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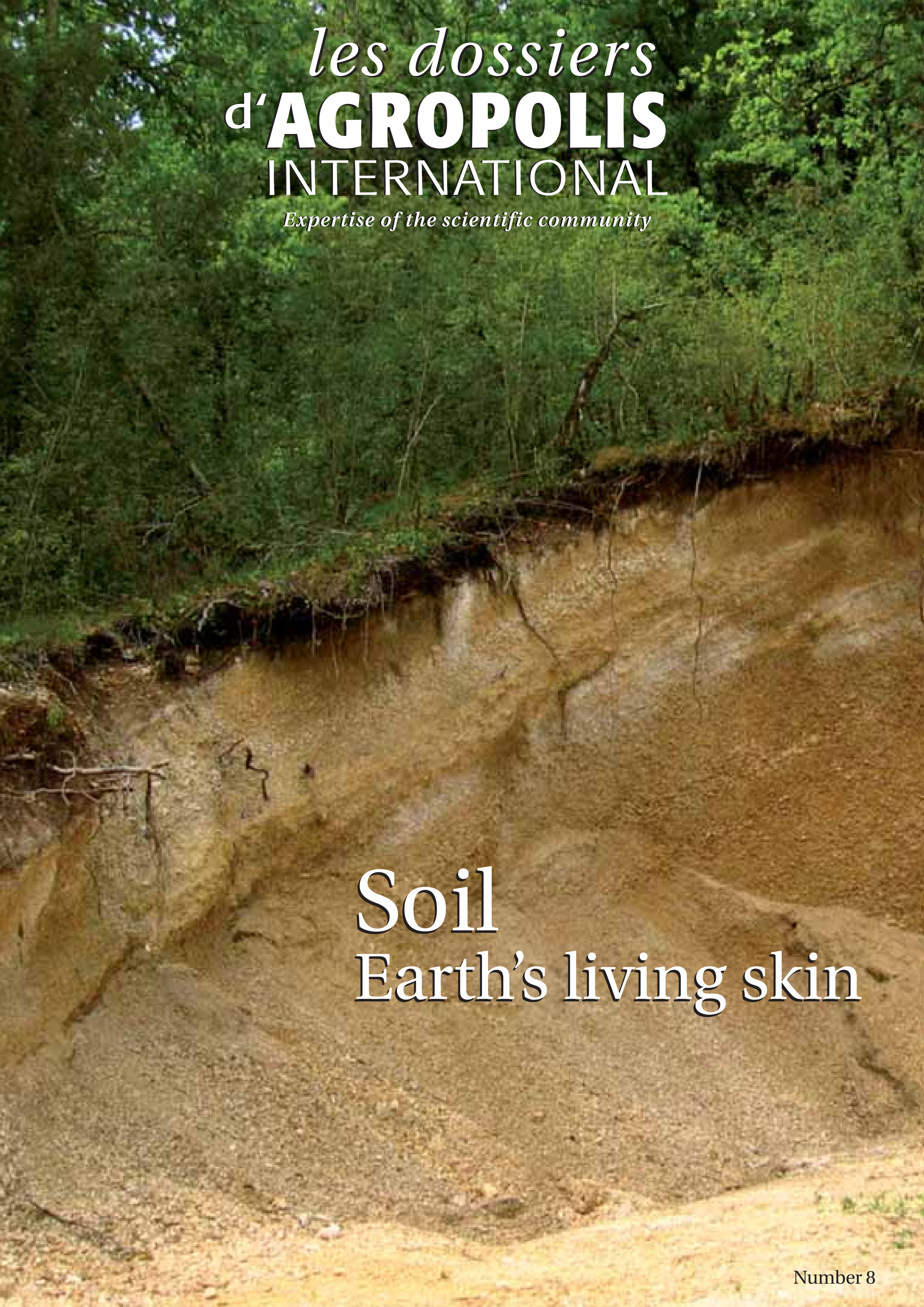

Soil
Earth's living skin

Number 8

AGROPOLIS INTERNATIONAL

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Agropolis International brings together institutions of research and higher education in Montpellier and Languedoc-Roussillon in partnership with local communities, companies and regional enterprises and in close cooperation with international institutions. This scientific community has one main objective– the economic and social development of Mediterranean and tropical regions.

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Soil
Earth's living skin

Soil research expertise in Montpellier and Languedoc-Roussillon

The soil was, until recently, considered simply as a substrate for plant cover. It is now acknowledged that, by supplying organic matter which in turn hosts intense bioactivity, plant covers are responsible for the formation of soils on the surface of every continent. The scientific community now considers that soils are biosphere products and the main reservoir of biodiversity. The soil is clearly the 'living skin' of our planet.

This living skin has many functions that are essential for the development of human societies. These functions range from the production of vital staple goods for humans to the regulation of large-scale hydrological and biogeochemical cycles, while even maintaining a record of our paleoecological and archeological history.

Pressure on soils is nevertheless increasing as human needs and soil-use intensification increase. This intensification, when excessive or poorly managed, often leads to soil degradation. This results in the loss of soil functions, thus in turn seriously threatening the sustainability of many ecosystems. Soil resources are fragile and must absolutely be preserved.

Agropolis International pools several hundreds of scientists involved in soil research and teaching–it is a major European hub of activities in this field, as highlighted in the present document. This *Dossier* was certified by the French committee of the **International Year of Planet Earth**, which aims to boost awareness on the role of Earth sciences in the development of human societies.

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summary

Cover photo: A humic forest soil developed on limestone scree, Dordogne, France
B. Jaillard © UMR Eco&Sols

The information presented in this dossier was valid on 30/05/2009

Agroforestry landscape with an association of poplars and canola.

Soils produce *food and clothing* for people

Soils produce plant biomass–roots, wood, stems, leaves, flowers, fruits, seeds, bark, sap, etc.–which (i) nurture, heal and clothe humans, (ii) supply them with fuel necessary for cooking food and heating, and (iii) provide them with material for building, housing and small- and industrial-scale activities. This natural function of soil has gradually been domesticated by humans throughout their history. Due to constantly increasing demand, they have had to simplify and intensify cropping systems which were originally managed at a pace that was in line with natural soil fertility renewal. The recent introduction of chemical inputs and mechanization has contributed substantially to this new strategy. These practices result in modifying soil properties while altering their capacity to sustainably preserve their functions. The food issue has thus now been further complicated by environmental problems. Hence, the hope that the Green Revolution inspired some 30 years ago has now been shrouded by:

(i) the fear that hunger and malnutrition will remain permanently entrenched in some regions on Earth, with a concomitant series of consequences ranging from outmigration to social conflicts
(ii) the questioning of production intensification, and thus confidence in this strategy based on a body of high cost knowledge
(iii) the uncertainty about the capacity of the Earth's soils to nourish all humans and on the capacity of human societies to set up production systems tailored to the new challenges.

At the end of the 20th century, in a surge of human solidarity, the international community set quantified objectives for reducing hunger worldwide. We are currently at the dawn of the third millenium and hunger still threatens the World. Hunger riots are taking place in countries where it was thought that food security had been definitively achieved.

The Earth's soil resources are limited. All of these soils are not arable, and those that are cultivated do not have the same production potential. The main constraints to their potential are acidity in tropical regions, salinity in Mediterranean areas, low exchange capacity and high susceptibility to compaction. Moreover, soils throughout the World are affected by more or less severe degradation resulting from their agricultural or nonagricultural uses. This degradation, which has long been overlooked or downplayed, has a major impact on food and environmental security. Many specialists agree that the necessary increase in agricultural production should preferentially come from already cultivated soils.

Our approach to soil use must therefore, more than ever, be reconsidered. The paradigms should change and cropping systems have to be viewed as key tools for sustainable soil management in order to be able to produce biomass to meet human needs, while protecting or even improving our soil resources. In turn this will enhance water and biological resources. This change is already under way and a 'new agriculture' is taking shape. It is more 'systemic' and based on ecological principles and intrinsic soil processes geared towards intensifying cropping while reducing chemical treatments. This agriculture is also more considerate of economic, social, environmental, political and institutional aspects, which both determine and are determined by production processes. French research teams are very involved in promoting this shift in strategy, as highlighted in this special *Dossier*.

Rabah Lahmar (UMR SYSTEM)

Soils produce *food and clothing* for people

Designing cropping systems that combine *economic performance* with natural resource *and environmental* conservation

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The **joint research unit (UMR) Tropical and Mediterranean Cropping System Functioning and Management** (**UMR SYSTEM,** CIRAD, INRA, Montpellier SupAgro), which has a footing in France and in different developing countries (Latin America, Africa, Oceania), produces knowledge and tools for assessing, managing or designing cropping systems geared towards boosting economic performance in environment-friendly ways. The focus is placed on using the biodiversity of cultivated species to achieve steady agricultural performance (yield, quality), while reducing detrimental environmental impacts.

The main hypothesis is that these objectives can best be fulfilled by combining several species. The studies are focused on:

- management of several species in the same plot (intercropping in association with perennial plants)
- crop rotations (banana, cotton, cereals)
- more complex spatiotemporal combinations in annual crop based systems (cropping on live or dead plant cover without tillage) or perennial crop based systems (plots with multispecies crops associated with agroforestry in wet tropical areas).

The unit is structured around two main scientific lines of research:
1. Methods for designing or assessing cropping systems
2. Role of cultivated biodiversity in cropping system productivity and sustainability.

These lines are mainstreamed under the 'Agroforestry' (Mediterranean and tropical), 'Perennial monocultures' (banana and viticulture), 'SAMBA' (multispecies annual crop based agroecological systems) and 'Weed infestation' research programmes.

Concerning system management (line 1), nitrogen management support tools have been developed by combining cropping models and soil or plant status indicators. Concerning assessment, research is focused on the design and validation of indicators required to analyse the state of crops under field conditions and integrating these indicators in multicriteria analysis tools.

