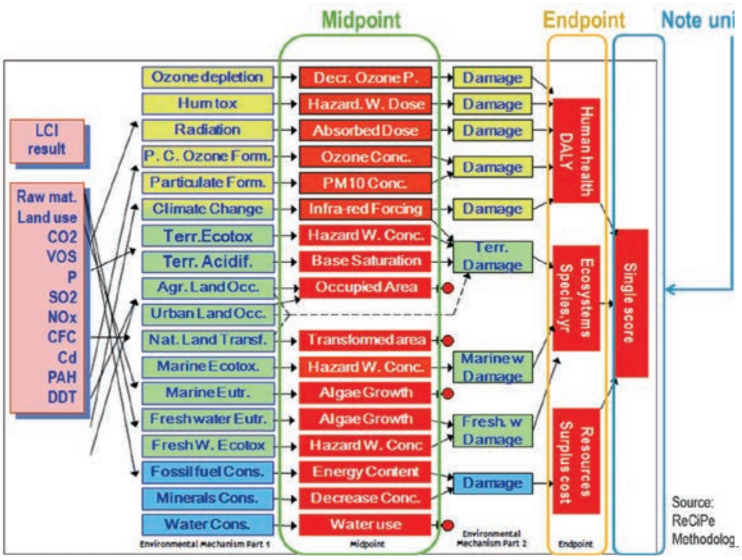
Multicriteria decision support methods for comparison of alternatives – application to environmental management

The KID team (LGI2P of IMT Mines Alès) has developed a recognized level of expertise on multicriteria analysis and decision support in uncertain environments, which prompted it to conduct the study «Using multicriteria analysis for decision making in life cycle assessment (LCA)»* in 2015-2016. LCA is an internationally standardized method for assessing the environmental impacts of products and processes based on a multicriteria functional approach (*see adjacent Figure*). The LGI2P engineering laboratory proposed a formalization of the assessment procedure, which was tested via calculation of the environmental impact of vehicles. LGI2P, in collaboration with ENGIE, the French energy supplier, has meanwhile carried out a comparison of low-carbon technologies with multicriteria analysis methods and tools for the French Environment and Energy Management Agency (ADEME). Environmental criteria must be complemented by technological, economic and social criteria for a more comprehensive comparison of technologies in terms of their uses. Modelling of decision makers' preferences will be enhanced as the aggregation model becomes more sophisticated, but the amount of information required will also conconcomitantly increase. For instance, a model based on a simple weighted average would require little information while a sophisticated model based on fuzzy integrals would need much more extensive data. Analysts are required to formalize knowledge building to help address decision-making issues raised by environmental management. Two types of reality must be considered, i.e. realities based on physical properties and sensory perceptions that may be verified by repeated experiments (e.g. toxic gas diffusion phenomena), and realities for which consensus is no longer based on perception, but instead involve value systems specific to a society or policy (e.g. vulnerability of a territory). KID analysts thus help decision makers to come up with a working hypothesis, and then to build knowledge useful for decision making by clearly distinguishing the two types of reality under this hypothesis, and finally to make their decisions reportable.

Contact: J. Montmain (LGI2P), jacky.montmain@mines-ales.fr

For further information on the Knowledge representation & Image analysis for Decision (KID) team:
http://lgi2p.mines-ales.fr/pages/equipe-de-recherche-kid-0

* Study carried out for the SCORELCA national association of large-scale industrial groups in France.



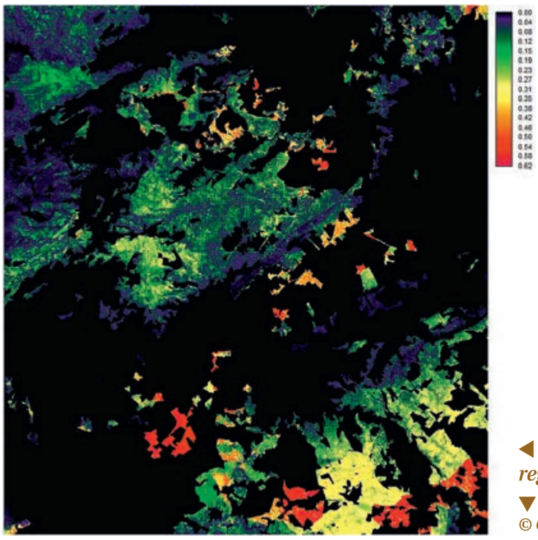
▶ *The impact indicators taken into account by LCA and necessary multicriteria aggregation steps, i.e. midpoint/endpoint aggregation, then endpoint aggregation to a single final score.*
Source : ReCiPe Methodology

Prospective territorial assessment – from spatiotemporal modelling to future scenarios

Two distinct spatiotemporal modelling approaches for future simulation applications are pattern-based modelling (PBM) and agent-based modelling (ABM). The first approach is based on land use/land cover patterns and characterizes their changes while striving to find drivers that could statistically explain the observed quantities and spatial distributions. Multi-agent models focus on between-actor and actor-environment interactions. Actors' representations and knowledge enable them to make decisions, communicate and progress within complex socioecosystems, which in turn can be spatialized and storyboarded over a time course.

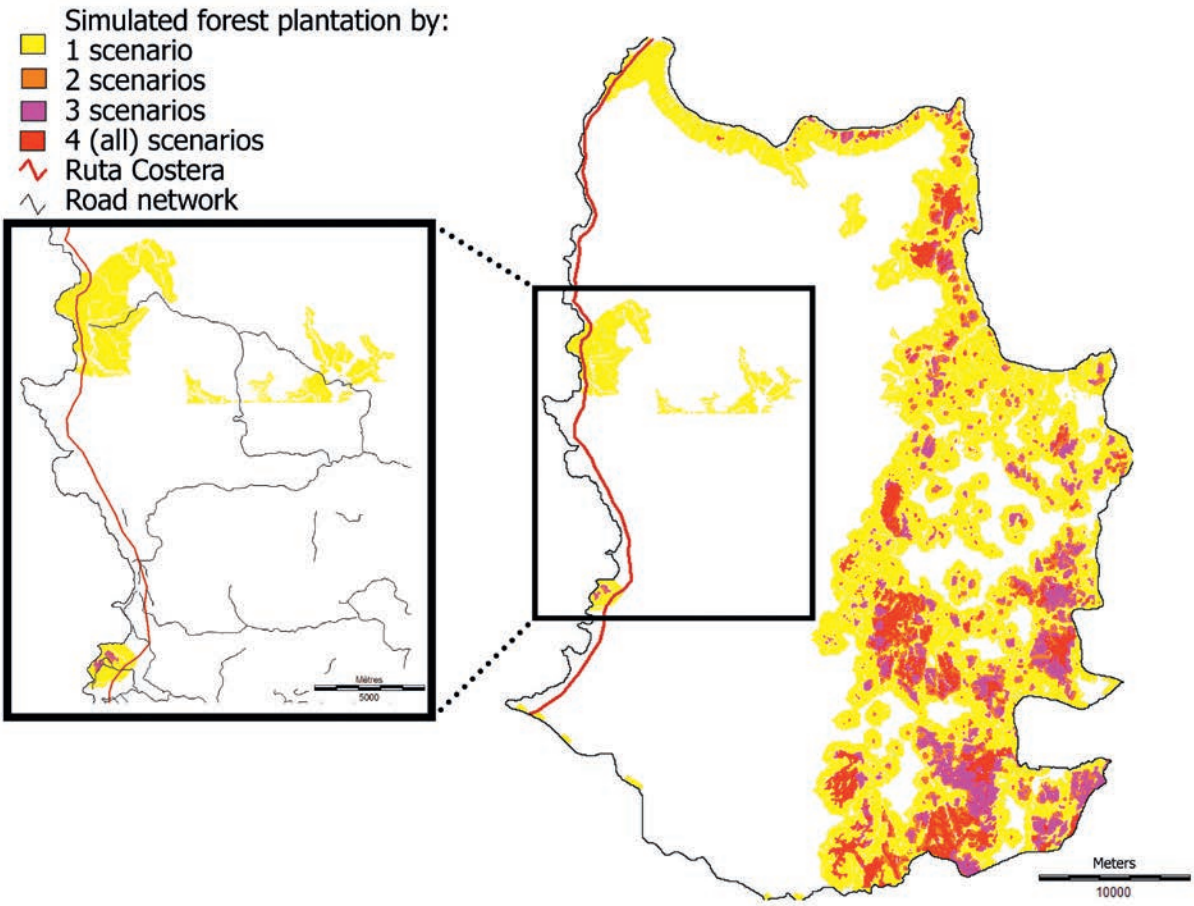
Prospective studies involve two tasks—projection in relation to the surface area of the modelled element (e.g. a forest area) and its spatial allocation. The methods used for each of these tasks depend on the type of prospective study involved. There are three families: business-as-usual (BAU), exploratory scenarios (trend and contrasting scenarios) that span from the present to the future (forecasting) and normative (backcasting). When calculating future transitions, most models use probabilistic estimation, often based on Markov chain analysis. The range of techniques available for the spatial allocation of simulated quantities is more extensive and includes (geo-)statistical solutions, suitability maps obtained by multicriteria assessment or neural network learning. The increased use of prospective territorial assessment, particularly with regard to agroenvironmental issues, enables spatially explicit assessment of the impact of human activities on a territory. Prospective territorial assessment involves anticipating, managing and scripting expected credible or possible changes in fields as diverse as risk management, impact studies, urbanization and global change impacts. In this setting, multicriteria evaluation enables management of many drivers and distinguishes between constraints and factors, while managing the factor weights and compensation level of the latter.

Contacts: M. Paegelow (UMR GEODE), paegelow@univ-tlse2.fr,
N. Maestripieri (UMR FRAMESPA), maestripieri@univ-tlse2.fr,
M. Saqalli (UMR GEODE), mehdi.saqalli@univ-tlse2.fr



◀ *Map of the rainfed to irrigated cropping transition potential, Murcia region (Spain).* © GEODE

▼ *Overlaying of four contrasting scenarios, San Juan de la Costa (Chile).* © GEODE



Model of a fisheries system combining the resource and fishing dynamics

Fisheries are complex systems that combine many interacting elements. As such they can be observed from different standpoints, and described according to a framework that combines some of these elements. Statistically, an operation is described on the basis of a summary of available data, including as much information as possible, and with reference to the initial questions, and sometimes to the questions raised after the data analysis. Regarding small-scale fishing in Senegal, these questions raised concern variability in the impact of fishing actions according to fishermen's decisions. Such variability is problematic if the initial question concerns the impact of a fisheries operation on a resource with a view to its 'rational' management. This impact variability results in a poor correlation between the fish abundance and fishing yields and in low quality of the number of fishing actions in terms of the impact control variable. However, this variability can be a source of sustainability for fishermen who, depending on the accessibility of fish populations, can at any given time opt for an effective fishing method from among those available to them. This choice option must then be incorporated in the representation framework according to a model that reconciles the dynamics of a multispecies resource with those of operations conducted by fishing units using several methods. The model parameters are estimated on the basis of values that lead to the reconstitution of data on fishing activities and yields as close as possible to the values resulting from surveys. It is then possible to answer, in the form of parameter estimation functions, questions involving fishermen's decisions in relation to multicriteria objectives regarding the state of the resource, economic returns and the social context.