Priority is given to tools for designing multispecies cropping systems, with crop associations and crop management sequences as adjustable variables. Candidate systems are designed by combining digital simulations, expert knowledge, agroenvironmental assessment indicators and multicriteria analysis methods. They are then tested in research stations or within the framework of prototyping projects in collaboration with stakeholder groups. •••

Agroforestry association of wheat and young walnut trees.

Agroforestry: producing more and better by mimicking nature

Most natural ecosystems are associations of trees and herbaceous plants. In agroforestry, trees and crops are voluntarily mixed in agricultural plots. The trees produce wood and fruits, fix carbon, enrich the soils, protect crops from wind and excessive climatic conditions, and reduce groundwater pollution by recovering fertilizers that are not taken up by crops. The crops produce foods, cover the soil, protect trees from competition with aggressive plants, and force trees to develop deep roots, thus enhancing their drought resistance. Mixtures of trees and crops boost biodiversity in the plot, which could help to naturally control parasite or predator attacks.

Studies under way (UMR SYSTEM) have highlighted the remarkably high productivity of these plots, i.e. 30–60% higher than the production of a cropping plan in which trees and crops are separated. Digital models can be used to simulate the function of these complex systems and to conduct virtual experiments to determine the most efficient management strategies. Research is now focused on describing the biodiversity of agroforestry plots. The aim is to obtain stable cultivated systems that are less susceptible to climatic variations, disease and predator attacks. Several millions of agroforestry hectares could be created in Europe over the next 20 years. This would enable progressive diversification of farms, without short-term income loss, because intercropping systems continue producing almost normally for a long time at currently recommended agroforestry tree densities (50–100 trees per hectare). In Europe, production of a fast-growing high quality wood resource could also reduce our dependence on tropical wood, thus reducing pressure on endangered tropical forests.

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Intercropping: a soil-friendly cropping strategy

Intercropping refers to situations in which two or several genotypes, species or varieties are cropped simultaneously in the same field. This generally involves associations of species of the pea family (pea, lupin, bean, French bean, cowpea, etc.) with cereals (wheat, maize, etc.) or perennial plants such as fruit, timber and gum trees. This system enables positive interactions between plants, especially for access to light, water and nutrients, with at least one or two genotypes benefitting from the presence of the other without detriment.

Niche complementarity thus occurs, with the more competitive uptake of soil nitrogen by the cereal crop, which in turn stimulates atmospheric nitrogen fixation via rhizobial symbiosis of the pea crop. Organic acid exudation or phosphatase activity stimulation by the pea crop increases soil phosphorus availability and facilitates uptake of this mineral by the cereal crop. Resource use is thus more efficient with intercropping as compared to monocropping.

This enhances soil fertility conservation. Soil erosion risks are reduced by the fact that, spatiotemporally, there is greater vegetation coverage, with a lower risk of infestation by weeds or various pathogens. Intercropping is also a more productive strategy than monocropping, i.e. crop yields are higher.

Indeed, crop yields may be as much as 35% higher, a benefit that is compounded by the fact that fewer fertilizer applications and pest control treatments are necessary, as in family farming conditions in developing countries. Intercropping thus provides a possibility to improve global food security through ecological intensification rather than via massive use of chemical inputs.

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UMR EMMAH
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Analysis and modelling of links between biodiversity of mixed crop species and the agricultural performances or environmental impacts of these systems provides a general framework for research carried out under line 2. Based on the hypothesis that this biodiversity fosters the productivity and resilience of the system, the role of functional diversity in cropping systems is analysed to:

- optimize resource use
- reduce risks associated with soil-climate variability and pests
- improve multiannual functional stability via the analysis of resilience capacities and facilitation within these systems.

The studies focus on:

- spatiotemporal sharing of resources (water, nitrogen, light) between intercrops and impacts on agricultural performance
- interactions between biocenosis* dynamics and the cropping system stability. The focus is placed especially on the dynamics of soil organic matter, the vegetation structure and pests and pathogens in multispecies systems.

* The association of species present in the cropping system.

Ecophysiology study and horticultural plant *management*

The **research unit (UR)** ***Plantes et Systèmes de culture Horticoles*** (**UR PSH,** INRA Avignon) conducts studies on the ecophysiology and management of horticultural plants. In this setting, the soil is a key constituent of the plant environment to consider when seeking to gain insight into water and mineral supply functions, as well as anchorage (especially for trees). More specifically, the unit conducts research on root system development and architecture, as well as water and nitrogen uptake. It develops dynamic and 3-dimensional simulation models to predict temporal changes in the location and structure of root systems in soil.

Models are thus used to simulate dynamic interactions between root development processes, on a single root scale (elongation, ramification radial growth, mortality), and the soil. According to the methods developed by the unit, the soil is viewed as a continuous medium defined by spatially varying properties (temperature, moisture, bulk density, nitrate concentration of the soil solution), or as a structured medium with fissures and pores of different sizes and geometric features. This modelling combines deterministic and stochastic approaches.

Concerning absorption, the unit collaborates with soil physicists (UMR EMMAH, *Environnement Méditerranéen et Modélisation des Agro-Hydrosystèmes,* INRA Avignon) for modelling water and mineral transfers between soil and roots. Moreover, within the root architecture, specific absorption sites have been analysed according to their permeability and conductivity (especially for water) or as a function of the plant's transport capacities and needs (nitrates). Other collaborations have also been organised with absorption physiologists studying transporters (e.g. UMR BPMP, *Biochimie et physiologie moléculaire des plantes,* CNRS, INRA, Montpellier SupAgro, UM2).

In addition, the unit participates in research on 'rhizodeposition', i.e. the transfer of organic compounds from roots to the soil substrate (dead roots, exudates). These studies are conducted in collaboration with INRA Bordeaux (UMR TCEM, *Transfert sol-plante et Cycle des Eléments Minéraux dans les écosystèmes cultivés).*

New cropping systems: direct seeding mulch-based cropping systems

Developing countries must increase their agricultural production and ensure its spatiotemporal sustainability in order to be able to cope with global population growth.

The internal research unit (UPR) Direct Seeding and Cover Crops (CIRAD) designs new cropping systems based on the function of forest ecosystems that enable in situ organic matter production and management.

By introducing multifunctional plant communities in direct seeding mulch-based cropping systems (DMC), biological tools take the place of mechanical tools. This permanent cover protects soil from erosion and restores biological activity, which helps ensure balanced and stable crop mineral nutrition. •••

** A mathematical method whereby statistical data are processed on the basis of probability calculations.

Potential of direct seeding mulch-based cropping systems

for ecological intensification of cropping systems in a Brazilian family farm setting

Harsh physical and socioeconomic conditions often prevail in developing countries: fragile soils and severe climate, and limited access to input markets and credit. Because of these constraints, international agricultural research has been oriented towards developing innovative systems to protect and make optimal use of available natural resources in the short and long terms. These systems are based on the ecological intensification concept. Direct seeding mulch-based cropping systems (DMC), for instance, offer a broad range of technical options, especially for organic matter management (crop residue left in the fields to create a mulch layer, or sowing crops directly in live plant cover).

The joint research unit (UMR) SYSTEM has set up controlled test plots on smallholdings in Unaí region (Brazilian *cerrados*) with the aim of assessing these cropping systems in actual field conditions. Water savings may be achieved by introducing grasses and plants of the pea family in relay in maize crop fields under DMC. This strategy reduces runoff water loss by 50%, soil evaporation water loss by 10–20%, and drainage water loss by 30% thanks to the mulch layer and water consumption by the cover plants. Moreover, DMC improves nitrogen nutrition of the commercial crop. Finally, the high phytomass recovery achieved through these systems can increase the soil carbon content (0.3–1 t ha^{-1} $year^{-1}$). Simulation models have also been developed to analyse the complex function of such DMC systems and to assess their actual impact on crop production and natural resources.

É. Scopel © CIRAD

Direct seeded maize crop in association with relay sown pigeon pea (Cajanus cajan) *in Brazil.*

These models are helpful for designing new cropping systems that: i) meet smallholders crop yield requirements, and ii) are in line with local socioeconomic conditions.

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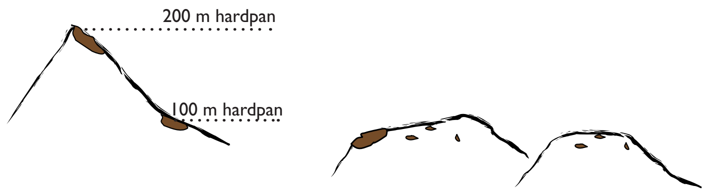
Study of relationships between tropical forest soils, diversity and production

Soils, in addition to the climate, determine the species composition and production of natural or planted tropical forests. For instance, tree diameters and heights are reduced when the soil layer under a tropical rainforest is shallow and the stand is very dense. Similarly, the viability of plantations of species that are fast growing (e.g. eucalyptus and acacia) and/or have a high added value (teak) is determined largely by the soil properties. Based on examples from natural forests (French Guiana) and tropical plantations (Congo Basin, West Africa), studies carried out by CIRAD (UPR Dynamics of Natural Forests and UPR Functioning and Management of Tree-Based Planted Ecosystems) are aimed at determining the role of the soil in the structure of tropical rainforests and in the sustainability of planted forests. For tropical rainforests, permanent tree vegetation research projects have been set up (northern French Guiana) with different geological substrates, soil types and under annual rainfall conditions ranging from 2 000 to 4 000 mm. The findings have revealed that the floristic composition is influenced at different scales (local or regional) by the soil type in interaction with the climate (hydromorphic gradient), and by the forest's Holocene history (climatic variations and human activities).



Hardpan distribution according to the model and elevation in French Guiana.

For plantations, the research involves studies of biogeochemical cycles carried out on instrumented sites (e.g. in Congo) and/or studies on regional soil characteristics. The findings have shown that the soil physical and chemical characteristics, the biological cycle (recycling via the litter layer), and stand management strategies that are geared towards preserving soil carbon and nitrogen reserves and limiting mineral export, are key factors that determine the production and sustainability of tropical plantations.