Contacts: F. Laloë, francis.laloe@laposte.net
and D. Hervé, dominique.herve@ird.fr (UMR GRED)

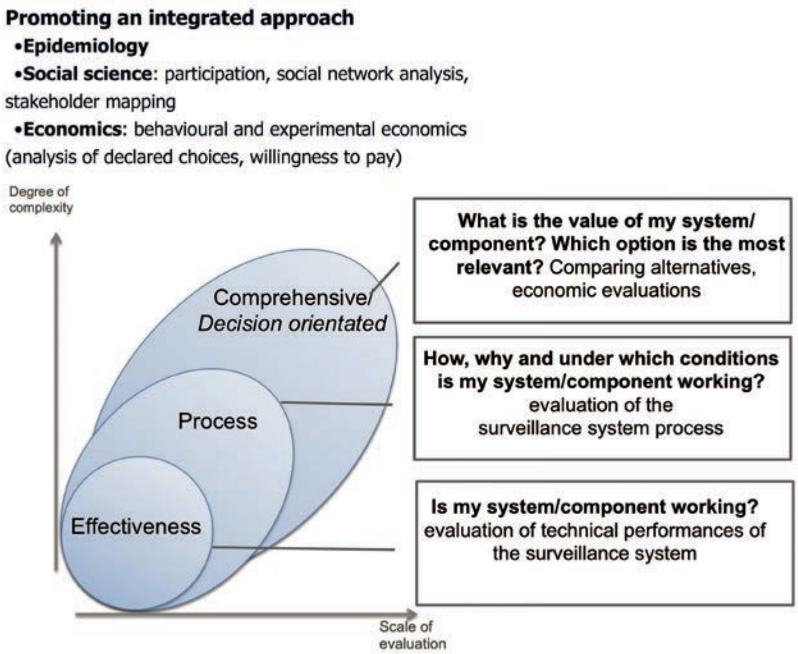
◀ ***Fishing off the coast of Senegal during a deep longline experiment.*** *Here the fishermen decided to set out handlines before using the longlines in boxes with the hooks arranged along the rim of the box (foreground). © Conrath/Laloë, 1987*

Innovative approaches and tools for assessing health surveillance systems

Agriculture and livestock production are crucial for the food security and survival of communities, especially the poorest. Early detection of animal diseases through efficient surveillance systems is vital to prevent their emergence or re-emergence. The effectiveness of these systems is still limited in the poorest countries, despite the efforts of the international community. There are also shortcomings in industrialized countries due to difficulties in communication and collaboration between stakeholders at local and national levels. This impedes the reporting of health-related events by farmers while also having a bearing on surveillance system operations. Given the complexity of the stakeholders' surveillance systems and decision-making processes, these factors must be assessed by integrative and interdisciplinary approaches that combine epidemiology, sociology, economics and political science. Until recently, these elements were not taken into account in the assessment and optimization of surveillance systems.

The ASTRE joint research unit (UMR) develops and applies methods and tools for integrated evaluation of surveillance systems, combining participatory epidemiology, modelling and econometric techniques. These approaches focus on health surveillance system processes (organization of stakeholder networks and decision making) and also on the implications of health information transmission with a view to gaining insight into the technical performance, acceptability and confidence levels, as well as the monetary and non-monetary benefits. These factors are essential for pinpointing suitable actions that could improve system performance and ensure sustainability through a collective change process. Such approaches have been applied in Southeast Asia as well as in Europe where there is a growing demand for health strategy decision support tools. These tools generate local information to boost awareness and enhance the framing of national health strategies, thus fostering dialogue between policy makers and system stakeholders.

Contacts: M. Peyre, marisa.peyre@cirad.fr and F. Goutard, flavie.goutard@cirad.fr (UMR ASTRE)
For further information:
www.fp7-risksur.eu
http://webtools.fp7-risksur.eu
http://revasia.cirad.fr



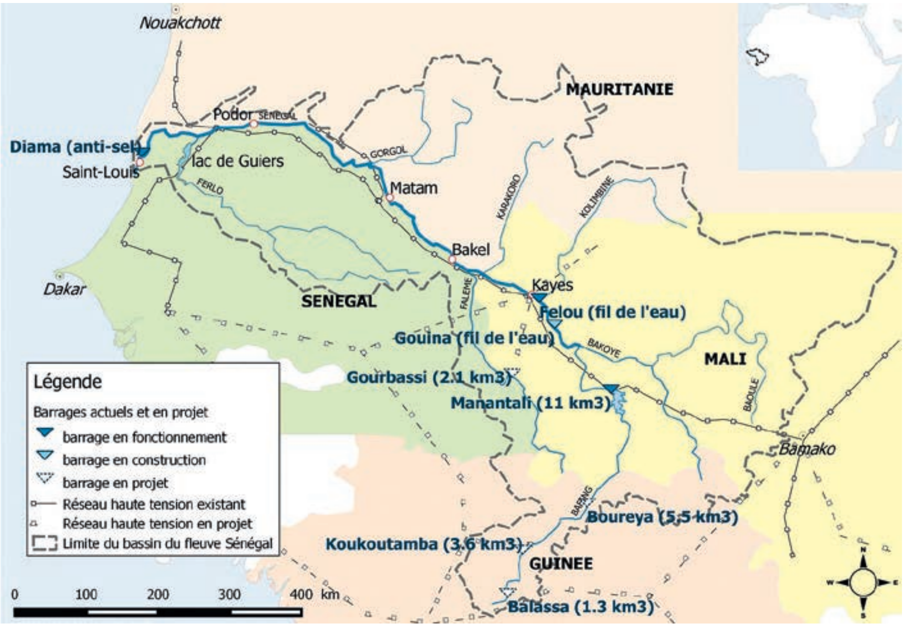
▶ ***Different levels of health surveillance system evaluation.*** *There are different types of health surveillance system evaluation, while integrative evaluation includes process and technical performance evaluation. Different technical, functional and socioeconomic issues can be addressed by each evaluation type and level. © M. Peyre/ASTRE*

Support for the management of multipurpose reservoirs in the Senegal River Basin – multicriteria assessment of different management strategies

Concerning four West African States (Guinea, Mali, Mauritania and Senegal), the development and management of water resources in the Senegal River Basin addresses two sets of competing objectives: (1) power generation, flood protection and low water replenishment for drinking water, irrigation and navigation, all of which are promoted by maximum flow regulation; (2) socioenvironmental objectives that require flood maintenance to ensure sufficient flow to the main riverbed in the valley so as to enable conventional flood recession cropping, while promoting groundwater recharge and averting loss of fish farming resources and biodiversity.

Numerical models have been developed to assess a broad range of reservoir management strategies that are consistent with the extent of available water resources. The simulation results are used to calculate indicators to help meet management objectives, including conflicting energy production and flood support objectives. The first studies focused on optimizing management of the Manantali dam (Mali). Original and innovative models are currently being developed to test different development and changing demand scenarios. They will simulate various concerted reservoir management strategies, corresponding to several decision-making levels: (1) annual strategic decisions for the entire basin, with one of the most critical being the decision to support annual flooding; various studies focused on seasonal flow forecasting based on climate models will provide decision support; (2) tactical decisions for concerted reservoir management with optimization tests on decision-making scopes of a few days to several months; and (3) daily decisions to optimize orders from authorities of different water projects based on available real-time information.

Contacts: J.-C. Bader, jean-claude.bader@ird.fr
and J.-C. Pouget, jean-christophe.pouget@ird.fr (UMR G-EAU)



▶ *Map of the Senegal River Basin with present and future dams.*

◀ *Fishermen in the Senegal River Valley near Lake Guiers.* © J.C. Pouget 2016

◀ *Fishermen and pumping for irrigation in the Senegal River Valley near Podor.* © J.C. Pouget 2014

Participation and consultation

Role of companion modelling in social change

From a complexity perspective, the research object is considered as a set of individuals and groups interacting with each other and with their environment—which has its own specific dynamics. The future of the system is thus impossible to foresee but the system is an evolving organization which will evolve from pattern to pattern, some of which are more ephemeral or stable than others. The scientist's work is in keeping with this uncertainty and aims to support decision-making processes for change towards new forms of organization or maintenance of the current situation, if this is the wish of individuals and social groups. Companion modelling supports decision-making processes by pooling the aims and knowledge of all stakeholders—including scientists—through methods and tools designed for modelling and investigating future scenarios (theatre, role-playing and computer simulation). Various experiments in France, Senegal, Bhutan, etc., have shown how groups can develop new forms of organization (management committees, laws, rules, land use, etc.) that change their relationships with the environment. Long-term monitoring also highlights that, when the context and problems change, groups apply the method and tools on different topics when new collective decisions are needed. The GREEN internal research unit (UPR) and the ComMod network propose companion modelling methods, training and tools based on almost 20 years of research on this issue.

Contacts: F. Bousquet, francois.bousquet@cirad.fr and W. Daré, william's.dare@cirad.fr (UPR GREEN)
For further information on the Companion Modelling (ComMod) network: www.commod.org

▲ *Bagrépoly role-playing game in Burkina Faso (Nov. 2016).* © *Farid Traoré*

Companion modelling to gain insight into interactions between water use and territorial dynamics

Sectoral policies and development choices each have an impact on the availability, quality and uses of water in a given area. Understanding the interactions between water- and land-use dynamics is essential to forestall potential inefficiencies or conflicts. 'Hydrological territories' refer to socioecological systems that are suitable settings for people in relation to water resources, while combining multiple viewpoints and interactions. Modelling these systems can generate tools to probe their dynamics under different scenarios. Companion modelling—based on multiagent systems and role-playing games—provides a framework to take heterogeneous viewpoints of both experts and laypeople into account and incorporate them in representation tools that are understandable and amendable by everyone.

For instance, we investigated the implications—in terms of drinking water supply risks—of intermunicipal, urbanization policy and resource access security choice scenarios*. Based on technical models, the actors criticized the lack of consideration of urbanization policy issues for mayors of municipalities located in the vicinity of large urban areas. These decision-making elements were added to the territorial dynamics in the modelling process. In some cases, role-playing games help participants understand these models by providing a more straightforward representation format. Participants, i.e. both observers and simulation stakeholders, discuss the representativeness of the levers at their disposal in the action (*see opposite*). These collaborative modeling approaches raise questions regarding the underlying power games and the terms of use of the produced models, while accounting for and highlighting the uncertainties. These methods can also be developed to deal with issues other than those related to water but, due to the many uses, resources and management territories involved, hydrological territories represent a particularly relevant focus for these methods.

Contacts: O. Barreteau, olivier.barreteau@irstea.fr and B. Bonté, bruno.bonte@irstea.fr (UMR G-EAU)

▲ *Interactive simulation in the city of George, South Africa.* © *C. Simi*

* SURGE project: *Solidarité Urbain-Rural et Gestion de l'Eau* (urban-rural solidarity and water management)

Complex-free water management – modelling and simulating complex systems without a computer

Researchers at the G-EAU joint research unit (UMR) are striving to develop companion modelling tools for integrated water management (*see previous article on p. 64*), with a view to facilitating its adoption, dissemination and use. The Wat-A-Game (WAG) kit produced in 2012 is designed to make participatory modelling and simulation more widely available, while empowering stakeholder groups and reducing the need for expert intervention. It provides material and methodological resources to analogically represent, design and simulate (with maps and marbles) watersheds, their resources and dynamics, users and practices, managers, rules and tools in the form of role-playing games. WAG includes an initiation kit, a methodological database used by actors to produce their own models, an IT infrastructure to structure the necessary knowledge and exchange experience, along with a database of local cases (>80) that can be queried and sometimes reused.

There are presently about 100 applications in some 20 countries, ranging from demonstration prototypes to finished packages. WAG can be applied to a wide range of situations in terms of scale (from community to large catchment area), issues and resources (water resources, pollution, floods, erosion, biodiversity, livestock, etc.). It assumes that all actors are able to co-construct models of their environment and the effects of their actions, and then to consider the conditions required for change (new practices, regulations). It is part of the COOPLAAGE package, which provides a set of simple, robust and easily adaptable tools and methods for implementing participatory workshops on modelling, simulation, planning, monitoring and assessment. COOPLAAGE also includes mechanisms for participatory planning, a tool for revealing and discussing legal principles, and a methodological framework for participatory monitoring and assessment. A network of facilitators trained on COOPLAAGE tools was launched in 2017 at COP 22.

▲ *Modelling session in Senegal with the WAG toolkit.*
© Géraldine Abrami

▶ *WAG initiation kit (INI-WAG).*
© Benjamin Noury

Contacts: N. Ferrand, nils.ferrand@irstea.fr and G. Abrami, geraldine.abrami@irstea.fr (UMR G-EAU)
For further information:
www.watagame.info
http://cooplanet.watagame.info

Participatory modelling and simulation on health issues

Zoonotic diseases—infectious diseases transmitted between animals and humans—drug resistance and environmental pollution are now major public health problems worldwide. The latter are closely linked to global environmental and socioeconomic change and trends, as well as to territorial-scale production system transformations. Health management is therefore becoming a complex issue to be addressed in close collaboration with veterinary public health, agriculture and environment specialists. Further uncertainties are arising and new social actors from civil society are emerging on the scene alongside conventional public health decision makers, thus complicating decision-making processes.

This complexity calls for adequate methods that will promote the joint expression of all viewpoints. The participatory modelling and simulation approach incorporates heterogeneous knowledge from all actors focused on the same problem. This facilitates co-construction of a shared representation of the studied system while generating scenarios—artefacts of possible forthcoming situations. This approach highlights the uncertainties and then enables capacity building and training on risk management, decision making and responsibility sharing. Participatory modelling and simulation is a pragmatic solution to mainstream health into land planning policies. This approach uses different tools, such as role-playing games and computer simulations. These tools were first developed for renewable resource management by the ComMod collective, and the ComAcross project (EuropeAid) has successfully implemented the approach by tailoring it to health issues in Thailand, Laos and Cambodia.

Contacts: R. Duboz, raphael.duboz@cirad.fr and A. Binot, aurelie.binot@cirad.fr (UMR ASTRE)
For further information on the ComMod collective:
www.commod.org
ComAcross project: www.onehealthsea.org/comacross

◀ *A role-playing game session with villagers in Cambodia on the prevention of two encephalitis diseases—Japanese encephalitis and Nipah virus—and on investigating new control measures.*
© ComAcross EuropeAid project – CIRAD 2017

Participatory Bayesian modelling to shed light on uncertainties between stakeholders on the socioecological functioning of agroecosystems

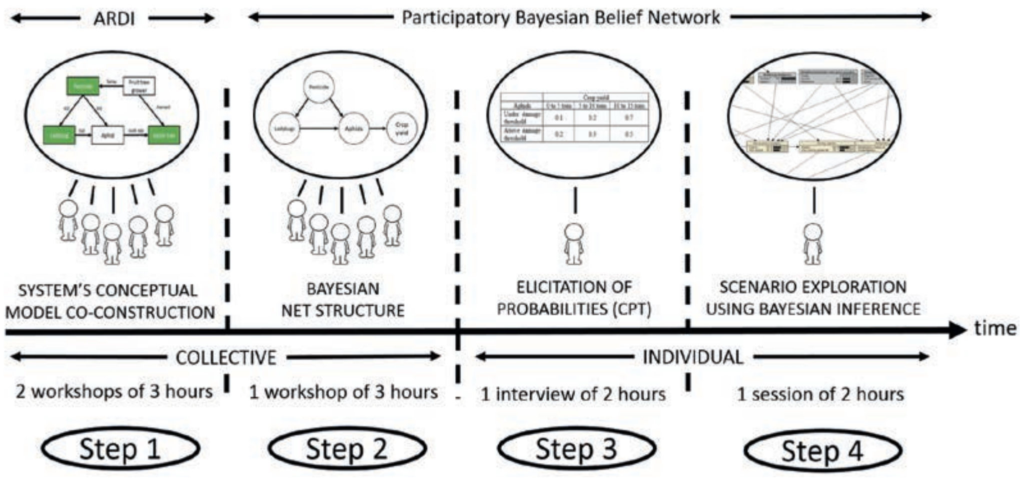
Reinvention of agricultural systems is being encouraged in order to embrace ecological issues. In the past, the complexity of agroecosystems was often reduced via the use of chemicals and mechanization, while economic objectives were given priority. Nowadays, ecological processes are harnessed in agricultural systems by integrating this complexity and taking into account ecological uncertainties on the processes at stake, as well as social uncertainties between the involved stakeholders. Together with scientific, technical and agricultural stakeholders in the arboriculture sector in *Tarn-et-Garonne* region (France), we studied these socioecological uncertainties in a quest for alternatives to pesticides through biological regulation with beneficial insects. In collective and then individual workshops, we facilitated the development—by stakeholders—of a Bayesian model of the socioecological system involved in this issue. Bayesian modelling is specifically tailored to address uncertainty issues. Several change scenarios were developed and analysed through different configurations defined by several types of stakeholder. This enabled us to compare the perceptions of the different stakeholders regarding uncertainties.

The comparison highlighted: (i) points of consensus or ambiguity between stakeholders regarding their understanding of the system in which they operate, and (ii) potential future innovations with regard to biological regulation. When stakeholders share similar viewpoints, this could serve as a basis for discussion and investigation of common innovation pathways at individual farm and territorial levels.

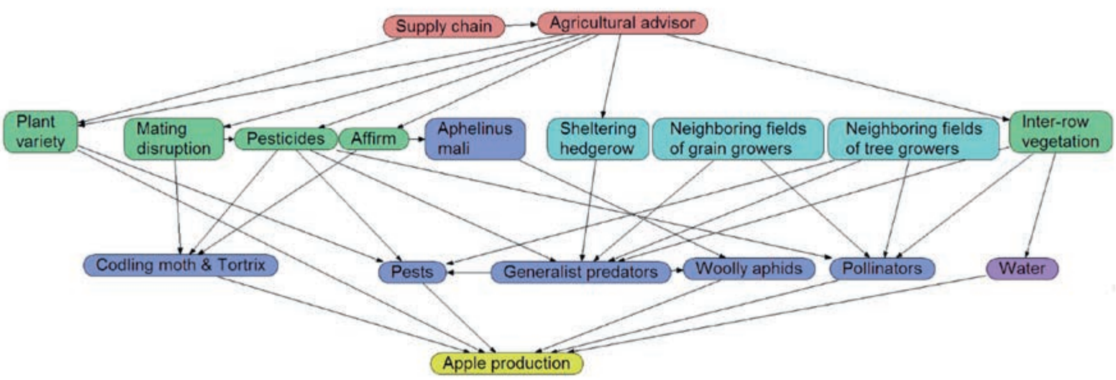
Meanwhile, identifying ambiguities could foster discussion and comparison of the diversity of viewpoints and stakeholders' knowledge regarding the complexity of their system. Explicit modelling of socioecological uncertainties thus promotes mutual understanding between stakeholders and development of agricultural practices that take the ecosystem complexity into account.

Contacts: N. Salliou, nicolas.salliou@gmail.com, C. Barnaud, cecile.barnaud@inra.fr and C. Monteil, monteil@ensat.fr (UMR DYNAFOR)

▲ ***Individual probability elicitation workshop to set up each participant's Bayesian network.*** *The use of cards facilitates discussion and elicitation of probabilities. This process is sometimes complex when many variables are involved. © Nicolas Salliou/UMR DYNAFOR*



◀ ***Main steps of the participatory Bayesian modelling process.*** *We used the ARDI method (actors, resources, dynamics and interactions) developed to co-construct conceptual models of socioecological systems based on stakeholders' knowledge. From Salliou N., 2017.* La gestion paysagère des ravageurs : exploration des verrous et leviers d'une innovation agroécologique par la modélisation participative. *PhD dissertation,* Université de Toulouse.



◀ ***Co-constructed Bayesian network variables.*** *Variables related to landscape (light blue), agricultural practices (green), social factors (red), insect populations (dark blue), abiotic factors (purple) and economic factors (yellow). From Salliou N., 2017.* La gestion paysagère des ravageurs : exploration des verrous et leviers d'une innovation agroécologique par la modélisation participative. *PhD dissertation,* Université de Toulouse.

Urban communal gardens are pivotal for studying transdisciplinary research-training on environment-health topics

The ecological transition is being forged in the dynamics of territories in which civil society plays a major role, particularly in the urban agriculture (UA) field. The UA boom must be placed in the context of social concerns regarding sustainable development and nature, as well as food confidence crises. It also challenges the forms and locations of food production. Cities become 'gardened' territories embellished with small vegetable gardens or huge market gardening areas. Meanwhile people worldwide mainly reside in cities (80% in 2050, according to projections) and 40% of urban growth is concentrated in slums (FAO, 2015; WEF, 2015).

The growing awareness among urban dwellers of the crucial importance of places of human activity (such as communal gardens), sustainable food and biodiversity preservation contributes to UA development as a vehicle for democratic ecology. Pollution nevertheless often prevails in highly anthropized urban areas, with inevitable repercussions on food crop quality. Due to the complexity of the biogeochemical mechanisms involved in the transfer of substances to terrestrial ecosystems and the diverse range of exposure scenarios, scientists seldom have a straightforward answer to questions regarding human exposure to pollutants in places such as urban gardens. Promoting the development of sociotechnical methodologies to avoid, reduce and remedy the impact of urban pollution is hence a major scientific and societal challenge that requires operational collaboration between researchers, citizens and managers. Environmental regulations are indeed still incomplete. The AgriVille Network aims to promote UA in tandem with ecological transition, particularly by fostering innovative and inclusive dynamics between the different university, public and business stakeholders.

Contact: C. Dumat (UMR CERTOP/INP-ENSAT/Network-AgriVille), camille.dumat@ensat.fr
Collaborators: L. Sochaki (CERTOP/ Network-AgriVille), M. Messina (Monlong Communal Gardens), D. Dupouy (Tournefeuille Communal Gardens), E. Schreck (UMR GET)
For further information on the Network-AgriVille: http://reseau-agriville.com

◀ *The various functions of UA.*
From Dumat C., 2017.

CORMAS simulation platform and training in support of a community of practice

With the aim of introducing agent-based simulation to researchers working on renewable resource management and who were not necessarily modelling specialists, in the late 1990s the GREEN research unit of CIRAD designed a 2-week training course on multiagent systems (MASs) to introduce the agent-based paradigm by relating it to other modelling approaches used in this field. A progression towards MASs was proposed based on cellular automata and game theory. This training focused on demonstrations and hands-on exercises with agent-based simulation models implemented using the CORMAS platform. Participants were encouraged to work in small groups to develop prototypes with CORMAS that could potentially be applied to their research issues. A library of educational models illustrated the main concepts taught (e.g. modelling the spread of a forest fire being fought by a fire brigade). In the 2000s, new generic platforms emerged in France, supported by researchers with an interest in applications to the environmental management field and participating in discussions on companion modelling. Each of these platforms focuses on the development of agent-based simulation models from specific angles:

• Mimosa covers all phases, from conceptual modelling to implementation.
• GAMA (*see p. 50*) focuses on coupling with geographic information systems and is based on an architecture that supports multilevel support.
• NetLogo, initially designed as an active pedagogical tool to teach complexity, has become an international reference platform.

The training was initially based on a single platform, but was subsequently adapted to encompass several platforms. It has been focused on the CORMAS, NetLogo and Mimosa platforms since 2011, while GAMA replaced Mimosa in 2013. Trainers from different institutions conduct this training, which is offered every summer in Montpellier (France).