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Through increased applied fertilizer efficiency, the process leads to increased above- and below-ground biomass production, which in turn sequesters atmospheric nitrogen within a few years. Overall, this restoration of plant and animal biodiversity in the cultivated ecosystem–an ecological intensification effect–enables the system to benefit from the restored soil functions. Efficient crop associations in systems in which chemical treatments are reduced by half have been developed through the research.

This intensification in the use of ecological processes also hampers parasite attacks in some cases. Consequently, plant breeding can be specifically targeted towards improving the nutritional quality of products. For instance, cropping new rice varieties under DMC in rainfed conditions has been shown to control rice blast 'naturally' while ensuring a rice production potential of 10 t/ha–so rice is now considered as the 'wheat of the tropics'.

Research is currently focused on solving two major problems:

- controlling weeds and plant pests for which treatments with glyphosate and other environmentally damaging herbicide molecules are no longer tolerable
- managing crop pests–phytophagous nematodes, pathogenic fungi and bacteria, and pest insects–by yet to be developed control methods. Baseline studies are required to take advantage of the allelopathic properties of plants and to develop industrial-scale production of elicitors and other natural organic molecules that could stimulate the immune functions of plants.

Close synergy between research and industry (to manufacture organic inputs of the future), associated with a vigorous researcher and farmer training policy, is required to ensure that these innovations will be adopted by farmers, especially in developing countries. It should be possible to recover millions of hectares of land that is currently abandoned due to the lack of suitable agricultural treatments.

The researchers are working on three continents. The unit has been collaborating with the University of Ponta Grossa State in Brazil (over 20 million ha cropped under DMC) for 30 years. Several researchers are working in Laos, in partnership with the Laotian Institute of Agriculture and Forestry, in Cambodia with the Cambodian Rubber Research Institute and in Thailand with the University of Kasetsart. A large-scale research initiative has been launched in Madagascar in collaboration with the *Centre de recherche agronomique pour le développement.*

Function of tropical plantation ecosystems

The main research focus of the **internal research unit (UPR) Functioning and Management of Tree-Based Planted Ecosystems** (CIRAD) is to measure, gain insight into and model functional processes of tree plantation ecosystems in the tropics. Those studied by the unit are eucalyptus plantations, i.e. pure or mixed with acacia (Congo, Brazil), oil palm plantations (Indonesia), rubber tree plantations (Thailand), coffee-based agroforestry systems (Costa Rica, India, Kenya), and *Acacia* sp. based forestry and agroforestry systems in dry areas.

The specific objectives are:

- gaining insight into the main functional processes concerning water (soil uptake, evapotranspiration, soil water transfers, etc.), carbon (photosynthesis, assimilate allocation in plants, autotrophic and heterotrophic respiration) and minerals (organic matter mineralization, soil uptake, alteration of soil minerals, symbiotic N_2 fixation) in tropical tree plantation ecosystems
- quantification of the main energy, carbon, water and mineral flows in tropical tree plantation ecosystems, as well as the services they generate (production, carbon sequestration, water balance, mineral balance)
- development of function models based on processes that facilitate the understanding and quantification of the respective effects of the environment (including climate change), former soil uses and cropping practices on the production and environmental impacts of tropical tree plantation ecosystems
- developing new sustainable tropical tree plantation ecosystem management strategies.

The research unit applies an ecosystem-oriented approach, involving joint research in ecophysiology, biogeochemistry and soil science, microbiology, agronomy and biometry, in field experiments (agronomic trials, instrumented workshop sites). It also applies a modelling approach aimed at representing the ecosystem heterogeneity (intra- and inter-rotation variability, inter-plot variability). The ecosystems studied span a broad range of management systems (small individual farms to large-scale plantations), environmental conditions, plant material heterogeneity, and nutritional imbalance risks. The findings of this research give rise to agricultural recommendations, production and function models, mineral input-output balances, greenhouse gas emission/sequestration balances, and agroenvironmental function indicators. The unit is based in France, at Montpellier and Nancy (INRA, UR *Biogéochimie des écosystèmes forestiers*), and also in developing countries within the framework of collaborations established with institutions of research and higher education of these countries. It also collaborates with other French joint research units.

Towards sustainable management of tropical *rainforests*

Tropical rainforests are disappearing at a mean annual rate of around 0.4%. This phenomenon is having multiple impacts, especially environmental: carbon release into the atmosphere, soil degradation and erosion, genetic diversity loss, etc. The 1992 Rio Protocol recognised the importance of sustainable management of these tropical rainforests, i.e. utilizing their resources while preserving their different ecological, economic and social functions over the long term.

In this setting, the aims of the **internal research unit (UPR) Dynamics of Natural Forests** (CIRAD) are: (i) to gain greater insight into the function of forest ecosystems according to abiotic (soil, rainfall, light, etc.) and biotic factors, and (ii) to quantify the impact of logging on different forest dynamics processes.

Most of the unit's research concerns dense tropical rainforests in the Amazon, French Guiana and the Congo Basin. Studies are focused specifically on forest stands and their main woody species communities on areas of around 100 ha.

This research is based on long-term monitoring of test plots, as well as the development of models to predict stand and species population patterns to help forest managers. The acquired knowledge and developed tools can be used to determine logging scenarios that are in line with the conditions necessary for stand renewal and preservation of their floristic and genetic diversity. ■

*Landuse pattern in KwaZulu-Natal (South Africa).
On the right, the land is intensively cropped in the rainy season
and grazed by herds in the dry season.
On the left, a former commercial farm is reserved for pastures.*

Soils regulate *inland water flow*

Soils are a key constituent of terrestrial hydrosystems, serving as an interface between the atmosphere and groundwater reserves. Flows that they host determine both the spatial distribution of water constraints affecting the biological environment and mass transports, which have marked impacts on the environment and agriculture. Efforts to measure, gain insight into and model flow processes are still not adequate enough to effectively address the many environmental and agricultural issues pertaining to cultivated environments.

Soil has a considerable impact on water resources and transfers, especially in cultivated environments, because this medium is both a producer and user of water resources (agricultural uses account for around 70% of all consumed fresh water). The impact of climate change, the increase in water and land use conflicts, soil degradation and water quality are major issues in almost every global region. Understanding and modelling the influence of soil use and management on the quantitative and qualitative aspects of water resource production is an essential step in developing sustainable management strategies for different environments. Research teams working on this topic are hence focusing specifically on issues concerning the formation of surface water resources and their use in irrigation, the origins of extreme floods, the impact of drought periods, and the influence of soil management on soil-subsoil-plant-atmosphere exchanges.

One key scientific challenge is to gain enough insight into the implications of different soil and cultivated environment characteristics (crust and other surface states, discontinuities caused by human activities, land use) with respect to the origin and control of flows circulating through these environments. A functional scheme must first be drafted to be able to come up with realistic predictions of flows in cropping areas. This is a major challenge because, even in 'natural' environments, current hydrological models require complex calibration to be able to represent flows. One reason for this problem is the current lack of understanding of spatiotemporal interactions between surface flows, underground flows and atmospheric inputs.

Moreover, it is important to connect the different flows through analyses of the impacts of natural variability and soil heterogeneity due to human activities. Such systemic analyses are especially important as they are also required for studying reactive solute transfers, which in turn necessitates a relatively accurate understanding of the porous matrices crossed, and thus the actual pathways followed by the water. In areas affected by human activities, knowledge on physical processes should be associated with an analysis of practices, especially irrigation practices and their key factors, e.g. soil types.

Agricultural and environmental issues concerning soil and water resources apply on a rural area scale of tens to several hundreds of square kilometres, whereas technical measures influencing these resources apply on a local plot scale. However, due to the high experimental costs involved, studies geared towards understanding and modelling hydrological processes are limited to small spatial scales (plots, elementary catchments).
This means that just a small part of the total soil and rural area variability can be taken into account, and it is hard to assess an entire rural area. Farmed landscapes, which characterize the target areas, would thus have to be investigated in detail. These agricultural landscapes are the result of interactions of natural factors (lithology, tectonics, soils, paleoclimates, former vegetation, etc.) and human activities (cropping practices, development, road systems, etc.) over time. They should therefore be the focus of specific analyses and modelling to assess their spatial organization and changes, while correlating the findings with those generated by hydrological models.

All of the research under way should enhance predictions of changes in soil quality associated with hydrological function and human activities (erosion, contamination, organic matter, salinization, etc.). Greater insight could also be gained by designing reliable tools for assessing and monitoring the impact of practices on water and soil resources.

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Soils regulate *inland water flow*

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Soil hydrology and cultivated environment studies

The ***Laboratoire d'étude des Interactions entre Sol, Agrosystème et Hydrosystème*** (**UMR LISAH,** INRA, IRD, Montpellier SupAgro) conducts research specifically on the hydrology of soils and cultivated environments.

The main objectives are to:

- increase knowledge on soil erosion water and mass transfers, and the fate of polluting substances (pesticides and metals) in soils and rural catchments in relation with their spatial organization and temporal variations
- develop tools to analyse and prevent risks induced by human activities in cultivated environments on hydrological regimes and variations in water and soil resources
- contribute to designing new methods for sustainable management of soils and rural areas
- train students on concepts and tools for the analysis and modelling of the spatial organization and hydrology of cultivated environments.

The scientific strategy of LISAH is based: (i) on hydrological field studies and experiments, (ii) on methodological research for the acquisition and processing of remote sensing soil and landscape data, and (iii) on the development of distributed hydrological modelling to highlight specific heterogeneity in rural landscapes. LISAH manages the *Observatoire Méditerranéen de l'Environnement Rural et de l'Eau* (OMERE), an environmental observatory which aims to analyse the impact of human activities on the physical and chemical erosion of Mediterranean soils and on water quality.