▲ *Discussion between participants to form groups of 2 to 4 people depending on the similarities between the research themes with the aim of jointly designing an agent-based prototype model.* © Pierre Bommel

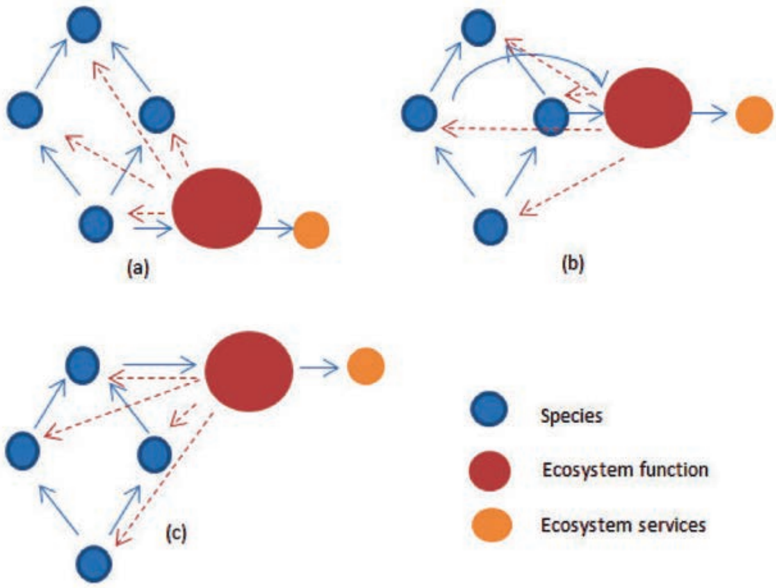
Contact: C. Le Page (UPR Green), christophe.le_page@cirad.fr
For further information on the MISS-ABMS summer school - Multi-platform International Summer School on Agent-Based Modelling & Simulation for Renewable Resources Management: www.agropolis.org/miss-abms

New decision-support models

Decision models for agroecology on a territorial scale

The Modelling of Agroecosystems and Decision research team (UR INRA-MIAT) conducts statistical, computer science and economics research in collaboration with its agriculture and ecology partners for the purpose of modelling and simulating agroecological management issues on a territorial scale. It also develops mathematical, computer and participatory tools for devising innovative agroecological strategies. The agroecological management issues we address with our partners are related to ecosystem service management on a territorial scale, in relation to agriculture, forestry, etc., while also seeking tradeoffs between these ecosystem services. To this end, the team develops:

1. Models of decision-making behaviours of farmers or forest managers in unstable conditions, which may take into account: (i) decision-makers' attitudes towards risk, (ii) 'limited rationality' behaviour, or (iii) biophysical and technical resource limitations. The relevant approaches are based on economics and artificial intelligence.
2. Simulation tools that facilitate the study or streamlining of complex decision-making processes on a territorial scale, potentially involving many interacting agents. This computer science and applied mathematics research is embodied in the simulation environments (spatial and multiagent) that we are co-developing: Virtual Laboratory Environment* and GAMA platform (*see p. 50*).
3. Research at the probabilistic graphical modelling-artificial intelligence interface focuses on modelling and approximate solving of problems of sequential decision-under-uncertainty in structured environments. These studies aim at finding tradeoffs between ecosystem services and biodiversity on a territorial scale, while also taking ecological interactions into account for the conservation of species communities. These issues require the development of innovative and powerful problem-solving methods to deal with decision problems that are too complex to be solved with conventional problem-solving tools.



Contact: R. Sabbadin (UR INRA-MIAT), regis.sabbadin@inra.fr
For further information: https://mia.toulouse.inra.fr/MAD_English

* www.vle-project.org

◀ ***Identification—for management purposes—of an ecological network and ecosystem services provided by a species community.*** *© MAD/MIAT*

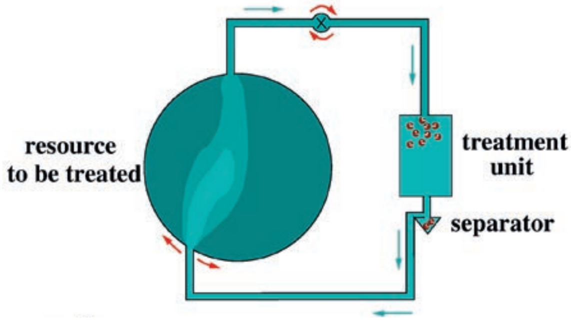
Closed loop purification of water resources

Biological depollution in wastewater treatment plants involves the use of microorganisms that degrade pollutant substances which they feed on for their growth. These microorganisms cannot be released into natural environments (lakes, ponds, reservoirs, etc.) because they would develop to the detriment of other life-forms, particularly through oxygen consumption—it would then be hard to remove them without draining the water resources. The contaminated water can nevertheless be pumped for continuous treatment in an external treatment unit (bioreactor) followed by its reintroduction after purification, while keeping the resource volume constant. A tradeoff between treatment rate and quality is thus sought by adjusting the flow rates and pump positioning to ensure timely purification of the water resources. The hydrodynamics of resources subject to pumping and discharge flows (governed by Navier-Stokes equations) is complex and depends on the resource geometry and pollutant diffusivity, thus making it very difficult to optimize the treatment time. A method combining numerical simulations of partial differential equations and simplified models of spatial heterogeneity representations has been developed, which helps:

- to optimize the pump flow rate, which is automatically adjusted to the pollution measurements at the pumping points over time
- and to determine the most efficient pump locations.

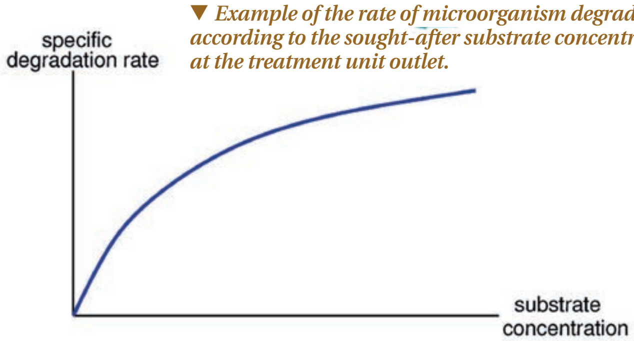
This method includes a first phase of calibration of a reduced model based on a more complex model while taking the geometry of the medium into account. The second operational phase uses optimal control tools to estimate the optimal treatment time.

Contacts: J. Harmand (UPR LBE), jerome.harmand@inra.fr, A. Rapaport (UMR MISTEA), alain.rapaport@inra.fr, A. Rousseau (INRIA-LEMON), antoine.rousseau@inria.fr



▲ ***Closed-loop water treatment principle.***
From Barbier et al. *J. Scientific Computing. 68:3 (2016).*

▼ ***Example of the rate of microorganism degradation according to the sought-after substrate concentration at the treatment unit outlet.***

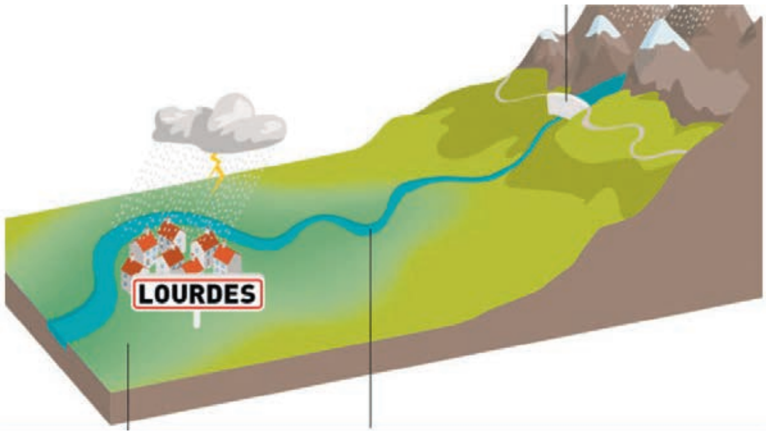


Spatiotemporal Bayesian network modelling of flash floods

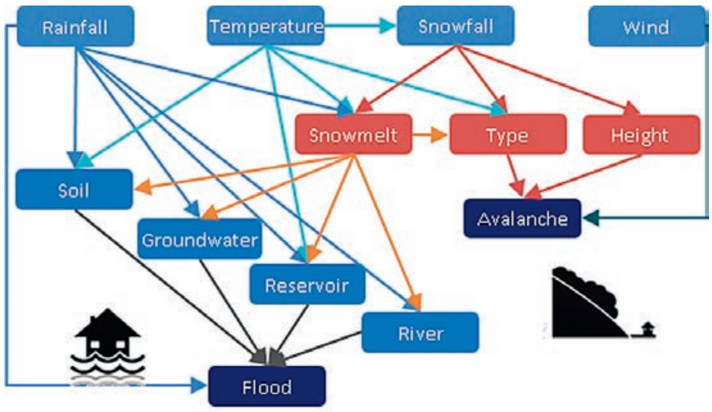
Flash flood prediction comes with some uncertainty due to monitoring and forecasting complications and insufficient insight into the processes involved. Current knowledge on flash flood risks must now be enhanced through the use, in the same framework, of contemporary analytical and empirical models in order to gain further awareness into the random component related to the occurrence and level reached by certain key variables when the feared event is under way. Analytical flow models have therefore been developed based on the physical features of the phenomena involved. The advantage of these models is that they can satisfactorily simulate the induced processes, however they do not shed light on the sheer complexity of the coupling of the variables involved. Conversely, probabilistic models are available but, owing to the infrequency of flash flood events, they do not take advantage of feedback to generate meaningful information on stochastic phenomena.

To bridge this gap, the aim of the Causal Model for Flood Risk Assessment (MERCI) project, jointly involving the *Institut de Mécanique des Fluides de Toulouse* (UMR IMFT) and the *Laboratoire Génie de Production* (EA LGP) of INPT-ENIT, is to develop a spatiotemporal causal model to explain and determine the probability of occurrence of the feared events for diagnostic and prognostic purposes. The modelling is based on Bayesian networks, which help dovetail analytical and statistical models. Since a flood is a phenomenon whose intensity varies over time, dynamic Bayesian networks that integrate the temporal dimension are used. Finally, the spatial dimension of the phenomenon is characterized—an elementary temporal model is used as a generic modelling brick under an object-oriented rationale, instantiated according to the modelled area and temporally sequenced according to the timeframe in which the phenomenon unfolds.

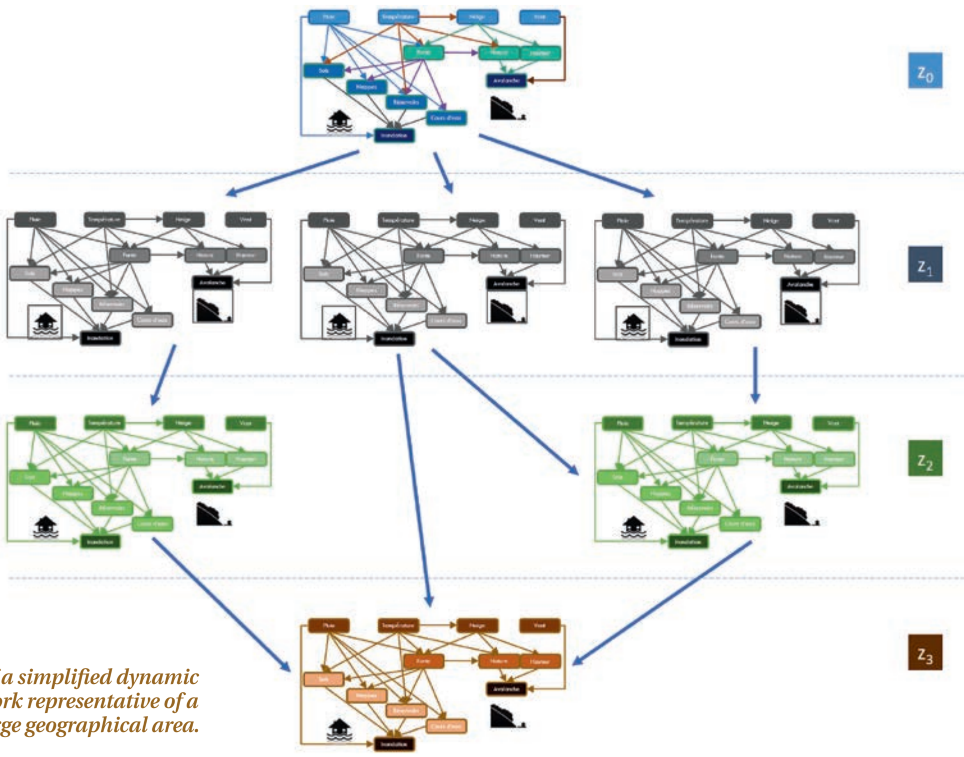
Contacts: Q. Liu (EA LGP), quan.liu@enit.fr, A. Tchangani (EA LGP), ayeley.tchangani@enit.fr, H. Roux (UMR IMFT), helene.roux@imft.fr, F. Pérès (EA LGP), francois.peres@enit.fr



▲ *Causal model for flood risk assessment.*



▲ *Example of a simplified Bayesian network representative of a primary geographical area.*



▶ *Example of a simplified dynamic Bayesian network representative of a large geographical area.*

Federative research bodies related to complex systems

XSYS: Toulouse Institute for Complex Systems Studies

XSYS brings together key players from Toulouse and Occitanie region whose complementary expertise is essential for building crosscutting methodological approaches that can be implemented to address the intrinsic complexity of major societal issues.

Complexity is included in most scientific fields and dealt with using different approaches from the perspective their specific fields of expertise. XSYS seeks to harness this diversity to address complexity by enhancing the integration of experimental and modelling practices, while rethinking the theoretical framework of complex systems science. The aim is to combine expert knowledge and formal approaches to analyse, understand and take action under three crosscutting research themes: dynamic networks, collective motions and mobilities, and risk adaptation.

XSYS is committed to developing interdisciplinary scientific research, collaborative innovation, training and knowledge sharing on complex systems and their applications. In-depth research on emergence, multiscale dynamics, feedback loops, cascade phenomena, bifurcations, non-linear dynamics, and stochastic environmental impacts concepts is carried out within the framework of the thematic projects.

XSYS coordinates a dynamic platform based on a core of 20 laboratories and more than 200 researchers, in addition to 17 non-academic structures (SMEs, associations, local authorities).

Contact: B. Jouve, bertrand.jouve@cnrs.fr
For further information:
http://xsys.fr/en/welcome
Twitter: @xsys_toulouse
LinkedIn: XSYS - *Institut d'Études des Systèmes Complexes de Toulouse*
Facebook: @XSYSTlse

#DigitAg: Digital Agriculture Convergence Lab

#DigitAg is one of the five Convergence Institute projects selected by the French National Research Agency (ANR) in its first call for proposals in July 2016. It is the only project located in the Occitanie/Pyrénées-Méditerranée region and includes more than 300 members from 17 public and private partners:
• 4 research organisations: IRSTEA, INRA, CIRAD and INRIA
• 3 higher education institutions: UM, Montpellier SupAgro and AgroParisTech
• 2 innovation and transfer structures: ACTA and AxLR
• 8 companies: ITK, SMAG, Vivelys, IDATE, Fruition Sciences, Pera-Pellenc, TerraNIS and Agriscope

It aims to become a world benchmark in digital agriculture by developing the knowledge underpinnings for the roll-out of digital agriculture in France and the Global South. Based on interdisciplinary research in agronomy, digital science, economic and social science, management science and law, #DigitAg seeks to address two major societal challenges: finding ways to produce better in agriculture while mainstreaming agriculture better into society. #DigitAg features a graduate school that offers 24 Master's programmes and hosts 300 students yearly. Innovative educational initiatives are under way: a digital agriculture usage observatory, *Mas numérique*, AgroTIC Chair, massive open online courses (MOOCs), an annual hackathon, etc. Finally, with eight partner companies and a technology transfer accelerator office (SATT), #DigitAg is committed to promoting innovation: business training, early innovation detection and provision of 10 years of IT development to spur technology transfer.

Key figures
• 9.9 million euro operating budget for 7 years
• 25 research units and joint research units (UMRs)
• 56 cofinanced PhD theses
• 50 accredited theses
• 150 Master's scholarships
• 18 years of post-doc studies
• 72 months of hosting top-notch researchers
• 120 months of computer development

Contact: P. Péré, contact@hdigitag.fr
For further information: www.hdigitag.fr/en

LabEx Laboratories of Excellence

Agro: Agronomy and Sustainable Development

LabEx Agro (funded under the French Programme "*Investissements d'Avenir*" 2011-2019) focuses on plants, agriculture, food and sustainable development. Managed by Agropolis Fondation, a Foundation for Scientific Cooperation, it brings together 41 research units and around 1,500 scientists from 12 public institutions. Overall, it represents a continuum of multidisciplinary competencies—biological sciences, agricultural sciences, engineering sciences, humanities and social sciences—from the study of genes and the plant, to the production, processing, final-use of plants and plant products and related societal issues. It has renowned expertise on numerous temperate, Mediterranean and tropical plant species and the corresponding production and processing systems. The network's scientific expertise is structured in five scientific fields:

- Genetics, genomics, ecophysiology, plant breeding
- Biotic interactions of plants, integrated crop protection
- Agroecosystem management and agroecology
- Processing technologies, food and non-food product quality
- Society-agriculture interactions, social management of innovation

LabEx Agro pools a broad spectrum of unique internationally-renowned scientific expertise. It addresses societal challenges via complex systems approaches: preparing tomorrow's crops, developing conditions for agriculture to adapt and mitigate climate change, understanding interactions between agriculture and food value chains, territories and sustainable development.

Contact: P. Kosuth, kosuth@agropolis.fr
For further information: www.agropolis-fondation.fr

CeMEB: Mediterranean Centre for Environment and Biodiversity

LabEx CeMEB federates 10 research units in Montpellier and Perpignan (AMAP, CBGP, CEFE, Eco&Sols, ECOTRON, IHPE, ISEM, CEE-M, MARBEC and MIVEGEC). Research is focused on biodiversity and ecosystem dynamics and functioning in a context of marked environmental change, notably alterations due to human activities. Scenario-based predictions of the biological impacts of global change and forecasting of changes in ecosystem services and human societies are key goals. The research units study a wide range of ecosystems (terrestrial and marine) and living organisms, while focusing specifically on wild biodiversity via numerous long-term field research programmes. The interdisciplinary approaches, based on the complex systems notion, combine monitoring, experiments and modelling using top-notch tools (e.g. European Ecotron of Montpellier) or the experimental facility at Puéchabon, as well as on shared technological platforms (e.g. (epi)genomics or bioinformatics). CeMEB contributes to the organization and streamlining of biodiversity research in Montpellier by providing financial support for research (e.g. funding research projects, postdoctoral grants, etc.). CeMEB also develops transfer activities to the socioeconomic sphere.

Contact: P. Jarne, philippe.jarne@cefe.cnrs.fr
For further information: www.labex-cemeb.org/en

NUMEV: Digital and Hardware Solutions and Modelling for the Environment and Life Sciences

LabEx NUMEV, accredited in 2011 in the framework of the French PIA1 programme, emerged from the organization of the UM Mathematics, Informatics, Physics and Systems (MIPS) community to address major societal challenges in formal and digital science fields at the crossroads of health, environment and life sciences. NUMEV promotes the development of innovative research programmes focused on modelling, tailoring these models to concur with the physical sphere, and on data display and mining methods, while enhancing them with algorithmic and computational features. The development of integrated projects related to environmental monitoring, human health care and assistance, and genome modelling (mathematical, physical and computer) enables the laboratory to meet complex and fundamental societal challenges. Some integrated projects have morphed into flagship projects geared towards strengthening the structure of research activities at the Montpellier (France) site, while broadening the global reach of the projects. NUMEV also dovetails research and training by supporting young researcher's projects, novel university training, international schools and initiatives that promote student's scientific initiatives. Finally, this LabEx strives constantly to reconcile academic and socioeconomic sectors by supporting several business start-up projects, some of which have benefitted from SATT AxLR maturation programmes. This laboratory brings together six joint research units (UMRs), INRIA teams and a host team (EA), while standing at the crossroads of multidisciplinary activities and expertise, thus providing a powerful tool for effective development and structuring of the MIPS community's scientific activities at the interface with environmental and life sciences.

Contacts: A. Parmeggiani and L. Torres, numev-direction@umontpellier.fr
For further information: www.lirmm.fr/numev

SMS: Structuring of Social Worlds

LabEx SMS has successfully established a social science research cluster in the Toulouse region, federating nine research units (history, geography, political economy, sociology, ethnology, social psychology, information and communication science, and political science), 450 permanent staff and about 300 PhD students to focus on 11 research initiatives, three methodology workshops, collaborative research and knowledge dissemination activities and a Master's network. The expression 'social world structures' represents a renewal of the approach to what were once called 'social structures' by focusing on dynamics and addressing social phenomena via interpersonal relationship networks, technical mechanisms, social rules and norms, and territories.

Contacts: M. Grossetti, Michel.Grossetti@univ-tlse2.fr
and C. Bauza,

For further information: http://sms.univ-tlse2.fr

TULIP, *Towards a Unified Theory of Biotic Interactions: Role of Environmental Perturbations*

LabEx TULIP aims at developing a global theory of interactions among organisms in order to study their roles in the adaptation of living organisms to environmental change. The project brings together seven agrobioscience and environmental science laboratories of excellence in Toulouse, Moulis and Perpignan, with around 600 research staff, of all categories, from INRA, CNRS, UT3, INPT-ENSAT and UPVD. Based on multidisciplinary approaches (biology, evolutionary ecology, genetics, modelling, etc.) involving diverse microbial, plant or animal organism experimental models (at every scale from molecules to semi-natural ecosystems), and by combining them with theoretical approaches, TULIP researchers propose predictions on the potential evolution of resources under changing environments. They also work to find solutions to the future impacts of global change on humanity. The TULIP research community explores the complexity of biotic interactions at various scales (genes to ecosystems), thereby transcending the thematic boundaries between environmental sciences and plant integrative biology by addressing a broad spectrum of questions, while establishing close links between the different dimensions and using shared concepts. Beyond its research activities, LabEx TULIP develops training courses (summer school, interface Master courses) and fosters innovation.

Contact: D. Roby, dominique.roby@inra.fr
For further information: www.labex-tulip.fr/labex-tulip_eng

LabEx EpiGenMed (From genome and epigenome to molecular medicine) also supports modelling activities on living organisms and the environment.

Contact: contact@epigenmed.fr
For further information: www.epigenmed.fr

Topics covered by the research teams

(January 2019)

The main research units and teams mentioned in this Dossier are listed in the following chart. Dark green areas ■ indicate a theme that is the main focus of the research body, while pale green areas □ represent other themes in which it is also involved.