The laboratory pools expertise in the fields of soil science, hydrology and agronomy in three research teams, studying:

- Water and pollutants in cultivated catchments
- Erosion and solid matter transport
- Spatial organization and functioning of agricultural landscapes.

LISAH is based in France (La Gaillarde agricultural campus, Montpellier) and in several Mediterranean and African countries (Kenya, Morocco, Syria, Tunisia), in collaboration with agricultural institutions of research and higher education in these countries: *Institut agronomique et vétérinaire Hassan II* (Rabat), Arab Center for the Studies of Arid Zones and Dry Lands (Damas), *Institut national de recherche du génie rural et des eaux et forêts* et *Institut national agronomique* (Tunis), and the World Agroforestry Center (Nairobi). LISAH has established partnerships especially with the French scientific community (e.g. *Institut Languedocien sur l'Eau et*

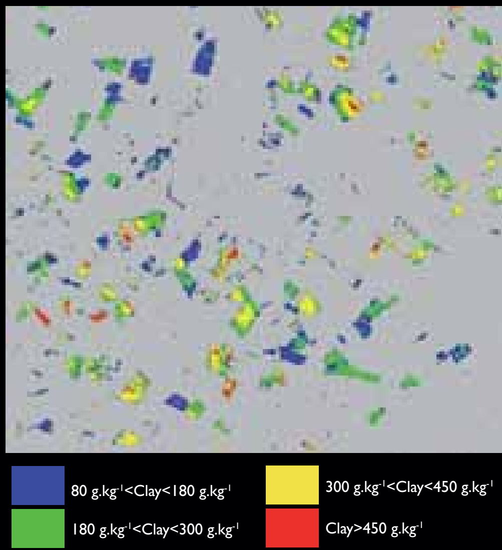
Determining soil property patterns for their functional modelling

Environmental models are used to understand and predict inland water flows. These models require an accurate understanding of how soil properties vary in target areas (small and large river catchments, cropping areas, administrative units). On the French or even global scale, information obtained from conventional soil maps are often too sparse or imprecise to meet this demand. This problem could be overcome via digital soil mapping, at lower cost, with increased accuracy and quicker mapping of target areas. The ultimate goal is to provide environmental scientists with exhaustive accurate images (resolution 100 m or less) of soil functional properties.

Digital soil mapping is based on landscape variables known to be related to soils and their properties (topography, lithology, land use, etc.), and to be available for large surface areas. These variables are necessarily interlinked, while also being associated with soil variables that apply for the studied area (soil maps, profiles, soil analyses). Relevant mathematical procedures have been developed for this purpose.

Digital soil mapping is now entering a new phase with the recent development of geophysical instruments for measuring soil properties (resistivity meters, electromagnetic induction meters, gamma-radiometers, seismic refraction meters, etc.) mounted on motorized vehicles, aircraft or even satellites (very high resolution images by pixy, airborne and satellite hyperspectral imaging, airborne gamma-radiometry). Substantial quantitative data are now available for large areas (cf. above example of hyperspectral data developed by UMR LISAH and TETIS). New computer procedures are currently being developed to optimize soil property estimations from signals generated by sensors and also to produce exhaustive soil property assessments on the basis of sensor-derived data on target areas.

P. Lagacherie © UMR LISAH



Estimation of topsoil clay content using an airborne hyperspectral image (HYMAP).
These estimations are only possible on bare soils.

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l'Environnement, Montpellier) and with the international scientific community, particularly in Mediterranean countries.

The research is focused especially on studying the impacts of agriculture (in Languedoc vineyards and West Indian banana plantations) on soil and water pollution by pesticides, analysis of the hydrological cycle of soil-crop systems in small Mediterranean catchments, development of digital soil mapping methods and soil information systems, analysis of key factors and processes involved in soil erosion and sediment transport processes in catchments, as well as studies on the impact of water management projects (ditches, levees, small lakes) on the hydrological functioning of cultivated soils and catchments.

Hydrosystems: uses and management

The joint research unit (UMR) Water Resource Management, Actors and Uses (G-EAU, AgroParisTech/ENGREF, CEMAGREF, CIHEAM/IAM.M, CIRAD, IRD, Montpellier SupAgro), which was founded on 1 January 2005, conducts research with the aim of:

- producing knowledge on hydrosystem function, uses and management
- proposing methods, tools and expertise to public decision makers and farmers' groups
- training students and professional stakeholders from developed and developing countries.

The UMR carries out its research both in France and abroad, while focusing specifically on North Africa and three large catchments: Niger, Limpopo (South Africa) and Mekong (Southeast Asia).

The unit's research activity spans many disciplines and is focused along three main lines:

- *Line 1: From operational management to the analysis of resource allocation scenarios.*

This line concerns the control of water flows on different time scales in systems that combine the use of groundwater, canals, rivers or dams. The unit has substantial expertise on the function of managed systems and on hydraulic structure manoeuvres in compliance with water allocation guidelines. The main disciplines concerned are hydrology, hydrogeology, hydraulics, hydrobiology, automation and informatics. •••

Soil erosion risk zoning in Hérault department (France)


September 2002 flood at Sommières (France).

The French Law of 30 July 2003 (n°2003-699) concerns the implementation of soil erosion control measures. Bylaw n°2005-117 (12 February 2005) specifies the need for erosion risk zoning under the responsibility of French prefects. The recent increase in zoning tests by public and private agencies highlighted the problem of streamlining zoning methods and making them reliable.

BRGM and UMR LISAH drew up specifications for zoning 'erosion' risks on a French department scale. INRA developed a method to map the 'soil erosion' risk throughout France (scale 1/1.000.000, MESALES model). Several steps were required:
■ A summary outlined the overall legal and technical setting (existing modelling approaches)
■ A technical study defined the most suitable structure and parametering based on two previous documented test cases in Oise and Hérault departments (France).

A series of sensitivity tests were conducted to optimize parametering of the MESALES model for zoning on a departmental scale. The tests verified the contributions and relevance of:
■ improving the resolution of the digital terrain model (DTM)
■ improving the 'slope' criterion by taking the drainage area (weighted or not by land use patterns, STREAM model)
■ a soil map validated on a regional scale (1/250.000, 'Sols' database) for calculating the 'erodibility' and 'soil capping' parameters
■ rainfall data tailored to the local setting.

The model was then validated by farming advisors *(Chambre Départementale d'Agriculture)* and agronomist-soil scientists (UMR LISAH).

In conclusion, it is essential to take the slope map drawn up according to the DTM of the French *Institut géographique national* (IGN) 50 m weighted by the runoff drainage area (considered for a given pixel of the catchment area and land use in this area). The DMT IGN 250 m slope map was substituted by the soil capping and erodibility maps drawn up on a regional scale (1/250.000) with data from the 'Sols' database (INRA).

Mean annual rainfall data are not suitable for conditions in the Cévennes region (France) because they underestimate highly intense storms. Researchers at the University of Montpellier 2 thus mapped maximum daily rainfall with variable return periods, so the map could thus be mainstreamed with a return period of 2 years which, after validation, is more compatible with the 'agricultural erosion' issue.

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■ *Line 2: Consultations on water, public policies and service management.*
This line includes assessments of public water policies in interaction with other policies (sectoral or land management) on water use regulation methods and institutions, and economic and information tools for water service management. The issues investigated concern water resource sharing and access to water and sanitation services, water environment quality and vulnerability to water-related risks (drought, flooding). The UMR deals with these issues using models developed in collaboration with stakeholders, which are computerized or not (experimental sociology, support modelling, experimental economics). The main disciplines involved are within the social science and humanities domain, i.e. economy, management, sociology, political science, geography and anthropology, along with skills in modelling complex systems and expertise in life science and engineering for model design and development.

■ *Line 3: Water practices and uses.*
This line includes research on users' behaviour and the key factors involved (concerning agricultural water supply), on the performance of agricultural production systems and irrigation equipment (especially their effects on the environment) and on the development of innovations for these agricultural systems. Soil modelling and experiments are also carried out, especially on their water and pollutant transfer capacities in different irrigation systems worldwide and under different practices. Metrology research to develop innovations for measuring the soil water status is conducted in the laboratory and research station in Montpellier (France). Disciplines of the three centres of the 'anthroposphere-technosphere-biosphere' triptych are involved in this line: fluid mechanics, soil physics, metrology, agronomy, economy, sociology and anthropology.

A fourth line is devoted to training activities.

Monitoring the soil water status and assessing technical irrigation innovations

Irrigated farming helps to meet increasing global food needs. Its efficiency must, however, be improved because of limited water resources.


I. Mubarak © CEMAGREF

Determination of soil hydrodynamic properties by the Beerkan method.

Research under way for almost 20 years at the Lavalette research station (Montpellier, France) has led to the development of methods and tools for the assessment of irrigation systems in different cash crop situations, especially under gravity irrigation. New available material has been used to reexamine the buried drip irrigation technique, which markedly reduces water consumption (25% according to some evaluations) and nitrogen loss. It is essential to assess the performance and viability of this strategy as a potential alternative to other cash crop irrigation systems. As part of a hydraulic rehabilitation project in the research station and carried out with public authority support, a permanent system was set up to compare different local irrigation conditions and management methods.

The soil water status in the root zone was characterized by conventional measurement methods (humidimetry, neutron flux metrology, gammametry and tensiometry), combined with continuous dielectric measurement, with the aim of analysing flows at different time steps. The first observations, supplemented with the crop results, confirmed the benefits of this technique. In parallel, transfers were modelled by different approaches to extend the results to other soil-climate settings in collaboration with economic stakeholders. The research station activities provide a platform for research and training on sustainable irrigated crops for UMR G-EAU, in association with Agropolis International and other research teams in developed countries (especially the CNRS *Laboratoire d'étude des Transferts en Hydrologie et Environnement,* France) and developing countries (especially in North Africa).