Chapter 1. Complex systems, data collection and management
1.1. Data harvesting
1.2. Data interpretation
1.3. Data provision-accessibility and interoperability

Chapter 2. Understanding and analysing complex systems
2.1. Organism dynamics
2.2. Population dynamics
2.3. Ecosystem dynamics
2.4. Territorial management

Chapter 3. Different applications of the complex systems approach
3.1. Use of observatories
3.2. Multicriteria decision support
3.3. Participation and consultation
3.4. New decision-support models

Research teams and units	Number of scien-tists	Chapter 1			Chapter 2				Chapter 3			
		1.1	1.2	1.3	2.1	2.2	2.3	2.4	3.1	3.2	3.3	3.4
Centre LGI2P • **Laboratoire de Génie Informatique et d'Ingénierie de Production** *(IMT Mines Alès)* Director: Jacky Montmain, jacky.montmain@mines-ales.fr http://lgi2p.mines-ales.fr	23							■		■		
CERFACS • **Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique** *(Airbus/CNES/EDF/Météo France/ONERA/Safran/Total)* Director: Catherine Lambert, catherine.lambert@cerfacs.fr www.cerfacs.fr	106						■					
CINES • *National Computing Center for Higher Education (MESRI)* Director: Francis Daumas, daumas@cines.fr www.cines.fr	18	■	■	■						■		
EA LGP • **Laboratoire Génie de Production** *(ENIT)* Director: Jean Denape, jean.denape@enit.fr www.lgp.enit.fr/fr/lgp.html	55	□	□	□						■	■	■
Virtual Plants project team • *French Institute for Research in Computer Science and Automation (INRIA/CIRAD/INRA)* Coordinator: Christophe Godin, christophe.godin@inria.fr www.inria.fr/equipes/virtual-plants	10	□	■	□	■					□		
IBC • *Computational Biology Institute (UM/CNRS/INRA/Montpellier SupAgro/IRD/CIRAD/INSERM/INRIA)* Director: Éric Rivals, rivals@lirmm.fr www.ibc-montpellier.fr	119				■							
OSU OREME • *Observatory for Research on the Mediterranean Environment (UM/CNRS/IRD/IRSTEA)* Director: Éric Servat, eric.servat@umontpellier.fr www.oreme.org	4	■	■	■	■	■	■	■		□		
UMI UMMISCO • *Mathematical and Computer Modeling of Complex Systems (IRD/UPMC/UCA/UCAD/Univ. Yaoundé 1/USTH)* Director: Jean-Daniel Zucker, jean-daniel.zucker@ird.fr www.ummisco.fr	75					■						
UMR AGAP • *Genetic Improvement and Adaptation of Mediterranean and Tropical Plants (CIRAD/INRA/Montpellier SupAgro)* Director: Patrice This, diragap@cirad.fr https://umr-agap.cirad.fr	191				■							
UMR AGIR • *Agroecologies - Innovations - Ruralities (INRA/INPT)* Director: Jacques-Eric Bergez, Jacques-Eric.Bergez@inra.fr www6.toulouse.inra.fr/agir	60							■			□	

Research teams and units	Number of scientists	Chapter 1			Chapter 2				Chapter 3			
		1.1	1.2	1.3	2.1	2.2	2.3	2.4	3.1	3.2	3.3	3.4
UMR AMAP • *Botany and Computational Plant Architecture (CIRAD/CNRS/INRA/IRD/UM)* Director: Thierry Fourcaud, diramap@cirad.fr http://amap.cirad.fr/fr/index.php	45											
UMR AMIS • **Laboratoire d'anthropologie moléculaire et imagerie de synthèse** *(CNRS/UT3)* Director: Éric Crubézy, eric.crubezy@univ-tlse3.fr http://amis.cnrs.fr	28											
UMR ASTRE • *Animals, Health, Territories, Risks & Ecosystems (CIRAD/INRA)* Director: Thierry Lefrançois, dir.astre@cirad.fr https://umr-astre.cirad.fr	74											
UMR B&PMP • *Biochemistry & Plant Molecular Physiology (CNRS/INRA/Montpellier SupAgro/UM)* Director: Alain Gojon, alain.gojon@inra.fr www1.montpellier.inra.fr/ibip/bpmp/index.htm	50											
UMR CBGP • *Centre for Biology and Management of Populations (INRA/IRD/CIRAD/Montpellier SupAgro)* Director: Flavie Vanlerberghe, dircbgp@supagro.inra.fr www1.montpellier.inra.fr/CBGP	34											
UMR CEE-M • *Center for Environmental Economics – Montpellier (CNRS/INRA/Montpellier SupAgro/UM)* Director: Brice Magdalou, brice.magdalou@univ-montp1.fr www.cee-m.fr	31											
UMR CEFE • *Center for Functional and Evolutionary Ecology (CNRS/UM/UPVM/IRD/Montpellier SupAgro/INRA/EPHE)* Director: Richard Joffre, direction@cefe.cnrs.fr www.cefe.cnrs.fr	89											
UMR CERTOP • **Centre d'Étude et de Recherche Travail Organisation Pouvoir** *(UT2J/CNRS/UT3)* Director: Marie-Gabrielle Suraud, marie-gabrielle.suraud@iut-tlse3.fr http://certop.cnrs.fr	139											
UMR CESBIO • **Centre d'Études Spatiales de la BIOsphère** *(UT3/CNES/CNRS/IRD)* Director: Laurent Polidori, laurent.polidori@cesbio.cnes.fr www.cesbio.ups-tlse.fr	58											
UMR CNRM • *National Centre for Meteorological Research* **(Météo France/CNRS)** Director: Marc Pontaud, marc.pontaud@meteo.fr www.umr-cnrm.fr	87											
UMR DIMNP • **Dynamique des Interactions Membranaires Normales et Pathologiques** *(CNRS/UM)* Director: Georges Lutfalla, georges.lutfalla@umontpellier.fr www.dimnp.univ-montp2.fr	55											
UMR DYNAFOR • *Dynamics and Ecology of Agriforestry Landscapes (INRA/Toulouse INP)* Director: Marc Deconchat, marc.deconchat@inra.fr www.dynafor.fr	25											
UMR Eco&Sols • *Functional Ecology & Bio-geochemistry of Soils & Agro-ecosystems (Montpellier SupAgro/CIRAD/INRA/IRD)* Director: Jean-Luc Chotte, eco-sols@ird.fr www.umr-ecosols.fr	53											
UMR ESPACE-DEV • *Space for Development (IRD/UM/Univ. des Antilles/Univ. de Guyane/Univ. Réunion)* Director: Frédérique Seyler, espace-dev@ird.fr www.espace-dev.fr	52											
UMR G-EAU • *Water Resource Management, Actors and Uses (AgroParisTech/CIRAD/IRD/IRSTEA/Montpellier SupAgro)* Director: Olivier Barreteau, olivier.barreteau@irstea.fr https://g-eau.fr	60											
UMR GEODE • *Environmental Geography (CNRS/UT2J)* Director: Didier Galop, Didier.galop@univ-tlse2.fr http://w3.geode.univ-tlse2.fr/index.php	37											
UMR GM • **Geosciences Montpellier** *(CNRS/UM/Université des Antilles)* Director: Benoît Ildefonse, dirgm@gm.univ-montp2.fr www.gm.univ-montp2.fr	80											
UMR GRED • *Governance, Risk, Environment, Development (IRD/UPVM)* Director: Bernard Moizo, gred@ird.fr www.gred.ird.fr	45											
UMR HSM • **HydroSciences Montpellier** *(CNRS/IRD/UM)* Director: Patrick Seyler, direction@msem.univ-montp2.fr, elise.deme@umontpellier.fr www.hydrosciences.org	55											
UMR IMFT • **Institut de Mécanique des Fluides de Toulouse** *(CNRS/Toulouse INP/UT3)* Director: Éric Climent, direction@imft.fr www.imft.fr	83											
UMR IRIT • *Toulouse Institute of Computer Science Research (CNRS/INPT/UT3/UT Capitole/UT2J)* Director: Michel Daydé, Michel.Dayde@irit.fr www.irit.fr	320											

Research teams and units	Number of scien-tists	Chapter 1			Chapter 2				Chapter 3			
		1.1	1.2	1.3	2.1	2.2	2.3	2.4	3.1	3.2	3.3	3.4
UMR ISE-M • *Montpellier Institute of Evolutionary Sciences (CIRAD/CNRS/IRD/UM/EPHE)* Director: Agnès Mignot, dirisem@univ-montp2.fr www.isem.univ-montp2.fr	130	□	□		■	■	■					
UMR ITAP • *Information-Technologies-Environmental Analysis-Agricultural Processes (IRSTEA/Montpellier SupAgro)* Director: Tewfik Sari, tewfik.sari@irstea.fr http://itap.irstea.fr	22		■					■		■		
UMR L2C • **Laboratoire Charles Coulomb** *(CNRS/UM)* Director: Pierre Lefebvre, Pierre.Lefebvre@umontpellier.fr www.coulomb.univ-montp2.fr	150		■		■	■		■				■
UMR LEASP • **Laboratoire d'Épidémiologie et d'Analyses en Santé Publique** *(INSERM/UT3)* Director: Sandrine Andrieu, sandrine.andrieu@univ-tlse3.fr www.u1027.inserm.fr/activites-scientifiques-341411.kjsp?RH=1304948096435&RF=1303915886944	103				□	■						
UMR LIRMM • *Montpellier Laboratory of Computer Science, Robotics and Microelectronics (CNRS/UM)* Director: Philippe Poignet, Philippe.Poignet@lirmm.fr www.lirmm.fr	167	■		■								
UMR LISAH • *Laboratory for the Study of Soil-Agrosystem-Hydrosystem Interactions (INRA/IRD/Montpellier SupAgro)* Director: Jérôme Molénat, jerome.molenat@inra.fr www.umr-lisah.fr	26						■	■				
UMR LISST • *Interdisciplinary Laboratory Solidarities, Societies and Territories (UT2J/CNRS/EHESS/ENSFEA)* Director: Olivier Pliez, olivier.pliez@univ-tlse2.fr http://lisst.univ-tlse2.fr	103	■	■	■		■	□	□			□	
UMR MARBEC • *Marine Biodiversity, Exploitation and Conservation (IRD/IFREMER/UM/CNRS)* Director: Laurent Dagorn, marbec-dir@listes.ird.fr www.umr-marbec.fr/fr	121				■	■	■					
UMR MISTEA • *Mathematics, Computer Science and Statistics for Environment and Agronomy (INRA/Montpellier SupAgro)* Director: Pascal Neveu, pascal.neveu@inra.fr www6.montpellier.inra.fr/mistea	14	■	■			■					■	■
UMR MIVEGEC • *Genetics and Evolution of Infectious Diseases (IRD/CNRS/UM)* Director: Frédéric Simard, frederic.simard@ird.fr, mivegec@ird.fr http://mivegec.ird.fr/fr	90	□	□	□		■	■			□		□
UMR SYSTEM • *Tropical and Mediterranean Cropping System Functioning and Management (CIRAD/INRA/Montpellier SupAgro/CIHEAM-IAMM)* Director: Christian Gary, christian.gary@inra.fr http://umr-system.cirad.fr	22		■				□	■		■		
UMR TETIS • *Spatial Information and Analysis for Territories and Ecosystems (AgroParisTech/CIRAD/CNRS/IRSTEA)* Director: Christiane Weber, christiane.weber@cnrs.fr http://tetis.teledetection.fr	48	■		■			■		■	■		
UMS CALMIP • **Calculateur en Midi-Pyrénées** *(CNRS)* Director: Jean-Luc Estivalèzes, jean-luc.estivalezes@imft.fr www.calmip.univ-toulouse.fr	7						■	■				
UPR GREEN • *Management of Renewable Resources and Environment (CIRAD)* Director: Aurélie Botta, dir-green@cirad.fr http://ur-green.cirad.fr	21							■			■	
UPR LBE • *Laboratory of Environmental Biotechnology (INRA)* Director: Nicolas Bernet, nicolas.bernet@inra.fr www6.montpellier.inra.fr/narbonne	15	■	■				■					■
UR MIAT • *Applied Mathematics and Informatics Toulouse (INRA)* Director: Sylvain Jasson, sylvain.jasson@inra.fr https://mia.toulouse.inra.fr/Accueil	25							■		□	□	■