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Development of tools and methods for *decision makers*

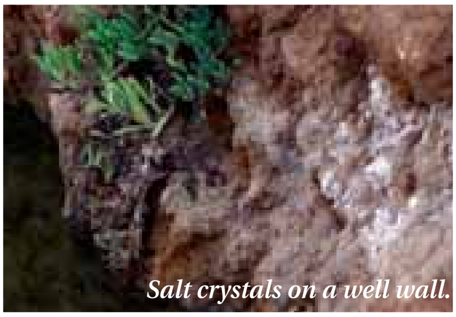
BRGM Montpellier is an institution with a staff of scientists affiliated with the ***Service géologique régional Languedoc-Roussillon,*** the Eau/RMD *(Eau /évaluation de la Ressource, Milieux Discontinus)* research unit and the ARN/ESL *(ARN/ Érosion des Sols et Littoral)* research unit.

The institution's research and public service activities are geared towards providing regional, national and international decision makers with tools and methods in the following domains:

- Mapping and geoinformation: management of the subsurface database, dissemination of geological information and digital mapping harmonized between departments, geological heritage
- Water: quantitative groundwater monitoring via piezometric networks, qualitative monitoring of the physicochemistry and levels of pesticides, chlorides, etc., in water, hydrogeological atlas, determination of groundwater vulnerability, characterization and assessment of water resources of karstic systems, role of groundwater in karstic environments in flood development
- Natural risks: departmental inventories of ground movements, management of the 'ground movement' risk with respect to the road system, departmental mapping of the 'clay shrinking-swelling' phenomenon, departmental inventories of underground cavities, assessment of seismic risks while supporting implementation of the French national seismic risk prevention plan *(Plan séisme)*
- Polluted sites and soils: inventory of former sites of activity that were potentially polluted, database on the groundwater quality downstream from classified installations
- Mineral resources and abandoned mines: 'littoral' schemes (monitoring coastal areas, coastal risks linked with climate change)
- Energy: geothermal potential, energy storage on water tables.

The 'flooding' research topic aims to introduce the 'soil and subsoil' dimension in this issue based on local activities carried out with the French *Service Central d'Hydrométéorologie et d'Appui à la Prévision des Inondations,* concerning flash floods (Gardon d'Anduze catchment) or for assessing floods in karstic environments (Nîmes, Lez, etc., in France). These activities are conducted via scientific (UMR Hydrosciences Montpellier, École des Mines d'Alès) and technical *(Service de prévention des crues Grand Delta et Méditerranée Ouest)* partnerships.

The 'soil erosion' research project is carried out in close collaboration with the BRGM Orléans research teams. Collaborations have been set up, through the different projects, with UMR LISAH, INRA (Orléans, France), IRD (Tunis, Tunisia) and the *Chambre d'agriculture de l'Hérault* (France). •••



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Salt crystals on a well wall.

Salinity management in irrigated areas: Fatnassa Oasis, Tunisia

Salinization involves a gradual increase in the soil salt concentration under the influence of a more or less saline irrigation water supply in specific hydrological conditions: arid climate, shallow water table, insufficient leaching, etc. This phenomenon affects 77 million ha, or 28% of the irrigated area, 8% of which are severely affected. Excessive salinity levels are detrimental to farms, reducing yields, making soils unsuitable for growing certain sensitive crops, or increasing production costs. Arid southern Mediterranean regions are especially vulnerable to salinization risks. UMR G-EAU and the Tunisian *Institut National de Recherche du Génie Rural des Eaux et Forêts* deal with the salinity management problem at Fatnassa Oasis (Tunisia) within the framework of the SIRMA *(Économie d'Eau dans les Systèmes Irrigués au Maghreb)* project. The first line of research is aimed at gaining insight into the nature of salinization processes in order to identify causes that could potentially be overcome, while differentiating processes that occur on the hydraulic system scale and on the plot scale.

This first line is based on the measurement and modelling of biogeochemical processes and water and salt balances as a function of flows at the periphery of the oasis (irrigation, drainage, natural groundwater flow and evapotranspiration), and the consequences on the soil salinity trends. The second line is aimed at gaining insight into farmers' adaptations and the production system performances with respect to salinity, soil fertility and water constraints. This line of research involves a triple analysis: (i) of the perception of constraints and farmers' practices; (ii) of how the area functions, including collective management of the irrigation system, individual strategies and practices, state of the environment and crop performances; and (iii) of farmers' income patterns.

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Brackish water in a well dug by farmers to irrigate their crops.

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Modelling the mechanical behaviour of soils *and mass transfers*

A major part of the research carried out by the *Couplages en Milieux Hétérogènes* (CMH) of the ***Laboratoire de Mécanique et Génie Civil*** (**LMGC**, UM2, CNRS) concerns soils. The models developed deal with the mechanical behaviour of soils, mass transfers and the combined effects of these two factors. They are studied using various theoretical tools: thermodynamics and macroscopic mechanics, scaling methods (homogenization and mechanics of granular media).

The following research topics concern soils:
- Thermodynamic balance of water and dissolved elements in the soil
- Evaporation, condensation, dissolution in hygroscopic soils
- Water transfers in low-moisture soils in the vicinity of soil-atmosphere interface
- Soil depollution by ventilation
- Soil thermo-hydro-dynamics
- Scaling approach to coupling: homogenization and mechanics of granular media.

Studies have been carried out on water transfers on the soil surface in arid regions as part of a cooperation programme for university and scientific research (CORUS) of the French Ministry of Foreign and European Affairs, in collaboration with the University of Bobo-Dioulasso (Burkina Faso) and INRA (Soil Science). Current studies on soil depollution are being carried out in collaboration with the University of Ouagadougou (Burkina Faso). The most innovative aspect of these two programmes is the fact that liquid-gas phase transitions in the soil surface horizon are taken into account.

Modelling the mechanical behaviour *of materials and* 'rainfall/flow' relationships

The ***École des Mines d'Alès*** (**EMA**) consists of three laboratories: the *Laboratoire Génie de l'environnement industriel et des risques industriels et naturels* (LGEI), the *Centre des Matériaux de Grande Diffusion* (CMGD) and the *Laboratoire de génie informatique et ingénierie de production* (LGI2P).

CMGD focuses research on materials commonly used in the 21st century, especially polymers and composite materials, as well as civil engineering construction materials. There are two civil engineering teams: the 'Separated media and complex mineral materials' team and the 'Geomechanics and hydrology' team. This latter team conducts studies on soil issues, with two lines of research: modelling the mechanical behaviour of block or grain materials, and modelling 'rainfall/flow' relationships by different approaches (neuron networks and sequential systems automata) in catchments ranging in size from one to hundreds of km².
The input data for neuron networks are rainfall radar images, while sequential systems automata are based on rainfall gauge data.

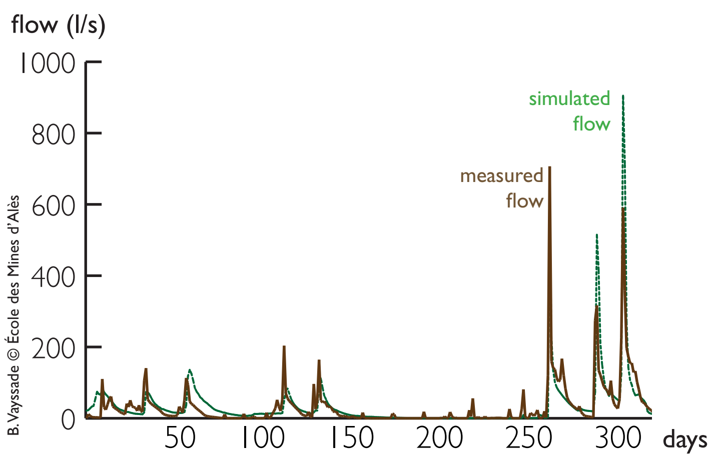
Software packages used by the 'Geomechanics and hydrology' team are custom made at EMA, but not always by the team. The measurements are obtained through partnerships with CNRS (UMR Espace, University of Nice Sophia Antipolis), the *Service Central d'hydrométéorologie et d'appui à la prévision des inondations,* University of Charles de Prague, etc. ■

Modelling the water budget of a mountain river catchment

The *École des Mines d'Alès* (EMA), UMR Espace (CNRS, University of Nice Sophia Antipolis) and other European partners (in Czech Republic, Germany and Spain) have developed a river flow simulation tool within the framework of the Land-use Optimisation With Regards to Groundwater Resources Protection in the mountain hardrock areas project (LOWRGREP) under the European Union's Fifth RTD Framework Programme. The aim of this project was to assess the extent of interference of human activities with the hydrosphere in different mountain areas.

Flow curves were plotted with measured (UMR Espace, University of Nice/CNRS) and simulated (EMA) data for a catchment of around 1 km² located on Mont Lozère (France). The modelling was performed using sequential automata on a daily time step. The river flow rate was considered to be the sum of three contributions: instantaneous runoff during a rainy day, hypodermic runoff over several days, and the groundwater contribution throughout a year. It was found that the simulated flow peaks were in phase with the actual situation but the amplitudes still have to be improved.

The advantage of this simulation tool is that it can be used to predict different scenarios that could arise as a result of human- or climate-induced modifications, and to determine their potential impacts on the water table and river flow. For instance, a simulation without hypodermic runoff shows that waters recede the day after a rainstorm. Even this rough simulation indicates that soils regulate inland water flows.



Measured and simulated flow rate curves for a catchment of around 1 km². La Sapine catchment, Mont Lozère (France).

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A well-managed agricultural landscape along the Dordogne River (France).