Federative research bodies	Number of scien-tists	Chapter 1			Chapter 2				Chapter 3			
		1.1	1.2	1.3	2.1	2.2	2.3	2.4	3.1	3.2	3.3	3.4
#DigitAg • *Digital Agriculture Convergence Lab (IRSTEA/INRA/CIRAD/INRIA/UM/Montpellier SupAgro/AgroParisTech/ACTA)* Coordinator: Pierre Péré, contact@hdigitag.fr www.hdigitag.fr/fr	352											
EquipEx GEOSUD • *GEOinformation for SUstainable Development (AgroParisTech/CEREMA/CINES/CIRAD/CNRS/IGN/IRD, IRSTEA/UM/Univ. des Antilles/Univ. de Guyane/Univ. de la Réunion/AFIGEO/GEOMATYS)* Coordinator: Pierre Maurel, pierre.maurel@irstea.fr http://ids.equipex-geosud.fr	100											
LabEx Agro • *Agronomy and Sustainable Development (CIHEAM-IAMM/CIRAD/CNRS/Inra/IRD/Irstea/Montpellier SupAgro/UAPV/UM/UPVD/UR/AgroParisTech/Agropolis Fondation)* Director: Pascal Kosuth, kosuth@agropolis.fr www.agropolis-fondation.fr	1500											
LabEx CeMEB • *Mediterranean Centre for Environment and Biodiversity (UM/CIRAD/CNRS/IFREMER/INRA/INRAP/IRD/EPHE/Montpellier SupAgro/UPVM/Unîmes/UPVD)* Director: Philippe Jarne, philippe.jarne@cefe.cnrs.fr www.labex-cemeb.org/fr	650											
LabEx NUMEV • *Digital and Hardware Solutions and Modelling for the Environment and Life Sciences (UM/CNRS/INRIA/INRA/Montpellier SupAgro)* Directors: Andréa Parmeggiani and Lionel Torres, numev-direction@umontpellier.fr www.lirmm.fr/numev	250											
LabEx SMS • *Structuring of Social Worlds (UT Capitole/UT2J/UT3/INP/IEP/CNRS/INRA/EHESS/ENSFEA)* Director: Michel Grossetti, Michel.Grossetti@univ-tlse2.fr http://sms.univ-tlse2.fr	450											
LabEx TULIP • *Towards a Unified Theory of Biotic Interactions: Role of Environmental Perturbations (CNRS/INRA/UT3/INP-ENSAT/UPVD)* Directors: Dominique Roby and Étienne Danchin, dominique.roby@inra.fr www.labex-tulip.fr	250											
XSYS • *Toulouse Institute for Complex Systems Studies (CNRS/Université de Toulouse)* Coordinator: Bertrand Jouve, contact@xsys.fr http://xsys.fr	200											

Training offered in the complex systems field in Occitanie

Universities, vocational schools and engineering schools in Occitanie region propose a broad range of degree courses (from Bac +2 to Bac +8: technician, engineering degree, Master's, specialized Master's PhD, etc.) and a comprehensive survey of these courses is underway throughout the region. Many training courses offered in the Occitanie region—irrespective of whether or not they lead to a degree—include modules that deal with complex systems. Below are some examples of these training courses.

Agropolis International proposes a complete training-education programme provided through its member institutions (universities and engineering schools, as well as vocational training institutions in Montpellier and throughout the Languedoc-Roussillon area—more than 80 degree courses as well as vocational training modules (existing or tailored upon request) may be found online (www.agropolis.org/training). Training courses offered by universities, *grandes écoles* and research organisations in the Toulouse Midi-Pyrénées area are available via the relevant training departments, a list of which can be found on the *Université Fédérale de Toulouse Midi-Pyrénées* website (https://en.univ-toulouse.fr/courses-all).

A few short non-degree training-education courses

Institution	Title	For further information
AgroParisTech	Towards a spatialized decision-making information system using ETL tools (2 days)	www2.agroparistech.fr/Presentation-of-AgroParisTech.html
	Introduction to consultation practices in the water sector (3 days)	
	Digital field model: methods and tools (4 days)	
	Spatial information uses in territorial assessments (4 days)	
CIRAD	Scientific database design for analysis and modelling (5 days)	www.cirad.fr/en/teaching-training/available-training
	Simulation of spatial dynamics with Ocelet (4 days)	
	Companion modelling: empowering actors to share representations and simulate dynamics (5 days)	
	Workshop on natural and artificial complex systems (1 days)	
	Dynamic systems modelling applied to infectious disease epidemiology (4 days)	
CIHEAM-IAMM	Integrated assessment of agriculture and sustainable development: (specialized intensive course offered in English)	www.iamm.ciheam.org/en/education/fpc
	Modelling and decision support (MSc module tailored upon request)	
Montpellier SupAgro	Data Science. Initiation to data science applied to agronomy and agrifood sectors (3 days)	www.montpellier-supagro.fr/formations/formation-tout-au-long-de-la-vie/recherche-une-formation-continue
Université Toulouse III - Paul Sabatier	Numerical simulation and sensitivity analysis: Direct sensitivity models and parallel resolutions for differential and integral formulations. Implementation for finite difference or finite volume resolutions and for Monte Carlo methods. Introduction to adjoint sensitivity models (3 days)	http://mfca.univ-tlse3.fr
	Statistical engineering of complex systems – Thermal: training on numerical simulation techniques and analysis of complex thermal systems using statistical approaches (3 days)	
	Statistical engineering of complexity – The Monte Carlo method: an introduction to the Monte Carlo method with a focus on engineer's needs when faced with a challenge of simulating and digitally analysing a complex system (3 days)	
Research schools		
ComMod Association	Research school – 'Companion modelling: placing actors in situations to share representations and simulate the dynamics' (1 week)	www.commod.org/en/formations
CIRAD, IRSTEA, *Université de Rouen, Université Toulouse 1 Capitole*, CNRS	MISS-ABMS - Multi-platform international summer school on agent-based modelling & simulation for renewable resource management (2 weeks)	www.agropolis.org/miss-abms (*description p. 67*)
INRA	Research school – 'Interdisciplinary approaches to agroecosystems: Complex system, Model, Code'	www6.inra.fr/record_eng (*see box on next page*)

Level	Degree	Title	Institution	For further information
Bac + 5	*Master* (MSc)	Biodiversity – Ecology – Evolution (B2E). Focus 'Integrated environmental, biodiversity and territorial management' (GeBioTE)	*Université de Montpellier*	https://biologie-ecologie.com/parcours-giebiote/
	Master (MSc)	M2 Neuroscience – Behaviour – Cognition	*Université Toulouse III - Paul Sabatier*	http://www.masterbiosante.ups-tlse.fr/m2-neurosciences-comportement-cognition-610626.kjsp?RH=1298890088210
	Master (MSc)	High Throughput Computation, Simulation	UPVD	www.univ-perp.fr/en/discover-the-upvd-1824.kjsp?RH=UPVD_FORMATION
	Ingénieur (Engineering degree)	Specialization I3D 'Sustainable development engineering' (via 6 schools of INP Toulouse)	INP Toulouse	www.ensat.fr/en/index.html
Bac + 6	*Mastère spécialisé®* (Specialized MSc)	Localized information systems for spatial planning (SILAT)	AgroParisTech	www2.agroparistech.fr/Presentation-of-AgroParisTech.html
		Ecological engineering	INP Toulouse	http://www.inp-toulouse.fr/fr/formations/l-offre-de-formation/mastere-et-dhet/msei.html
Bac + 8	*Doctorat* (PhD)	International Doctoral Programme 'Complex systems modelling' (PDI MSC)	IRD/UPMC/UMMISCO	www.pdimsc.upmc.fr/fr/le_programme_doctoral_international.html

RECORD platform and research school devoted to agroecosystem modelling and simulation

Multidisciplinary research is increasingly essential for studying agroecosystems to address current environmental challenges regarding agriculture and society, particularly in relation to climate change. Systemic analysis, modelling and virtual computer experimentation are used to analyse and appraise a multitude of possibilities in a range of situations. INRA has launched initiatives to foster the development of modelling and simulation platforms to help scientists in this comprehensive and prospective work, including the RECORD platform that was specially developed for studying agroecosystems. But these platforms are still relatively unknown, although they provide a tremendous sharing and multidisciplinary research tool. To remedy this situation, the Interdisciplinary Approaches to Agroecosystem Modelling: Complex System, Model, Code research school was developed by a multidisciplinary scientific committee. The challenges the school is seeking to meet include helping researchers develop their skills in systemic analysis and modelling of complex systems, while broadening the current RECORD community to achieve progress on agroecosystem analysis, assessment and design issues. Its objectives are to apply the systemic approach for interdisciplinary model building, to implement systemic modelling on a common thread example (a territorial water management model that includes agricultural, societal and environmental issues), to develop good modelling practices (code, assessment, etc.), to be familiar with the main modelling platforms and position them relative to each other, and finally to discover and get to know the RECORD platform. A first research school session was held in March 2017 (4 days) and was attended by some 20 participants from different disciplines. A massive open online course (MOOC) is currently being set up on the basis of interventions at the research school. In addition, training courses on the use of the platform are held annually.

Contact: H. Raynal, Helene.Raynal@inra.fr
For further information: www6.inra.fr/record_eng

Institute for Ecological, Economic and Energy Transmission (IT3E)

IT3E—a lifelong training institute focused on sustainable development—aims to address to the urgent need to enhance the expertise required to oversee changes associated with societal transitions, in fields ranging from the hard sciences to sociology, economics and law. The institute benefits from the many diverse research and training structures within the *Université Toulouse III – Paul Sabatier*, the *Université Fédérale de Toulouse*, and throughout the Occitanie region to help it achieve its goals. This wealth of assets is tapped to mobilize specialists and 'expert' actors at both regional and national levels in each theme to deal with the myriad dimensions associated with the three transitions. XSYS offers modules and participates in the provision of courses on complex systems and their applications in the transition context in order to compliment the training services offered by IT3E.

The training courses provided by IT3E are innovative in terms the educational tools offered: mentoring, e-learning (MOOCs, webinars), flipped classrooms, experience sharing, open forums, mind mapping, serious games, hackathons, role-playing games, case studies, etc. The many courses offered are targeted at professionals from all backgrounds—business leaders, senior executives, local elected officials, scientific and political leaders, etc. The training is tailored to trainee's needs: the course time schedules are adjustable; the courses can be completed online; the subjects can be selected from a catalogue, à la carte or upon request; and the training is adapted to each level (awareness, in-depth studies and expertise).

Contact: V. Le Dantec, valerie.le_dantec@it3e.org
For further information: www.it3e.org

List of acronyms and abbreviations

AFIGEO	*Association française pour l'information géographique* (France)
ANR	French National Research Agency / *Agence Nationale de la Recherche*
CEREMA	*Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement* (France)
CIHEAM-IAMM	International Centre for Advanced Mediterranean Agronomic Studies – Mediterranean Agronomic Institute of Montpellier / *Centre international de hautes études agronomiques méditerranéennes - Institut Agronomique Méditerranéen de Montpellier* (France)
CINES	National Computing Center for Higher Education / *Centre Informatique National de l'Enseignement Supérieur* (France)
CIRAD	Agricultural Research for Development / *Centre de coopération internationale en recherche agronomique pour le développement* (France)
CNES	National Centre for Space Studies / *Centre national d'études spatiales* (France)
CNRS	National Center for Scientific Research / *Centre national de la recherche scientifique* (France)
EA	Host team / *Équipe d'accueil*
EHESS	School for Advanced Studies in the Social Sciences / *École des hautes études en sciences sociales* (France)
ENSFEA	*École Nationale Supérieure de Formation de l'Enseignement Agricole de Toulouse* (France)
EPHE	*École Pratique des Hautes Études* (France)
EquipEx	Laboratory equipment enhancement projects / *Équipement d'excellence*
IEP	Toulouse Institute of Political Studies / *Sciences Po Toulouse* (France)
IFREMER	French Research Institute for Exploitation of the Sea / *Institut Français de Recherche pour l'Exploitation de la Mer*
IGN	National Institute of Geographic and Forest Information / *Institut national de l'information géographique et forestière* (France)
IMT	*Institut Mines-Télécom* (France)
INP Toulouse	National Polytechnic Institute of Toulouse / *Institut national polytechnique de Toulouse* (France)
INP-ENIT	*École nationale d'ingénieurs de Tarbes* (France)
INP-ENSAT	School of Agricultural and Life Sciences / *École nationale supérieure agronomique de Toulouse* (France)
INRA	National Institute for Agricultural Research / *Institut national de la recherche agronomique* (France)
INRAP	*Institut national de recherches archéologiques préventives* (France)
INRIA	French Institute for Research in Computer Science and Automation / *Institut national de recherche en informatique et en automatique*
INSERM	French Institute of Health and Medical Research / *Institut national de la santé et de la recherche médicale*
IRD	French Research Institute for Development / *Institut de recherche pour le développement*
IRSTEA	National Research Institute of Science and Technology for Environment and Agriculture / *Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture (France)*
LabEx	Laboratory of excellence / *Laboratoire d'excellence*
MESRI	French Ministry of Higher Education, Research and Innovation / *Ministère de l'Enseignement supérieur, de la Recherche et de l'Innovation*
ONERA	French Aerospace Lab / *Office national d'études et de recherches aérospatiales*
OREME	Observatory for Research on the Mediterranean Environment / *Observatoire de Recherche Méditerranéen de l'Environnement (France)*
OSU	Observatory for Science of the Universe / *Observatoire des Sciences de l'Univers* (France)
PIA	Investments for the Future / *Programme 'Investissements d'Avenir' (France)*
RNSC	French National Network for Complex Systems / *Réseau national des systèmes complexes*
UAPV	*Université d'Avignon et des pays de Vaucluse* (France)
UCA	*Université Clermont Auvergne* (France)
UCAD	*Université Cheikh Anta Diop* (Senegal)
UM	*Université de Montpellier* (France)
UMI	International joint unit / *Unité mixte internationale*
UMR	Joint research unit / *Unité mixte de recherche*
UMS	Joint service unit / *Unité mixte de service*
UMT	Joint technology unit / *Unité mixte technologique*
Unîmes	*Université de Nîmes* (France)
UPMC	*Université Pierre et Marie Curie / Sorbonne Université* (France)
UPR	Internal research unit / *Unité propre de recherche*
UPVD	*Université de Perpignan Via Domitia* (France)
UPVM	*Université Paul-Valéry Montpellier 3* (France)
UR	Research unit / *Unité de recherche*
USTH	University of Science and Technology of Hanoi (Vietnam)
UT Capitole	*Université Toulouse 1 Capitole* (France)
UT2J	*Université Toulouse - Jean Jaurès* (France)
UT3	*Université Toulouse III - Paul Sabatier* (France)
WASCAL	West African Science Service Center on Climate Change and Adapted Land Use
XSYS	Toulouse Institute for Complex Systems Studies / *Institut d'Études des Systèmes Complexes de Toulouse* (France)

This document was published with the support of Agropolis Fondation (*Investissements d'Avenir programme* - LabEx Agro [ANR-10-LABX-001-01]) in the framework of I-SITE MUSE (ANR-16-IDEX-0006) and with the support of Occitanie/Pyrénées-Méditerranée Region.

Member organizations and partners of Agropolis International involved in this *Dossier*

ACTA
AFIGEO
AgroParisTech
Airbus
Cerema
CIHEAM-IAMM
CINES
CIRAD
CNES
CNRS
EDF
EHESS
ENSFEA
EPHE
GEOMATYS
IFREMER
IGN
IMT Mines Alès
INP-ENIT
INP-ENSAT
INP Toulouse
INRA
INRAP
INRIA
INSERM
IRD
IRSTEA
Météo France
Montpellier SupAgro
ONERA
Safran
Sciences Po Toulouse
Total
UAPV
UCA
UCAD
UM
UNîmes
Université de Guyane
Université de La Réunion
Université de Yaoundé 1
Université des Antilles
Université Fédérale Toulouse Midi-Pyrénées
UPMC Sorbonne Université
UPVD
UPVM
USTH
UT Capitole
UT2J
UT3

Director in Chief: Jean-Luc Khalfaoui (President, Agropolis International)

Scientific Coordination: Nicolas Arnaud (CNRS), Bertrand Jouve (CNRS), Jean-Pierre Müller (CIRAD)

Chapter Editors: Nicolas Arnaud (CNRS), Olivier Barreteau (IRSTEA), Bertrand Jouve (CNRS), Thérèse Libourel (UM), Pierre Maurel (IRSTEA), Claude Monteil (INP-ENSAT), Jean-Pierre Müller (CIRAD)

Editorial Coordination: Isabelle Amsallem (Agropolis International), Aurélie Crette (XSYS), Bernard Hubert (Agropolis International)

Layout and Computer Graphics: Frédéric Pruneau

Communication: Nathalie Villeméjeanne (Agropolis International)

Translation: David Manley

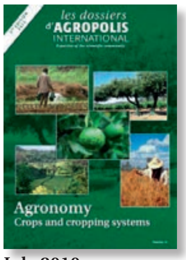
Participated in this issue: G. Abrami, A. Affouard, C. Albergel, F. Amblard, M. Andrello, S. Andres, A. Apolloni, N. Arnaud, S. Aubert, Y. Aumeeruddy-Thomas, J.-C. Bader, C. Barnaud, O. Barreteau, D. Bazile, A. Béchet, M. Belém, J.-E. Bergez, N. Bernet, L. Berti-Equille, A. Biarnès, A. Binot, P. Bonnet, B. Bonté, F. Bouchette, F. Boudon, F. Boulier, Y. Boursiac, F. Bousquet, J.-C. Calvet, F. Campillo, B. Cappelaere, A. Caron, H. Chahdi, V. Chapurlat, R. Choquet, L. Ciandrini, E. Climent, D. Cornelis, C. Coste, P. Couteron, A. Crette, W. Daré, F. Daumas, M. de Garine-Wichatitsky, P. Degenne, L. de Knyff, C. Delenne, C. Delpierre, J. Demarty, P. de Reffye, J.-C. Desconnets, G. Despaux, M. Despinoy, N. Dessay, A. Drogoul, R. Duboz, V. Ducrocq, C. Dumat, Y. Dumont, J.-L. Estivalèzes, J.-C. Fabre, M. Fargette, D. Felbacq, N. Ferrand, J. Fize, J.-M. Fromentin, T. Fourcaud, D. Galliano, C. Gaucherel, B. Gaudou, C. Gary, L. Gavotte, M. Gibert, S. Glémin, C. Godin, H. Goëau, A. Gojon, F. Goutard, M. Grossetti, Y. Guédon, L. Guerrini, J. Harmand, V. Herbreteau, D. Hervé, L. Houssou, B. Hubert, B. Ildefonse, M. Jaeger, B. Jaillard, P. Jarne, A. Joly, H. Joly, B. Jouve, D. Kaplan, S. Kéfi, M. Kelly-Irving, P. Kosuth, V. Labeyrie, F. Laloë, R. Lancelot, A. Laurent, V. Le Dantec, J. Le Fur, P. Lemoisson, V. Leonardi, C. Le Page, A. Lesne, C. Lett, T. Libourel, Q. Liu, M. Loireau, J.-C. Lombardo, D. Lo Seen, S. Luque, C. Madera, N. Maestripieri, S. Manel, M. Mangeas, S. Mangiarotti, M. Manna, G. Martin, M. Massol, P. Maurel, D. McKey, R. Métral, A. Miralles, F. Molino, N. Monnier, C. Monteil, J. Montmain, P. Montoro, I. Mougenot, D. Mouillot, C. Moulia, F. Munoz, J.-P. Müller, M. Paegelow, A. Parmeggiani, P. Péré, F. Pérès, C. Peugeot, M. Peyre, E. Pitard, O. Pliez, J.-C. Pouget, R. Pradel, O. Radulescu, A. Rapaport, H. Raynal, H. Rey-Valette, E. Rial-Sebbag, E. Rivals, D. Roby, B. Roche, M. Roche, O. Rouchon, A. Rousseau, E. Roux, H. Roux, R. Sabaddin, M. Saenz, J.-M. Salles, N. Salliou, M. Saqalli, T. Sari, F. Sedes, E. Servat, D. Sheeren, F. Simard, P. Taillandier, A. Tchangani, M. Teisseire, O. Therond, L. Torres, A. Tran, J. Villerd, C. Violle, M. Voltz, J. Wery

Illustrations: we thank all contributors to this *Dossier.*

Printing: LPJ Hippocampe (Montpellier, France)

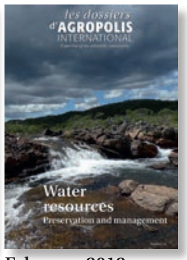
ISSN: 1628-4259 • Copyright registration: February 2019

Also available in French

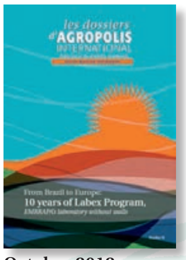


July 2010
68 pages (2nd ed., 2012)
French & English

October 2010
84 pages
French & English



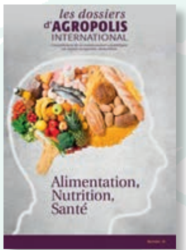
February 2012
72 pages
French, English, Spanish



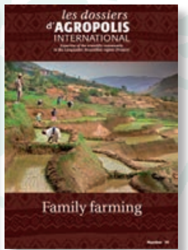
October 2012
48 pages
French & English

February 2013
48 pages
French, English, Spanish

October 2013
76 pages
French



December 2013
72 pages
French



February 2014
64 pages
French, English, Spanish

February 2015
88 pages
French & English

November 2015
76 pages
French & English

April 2016
72 pages
French

Dossiers d'Agropolis International

The *Dossiers d'Agropolis International* collection is a flagship vehicle for presenting and promoting the expertise of Agropolis International members on major scientific issues. Each *Dossier* is devoted to a specific theme.
The research units and training courses concerned are showcased, alongside the research and associated results. Contributions of civil society, the economic sphere and local authorities in the target areas are also highlighted.
Each *Dossier* is available in hardcopy and digital format, generally in two languages (English and French).

***Dossier* issues can be downloaded at:**
www.agropolis.org/publications/thematic-files-agropolis.php

The information presented in this Dossier is valid as of 01/01/2019.

AGROPOLIS INTERNATIONAL

1000 avenue Agropolis
F-34394 Montpellier CEDEX 5
France
Tel: +33 (0)4 67 04 75 75
Fax: +33 (0)4 67 04 75 99
agropolis@agropolis.fr
www.agropolis.fr