Soils regulate *biogeochemical nutrient* and pollutant cycling

Soil is the main reservoir of minerals essential for life in terrestrial ecosystems, while also providing a substrate for primary production (cf. Chapter 1). In addition to biomass production (in quantitative terms), nutrient bioavailability also governs the quality of produced biomass through, for instance, the protein and mineral contents of foodstuffs derived from agriculture. Sparing management of these minerals has always been one of the keystones of the 'sustainability' of agricultural production. Excessive fertilizer inputs can have negative environmental impacts. For instance, nitrogen is a major plant nutrient but also a source of 'pollutants' via vertical soil transport (leaching) of excess nitrates into the water table or emissions of nitrous oxide, i.e. a gas that is a major contributor to the greenhouse effect. Excess phosphorus in soils can, through its transfer by erosion, lead to surface water eutrophication phenomena. Soil fertility management is, in this respect, the main issue identified through research on 'soils, media for biogeochemical cycles'.

Soil forms many interfaces with inland biosphere organisms, especially plants through their roots, the atmosphere for gas exchanges and the hydrosphere for water exchanges (cf. Chapter 2). Flows at these interfaces are at the core of biogeochemical cycles and generally determined by the physical and chemical soil properties, but also by various biological agents. Soils host a diverse range of organisms (microorganisms, animals and plants), most of which are responsible for biotransformation processes and transfers of elements and compounds. Through these living agents (cf. Chapter 4), the 'soil' compartment plays a complex role in the regulation of biogeochemical cycles. Soil is thus one of the main carbon sinks in the biosphere, with organic forms of this element being a key energy source for many heterotrophic organisms.

Organic matter also has many functions. Its dynamics are pivotal to the carbon storage and greenhouse effect issues through the regulation of emissions of high radiative-potential gases derived from its decomposition (carbon dioxide, methane, nitrogen oxides).

Soil also hosts potentially toxic elements present in parent material from which soils are derived. Moreover, it is the receptacle of various compounds resulting from the utilization of terrestrial ecosystems (agricultural, industrial and urban waste, chemical and organic amendments) and various other inputs (metals, nonmetallic minerals, pesticides and other xenobiotics). These compounds may also undergo transfer and transformation processes (mineralization, changes in physical or chemical form/ speciation). In this respect, the soil has a key role as a physical filter, as well as a complex bioreactor, in the depollution of terrestrial ecosystems (purifying power). Understanding the fate of various contaminants is another major challenge for research on 'soils, media for biogeochemical cycles'. Hence soil is central to questions concerning the environmental assessment and rehabilitation of polluted sites.

Research on soils carried out by Agropolis International teams is primarily focused on Mediterranean and tropical ecosystems, affected more or less by human activities. In addition to the issues discussed above, the teams deal with problems associated with the impact of soils on global changes (climate change and land use changes). Studies carried out in this framework are supported by the teams' skills in implementing physicochemical and biological analysis tools and digital tools (modelling used as both a research and prediction tool), and also instrumented sites and working areas such as the Ecotron platform at Baillarguet and the Puéchabon forestry research site (Hérault, France).

Nathalie Fromin (UMR CEFE)
and Philippe Hinsinger (UMR Eco&Sols)

Soils regulate *biogeochemical nutrient* and pollutant cycling

Main teams

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...continued on page 24

Study on the environmental impacts *of human activities:* pollutant transfers

The ***Laboratoire Génie de l'Environnement Industriel et des risques industriels et naturels*** (**LGEI** research centre, EMA) conducts research on the environmental impacts of human activities (industrial, urban, agricultural), especially pollutant transfers through vectors such as water, the water/soil interface and air. It is indeed essential to be able to assess human induced disturbances of biogeochemical cycles that govern aquatic and terrestrial ecosystems.

More specifically, solid matrices (soils, sediments) and phenomena that occur within them have a major impact on water quality. A study of organic matter associated with these solid media is required to estimate its impact on the aquatic environment. Certain pollutants (e.g. polycyclic aromatic hydrocarbons [PAH], p. 23) are known to be mobilized in heterogeneous fractions (suspended matter, colloids, organic matter). It is therefore essential to analyse these heterogeneous fractions to gain further insight into phenomena governing the fate of such pollutants. Some of these fractions form a reserve of potentially remobilizable pollutants, especially during floods, and could thus have relatively marked environmental and sanitary impacts. LGEI has developed a simple rapid method for the analysis of organic matter in soils and sediments based on ultrasound-assisted extraction using different solvents, followed by UV/visible spectrophotometry. Based on the complementary expertise of LGEI and the *Centre des Matériaux de Grande Diffusion* (CMGD), as well as the joint analytical potential, the range of possibilities for analysing these fractions and macromolecules (humic substances, etc.) is very broad.

The LGEI centre also develops:
(i) physicochemical probes for measuring levels of contamination of certain pollutants (nitrates, detergents, PAHs, pesticides, etc.), and (ii) systems based on biodetection to assess concentrations and/or effects of certain xenobiotoxic substances.
It is also interested in territorial management of risks and natural crises. The research is focused on modelling (development of operational prediction tools), development of concepts and methods for assessing vulnerability, and the use of geomatic tools for spatial analysis of study areas and for streamlining crisis prediction, prevention and management.

In this setting, studies on soils, especially their permeability, are crucial with respect to setting up flood prediction tools, etc. Research projects have been carried out to this end, on catchments in the Cevennes and Nîmes regions, in collaboration with other research units from the French Languedoc-Roussillon region (UMR Hydrosciences Montpellier, BRGM). The centre's contribution has been most marked with respect to rainfall simulation trials conducted to

PAH screening of contaminated soils

É. Touraud © École des Mines d'Alès

Field kit for the determination of PAH contents in contaminated soils.

Polycyclic aromatic hydrocarbons (PAHs) are organic compounds produced during combustion reactions. They may be of natural (barbecues, forest fires, etc.) or human (combustion engines, industrial processes, etc.) origin. These compounds are thus widely disseminated in sediments, water, air, plants and animals. Their presence in soils is generally associated with gas production activities (coking plants, former gas plants), petroleum refining and wood treatment. Many industrial sites are therefore contaminated by these major pollutants. Around 50 PAH compounds have been indexed, 16 of which are considered as priority pollutants by the United States Environment Protection Agency (USEPA) because they have proven toxic properties, and some of them are carcinogenic.

The first step in the rehabilitation of contaminated sites is to conduct an environmental audit. Many analyses are required for this audit because of the heterogeneous distribution of PAH pollutants in soils. Laboratory analyses are expensive and time consuming. In partnership with Total and Secomam (company specialized in designing and manufacturing analysis and test instruments), EMA (LGEI) developed a simple, rapid, accurate and portable method for estimating PAH concentrations in 20 min in the field. This method is based on UV spectrophotometric analysis of an organic soil extract. The concentration obtained refers to 16 PAHs on the USEPA priority pollutant list. A 'maturity' index also provides information on the PAH biodegradability potential. The measurement range is from 20 to 2 000 mg/kg.

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determine the infiltration capacity of soils. These research projects have taken soils into greater account, thus enhancing the understanding, modelling and prediction flash floods.

Agricultural practices and purifying power of the soil and plants

Agricultural intensification–increase in agricultural production and preservation or even enhancement of its quality–is required to meet the increasing food demand of human communities. In this setting, a major challenge is to effectively manage raw or transformed organic matter and various residues. These products should be recycled to preserve natural resources (soils, atmosphere, water) in areas under high pressure from human activities (islands, urban and periurban zones) and where they are potential sources of pollution. This is also the case in areas where cropping is less intensive and where these products have always considered as a resource. Hence, for the **internal research unit (UPR) Environmental Risks of Recycling** (CIRAD), this challenge is being addressed by research and development of farming practices that tap the full purifying power of the soil and plants as a means to recycle organic matter and waste such as livestock farming and agroindustrial effluents, sewage sludge, green waste and household garbage.

Developing and monitoring an agricultural recycling system requires: (i) an understanding of the factors that determine the functioning of farms with respect to recycling practices, and (ii) an understanding of the impact of farming practices on waste and organic matter transfer and transformation processes in 'soil-plant-atmosphere' systems.

The crop plot is an ideal scale for studying biophysical processes, whereas integrated management of production systems is dealt with on a territorial level. The 'soil-plant' system is a key focus of study as an agricultural production framework, target of technical crop management interventions, and site of accumulation, transformation and transport of various products.

To assess this diverse range of scales and approaches, the UPR seeks situations in which: (i) most of the secondary raw materials mentioned above are produced, (ii) a diverse range of environments occur within a small area, with a high population density, and (iii) the regulatory framework is especially strict.
On the basis of these criteria, the UPR selected Réunion as its main research site because it is highly suitable for developing processes that could be extrapolated to many other tropical situations in a global regulatory framework that is bound to become stricter. Other research sites have also been selected on the basis of the socioeconomic settings (private industrial partnership) or the type of wastes present. •••

Sewage sludge, trace metal elements and sugarcane

The economic and agricultural advantages of recycling waste in agriculture are well documented, but it is essential to manage the environmental impact. Metallic trace elements (MTE) are amongst the potential pollutants involved in such recycling. These elements should be carefully monitored because most of them are toxic to animal and plant communities.

Agricultural spreading of sewage sludge is under strict French regulation so as to ensure, amongst other aspects, protection against the risk of contamination of soils and the environment (ecosystems, agrosystems, inland waters). To reduce risks associated with MTEs, waste spreading is therefore prohibited when sewage sludge has an excessively high MTE content or when the field soils to be treated already have a high level of these elements.

On the island of Réunion, many soils are formed on volcanic materials that naturally have nickel, chrome and copper contents above legally authorized levels. Sludge spreading therefore cannot be authorized on these soils unless the farmer has obtained an official waiver.

Following a large-scale soil and sugarcane sampling campaign, the internal research unit (UPR) Environmental Risks of Recycling (CIRAD) studied MTE mobility, i.e. the ability of these elements to pass into the liquid phase, and also their phytoavailability, i.e. the quantity of MTEs taken up by plants.
The findings revealed that the studied MTEs were not very mobile and that sugarcane plants growing on soils with very high MTE contents did not take up more nickel, chrome or copper than cane plants growing on less MTE-rich soils. These results could potentially be used to request a waiver, which in turn would pave the way to new prospects for utilizing sewage sludge in Réunion. The current setting in which fertilizer costs are sharply rising suggests that these prospects could become reality

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Development of tools for the analysis and prediction of Mediterranean agrohydrosystem function

The **joint research unit (UMR)** ***Environnement Méditerranéen et Modélisation des Agro-Hydrosystèmes*** **(EMMAH)** groups researchers from INRA and physicists and hydrogeologists from the University of Avignon and Pays de Vaucluse (UAPV). The unit's thematic and technical expertise spans the following domains:
■ Crop function/agronomy, bioclimatology and remote sensing
■ Physics of transfers and biogeochemistry of soils and porous media
■ Hydrogeology, hydrochemistry and hydrology.

The aim is to develop tools for analysis and prediction of the physical, biological and biogeochemical functioning of agrohydrosystems, especially Mediterranean, in terms of agricultural production, water flows and pollutant transfers, while considering a setting under possible climate and soil use changes.

The scientific strategy is based partially on experiments carried out on various scales (from a closed laboratory reactor to a catchment, including the column and plot), and also on the development of modelling tools to simulate the function of studied systems.

Concerning soil related activities, research is focused on modelling runoff and quick infiltration phenomena, on mineral or biotic (bacteria) colloidal particle movement, and on monitoring interactions between transport mechanisms (water, heat, solutes, gas) and biogeochemical processes controlling the fate of elements and compounds in solution (nitrates, dissolved organic carbon, trace metal elements). Various simulation tools have been developed: model of transfers in the unsaturated zone, combining transport, geochemistry and biological processes, 3D model of water extraction by root systems, crop development simulation models, 'soil-vegetation-atmosphere' transport (SVAT) models, assimilation of remote sensing data in vegetation models, models for simulating transfers in water tables, etc. •••


S. Rambal © UMR CEFE

Tower for the determination of energy, water and carbon dioxide fluxes over a green oak forest canopy at Puéchabon (France).

Carbon balance of terrestrial ecosystems

Mass and energy balances must first be accurately determined on the ecosystem scale to be able to gain insight into the global functioning of our planet. The turbulent correlation method can be used for ongoing assessment of energy, H_2O and CO_2 flows entering or leaving a given ecosystem. This method can be used: (i) to quantify carbon sinks, (ii) to highlight interactions between water and carbon cycles, (iii) to understand how biotic and abiotic variables control the system functioning, and (iv) how extreme events (e.g. severe heat waves or droughts) make ecosystems switch states from sink to source. Balances on a broad range of ecosystems, from temperate grasslands to Amazonian forests, have been determined through the networking of European (CarboEurope) and global (FLUXNET) observation sites.

The flux measurement tower at Puéchabon (France) has been running continuously for around 10 years. It is set up in a stand of green oak *(Quercus ilex)*, i.e. an emblematic species that grows on several millions of hectares in the Mediterranean Basin. It is now a recognized international reference site for evergreen forest ecosystems. The average net annual balance is 290 g C m^{-2}, with a gross assimilation of 1 290 g C m^{-2}.

The ecosystem respiration rate, i.e. the sum of autotrophic and heterotrophic respiration for which the 'soil' is a predominant constituent, is around 1 000 g C m^{-2}. This term is highly sensitive to current temperature increases and expected modifications in the rainfall regime. Its magnitude will largely determine the extent of future carbon sinks.

Rainfall exclusion experiments are also under way at the Puéchabon site. In one of these, 30% of the incident rainfall has been excluded since 2003. The initial results showed the functions of soilborne microbial populations were significantly affected, along with symbiot diversity and activity. In another set up, rainfall is totally excluded over long time intervals so as to simulate spring and summer droughts that occur at a centennial frequency.

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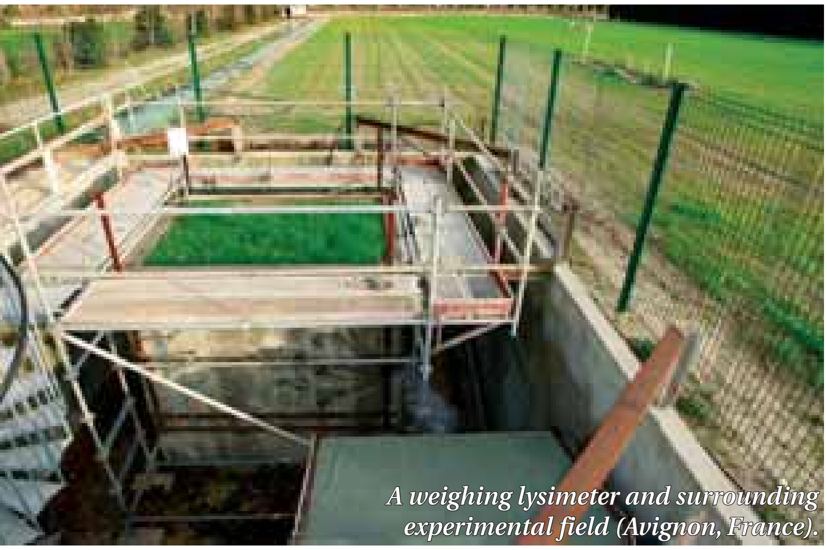
A research site to quantify soil water flows at different scales



A weighing lysimeter and surrounding experimental field (Avignon, France).

J-C Gaudu © UMR EMMAH

The soil is a structured medium composed of overlapping layers of aggregates. Water and solute transfers in soils are still far from being fully understood because of this structure. In particular, predictive models, which include rapid transport associated with preferred pathways or with spatial variability in hydraulic properties, have not yet been validated. Since 2003, the joint research unit (UMR) EMMAH set up a research site to quantify soil water flows (infiltration, slow and rapid drainage, root uptake, groundwater recharge) on different scales and to test geophysical methods (electric tomography, spontaneous potentials, etc.) tailored to the unsaturated soil zone. The specificity of this site is related to the multiscale approach (column [dm^2], lysimeter [5 m^2], plot [0.7 ha]) for analysing soil water flows. This combination of a real field plot, a shallow alluvial water table and a lysimeter representing a reduced model of this site is unique to the French research system.

This semicontrolled experimental set up facilitates: (i) the development of methods prior to their full-scale use for environmental monitoring, and (ii) the analysis and modelling of complex processes that describe transfers of water and associated substances (especially colloids) in the groundwater-soil-plant-atmosphere continuum. The plot is equipped with an irrigation system, piezometers for spatialized groundwater sampling (piezometry, chemistry), water balance monitoring sites with manual recording instruments (tensiometers, neutron probes) and ceramic cup water samplers. The lysimeter is equipped with similar automated sensors and flowmeters for recording drainage flows.

The entire team has free access to this site. Researchers may use it individually, or with the support of the UMR (cropping interventions, technical support, analytical laboratories) when their protocols are compatible with the constraints of the site.

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The laboratory also develops metrological tools associated with its research topics, e.g. characterization of surface water retention and monitoring the composition of the soil atmosphere and gas exchanges at the soil-atmosphere interface. Moreover, it implements physical, chemical, isotopic and biological measures to monitor variations in studied systems. The laboratory's physicists investigate new theoretical approaches for modelling transport in heterogeneous porous media.

The laboratory is involved in teaching at BSc and MSc levels at the University of Avignon, while also participating in educational courses at other universities. It is affiliated with the SIBAGHE Doctoral School in Montpellier (France), and belongs to the *ÉCosystèmes COntinentaux et Risques EnVironnementaux* (ECCOREV) research federation and the *'Agronomie, Sud et Méditerranée'* advanced research thematic network in Montpellier.

The UMR is based on the INRA site in Avignon (France), and also on the University campus and the Agroparc site (Avignon). In addition to standard laboratories devoted to physical, chemical, isotopic and biological analyses, it has two external research platforms. One concerns remote sensing techniques, and the other enables local (lysimeter) and spatialized (plot) monitoring of flows in the unsaturated zone and relationships with the water table.

Fate of active pesticide compounds in vineyard soils and runoff water

Substantial runoff and erosion occurs in the Mediterranean region, which increases the risk of dissemination of organic pollutants of agricultural origin, and thus the risk of soil and water contamination. Vineyard cropping practices have an even greater impact on soils and water resources because of the sparse canopy and the fact that the vines are often grown on relatively impermeable soils. In viticulture, many herbicides are sprayed in vineyards in the spring, and a fraction is degraded or adsorbed on soil particles and the other mobilizable fraction is transported by runoff during rain storms. Organic matter microbiological degradation processes are reduced during extended dry periods.

Measured pollutant concentrations in water are high (up to several hundreds of µg/L) and above the maximum concentration authorized in drinking water (0.1 µg/L, Directive n°80/778/EEC). Water transits through complex pathways from field plots before reaching drinking water supply outlets. Along this route, initial concentrations decrease due to degradation, adsorption and dilution processes. The level of contamination at the catchment exit is thus more variable and limited than at the field plot exit.

Guidelines for cropping practices have been drawn up on the basis of study findings. These include: (i) reducing herbicide treatments; (ii) increasing the soil infiltration capacity by surface tillage or by leaving grass strips between planting rows; (iii) reducing erosion by maintaining plant cover in the vineyards after the grape harvest; and (iv) restoring the biological activity in the soil via grass cover, leaving pruned shoots on the soil and applying organic amendments. The impact of grass cover on vine nitrogen nutrition and water supplies should also be assessed.

Surface water contamination by pesticide entrainment is a spatiotemporally variable phenomenon. Its management requires research into cropping practices that will reduce runoff and erosion and promote degradation of pesticide compounds on the sprayed site. Because of the broad range of factors involved, the phenomena should be modelled in addition to experimental research with the aim of designing more environment-friendly farming practices for the future.

P.Andrieux © UMR LISAH

Grass-covered vineyard to control water contamination by pesticides (Languedoc, France).

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Physicochemical analyses of soils, water and *plants performed* for research

The **service unit (US)** ***Water, Soil and Plant Analysis*** (CIRAD), which is based in Montpellier (France) and Saint-Denis in Réunion, conducts physicochemical analyses of soils, sediments, crop substrates, fertilizers, water and plant matter. Thirty thousand results are obtained annually from 2 500 to 3 000 analysed soil samples. They are derived from conventional assays of particle-size, exchange complex, pH, organic matter, assimilable phosphorus, total elements, etc. They are also from specific analyses of tropical soils, including the characterization of soil exchange complexes and pH, of specific forms of assimilable phosphorus, of the soil solution or so-called amorphous constituents.

The US provides CIRAD research units with support for analysing soils, assessing their fertility, monitoring changes under cropping conditions and screening for unwanted elements. It also fulfils similar requests from other French (INRA, CNRS, IRD, etc.) or foreign (national agricultural research centres, etc.) research institutions, NGOs, development organizations or private clients.

In addition to conventional solution treatment equipment (muffle furnaces, microwave ovens, centrifuges, etc.), the laboratory is equipped with other highly advanced instruments, including a simultaneous plasma emission spectrometer, continuous-flow colorimeter chains, elemental analyzers, automatic instrument for particle-size determination, etc. It also recently installed a polarograph for metallic trace element speciation.

The quality of the results is constantly monitored through rigorous internal checks and participation in French national (BIPEA) and international (ISE-Wageningen) intercomparison surveys. Hence, in 2002, it was awarded an accreditation by the French Ministry of Agriculture and Fisheries for physicochemical and particle-size analyses of soilborne trace elements and residual nitrogen. •••

P. Hinsinger © UMR Eco&Sols

Rhizosphere– the site of soil to plant nutrient flows

The rhizosphere is the soil volume influenced by roots and also the site of exchanges between soil, roots, microorganisms and associated fauna. These intense exchanges lead to bi-directional flows of water and nutrients within biogeochemical cycles. Around 40% of the carbon fixed during photosynthesis is allocated to roots. Half of this carbon is released into soil, which stimulates microbial activities. The architecture of the root system and its plastic development depend on the allocated carbon and on the environmental conditions encountered, while also determining the rhizosphere volume.

This volume varies according to the type of elements and biogeochemical processes. Water and elements such as nitrate nitrogen are highly mobile in the soil–their root uptake leads to bulk and diffusion displacement of several centimetres. All soil horizons highly colonized by roots are subjected to their influence and can therefore be considered as rhizospheric.

Roots of the same plant and neighbouring plants (of the same species or not) are thus frequently competing for this resource. Conversely, potassium, and even more so phosphorus, are much less mobile in soil–their root uptake induces a diffusion gradient spanning just a few millimetres, or even less than a millimetre. The rhizosphere volume can therefore only represent 1–3% of the soil horizon volume, even in the surface horizon. For instance, in a 5-year-old oil palm plantation, the AMAPsim root architecture model highlighted that specific soil volumes for sampling phosphorus and potassium throughout the profile were 33 and 235 m^3 ha^{-1}, respectively. Estimating and modelling root growth rates, and the resulting spatial and temporal rhizosphere dynamics, is thus essential for integrating flows measured around the rhizosphere of root segments on the soil profile and plot levels.

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The laboratory was authorized by the regional crop protection service to import non-European soils, thus broadening its scope for intervention in Mediterranean and tropical countries.

Three additional activities supplement and enhance its core activity:

■ Tailoring methods: conducting one-time studies to address specific needs arising in the course of normal analytical activities, adapting existing methods that are not listed in its catalogue to the laboratory facilities, and developing experimental designs to meet specific client requests. This also includes a study that is currently under way on the determination of particle-size fractions in andosols.

■ Knowledge transfer to individuals not on the laboratory staff, in the framework of diploma or practical training on analytical methods, techniques and laboratory organization principles and management.

■ Expertise may be focused on different topics of varying complexity, ranging from simple advice on improving laboratory operations (or other domains within the range of the laboratory's expertise) to complete studies that are carried out with the aim of setting up an analysis unit. These operations target CIRAD staff or external clients and are conducted over periods of varying length (1 day to several weeks).

The laboratory's organization system for all of its activities was certified under the ISO 9001 standard in 2000, thus ensuring that it will be constantly improved and remain attentive to, and thus able to better meet, clients' needs. ■

▲ *Iron oxide accumulation around a eucalyptus root several metres below the soil surface in a sandy soil in western Australia.*

Macrocosm domes at the European Ecotron, Montpellier (France).

Studying 'biogeochemical cycle-environment' interactions at the European Ecotron, Montpellier (France)

Biogeochemical cycles are markedly restricted by interactions between environmental resources, the diversity and activity of living organisms and environmental conditions. These numerous interactions are also dynamic–living organisms respond to an environmental variation in a plastic way in the short term, structurally and demographically in the medium term, and evolutively in the long term. This complexity should be taken into account when predicting the fate of biogeochemical cycles and their effects (e.g. impact of carbon dioxide and methane on the climate).

Ecotron provides a key link between the analysis of elementary functions in simplified conditions and the *in situ* study of ecosystems. By confining ecosystems in chambers, it is possible to simulate a broad range of environmental conditions (temperature, water conditions, CO_2, pollutant) by correlating the levels of several factors and also accurately measuring the main flows generated by the ecosystem, while determining the balances. Ecotron has a high measurement capacity, especially with respect to line measurements of photosynthesis, respiration, transpiration, methane and nitrous oxide release and $^{13}C/^{12}C$ and $^{18}O/^{16}O$ isotope ratios of CO_2. The isotope approach also includes ^{13}C labelling of newly formed organic matter.

These measurements are sometimes supplemented by noninvasive measurements (spectral reflectance, etc.), or measurements of soil or plant samples. Ecotron, which is based on the Baillarguet campus (France), consists of three research platforms. The macrocosms (12 units, 35 m^3 each) can handle ecosystem samples of 1–8 t. The mesocomes (24 units, 2–3 m^3 each) can handle ecosystem samples of 0.2–1 t, especially the standard lysimeters currently in service in Europe. The L2 laboratory microcosm platform will handle various types of microecosystem in 1–200 dm^3 units.

Ecotron is open to the international scientific community. Its European scientific committee selects projects from team consortiums that effectively promote the platform. The role and response of soil biology are taken very seriously by many of them, regardless of whether the projects are oriented towards ecosystem physiology, population biology or communities.

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É. Blanchart © UMR Eco&Sols

Earthworms, emblematic animals of the soil.

Soils are living *environments that harbour* multifunctional organisms

Soil is clearly of primary importance as a plant support, physical substrate for most human activities and on account of its environmental functions. In natural and cultivated systems, soil serves as a hub for the regulation of most ecosystem services necessary for human wellbeing. Soil is therefore essential for terrestrial ecosystem functioning, while being a natural resource of major importance for sustainable ecosystem management.

Soil supports much of the Earth's biodiversity. It is estimated that a quarter of all currently described species inhabit soil. The recent advent of molecular screening techniques has revealed the extraordinary biodiversity present in soils, but little is really known about it. This biodiversity–from microorganisms to certain mammals–is largely due to the physical and chemical heterogeneity of soil, which in turn is conducive to the development and preservation of a very substantial number of ecological niches. This biodiversity is associated with high functional diversity and extremely complex ecological interactions. Soil functioning, and its contribution to ecosystem services essential for sustainable ecosystem functioning, are based mostly on the functional roles played by soil organisms in ecological processes. For instance, many processes involved in biogeochemical cycles take place in soil via the activity of a broad range of soilborne organisms (bacteria, fungi, protozoans, roots, fauna).

Soil organisms also affect plant productivity, either directly or indirectly (modifications in carbon and nutrient cycles, in the soil structure, trophic interactions and control of parasites and pathogens). The spatiotemporal distribution of biological processes is not random or homogeneous, i.e. research has shown that the activities of soil organisms are focused in 'hot spots' of activities generally linked with the availability of carbon substrates. Microbial habitats are hence associated with organic fractions, aggregates (aggregatosphere), decomposing litter (detritusphere), earthworm-altered soil (drilosphere), certain types of porosity (porosphere) and close contact with roots (rhizosphere).

The role of organisms in these biophysical and biogeochemical processes is still, however, poorly understood. Is there, for instance, a causal relationship between biodiversity and ecosystem functioning? How many species are needed to ensure each ecosystem function? The responses to these questions are complex because many species perform the same function (functional redundancy), some species have different functions (multifunctionality), while others contribute relatively little to ecosystem properties. Recent research has led to the identification of functional groups responsible for essential ecosystem processes: microsymbiots (nitrogen fixers, mycorrhizae), decomposers (of lignin or cellulose), element transformers (nitrifying and denitrifying), soil engineers (earthworms, termites), pathogens (white grubs, phytoparasitic nematodes), microregulators (predators, parasites) and growth-promoting rhizobacteria. Metagenomics (the study of all microbial genomes)–via comparative genomic approaches–can shed light on the overall functioning of soils and pinpoint microbial groups responsible for the different processes that occur in soils.

Soil ecology research is more crucial than ever to cope with current societal issues (alteration of biodiversity and ecosystem services, ecosystem sustainability when more food and fibre must be produced for a growing population and climate change that is currently under way). Knowledge on soil organisms and their functions is a key to the sustainable management of terrestrial ecosystems. The development of sustainable production systems should be based on the efficient use of soil resources and thus of organisms whose functional potential has yet to be fully tapped. In this setting, ecological engineering is especially promising, especially by targeting organisms that have nutrient recycling, soil structure modification and biological control capacities.

Research carried out by Agropolis International teams is shedding considerable light on the biological functioning of soils.

Éric Blanchart (UMR Eco&Sols)
and Isabelle Navarro (UMR LSTM)

Soils are living *environments that harbour* multifunctional organisms

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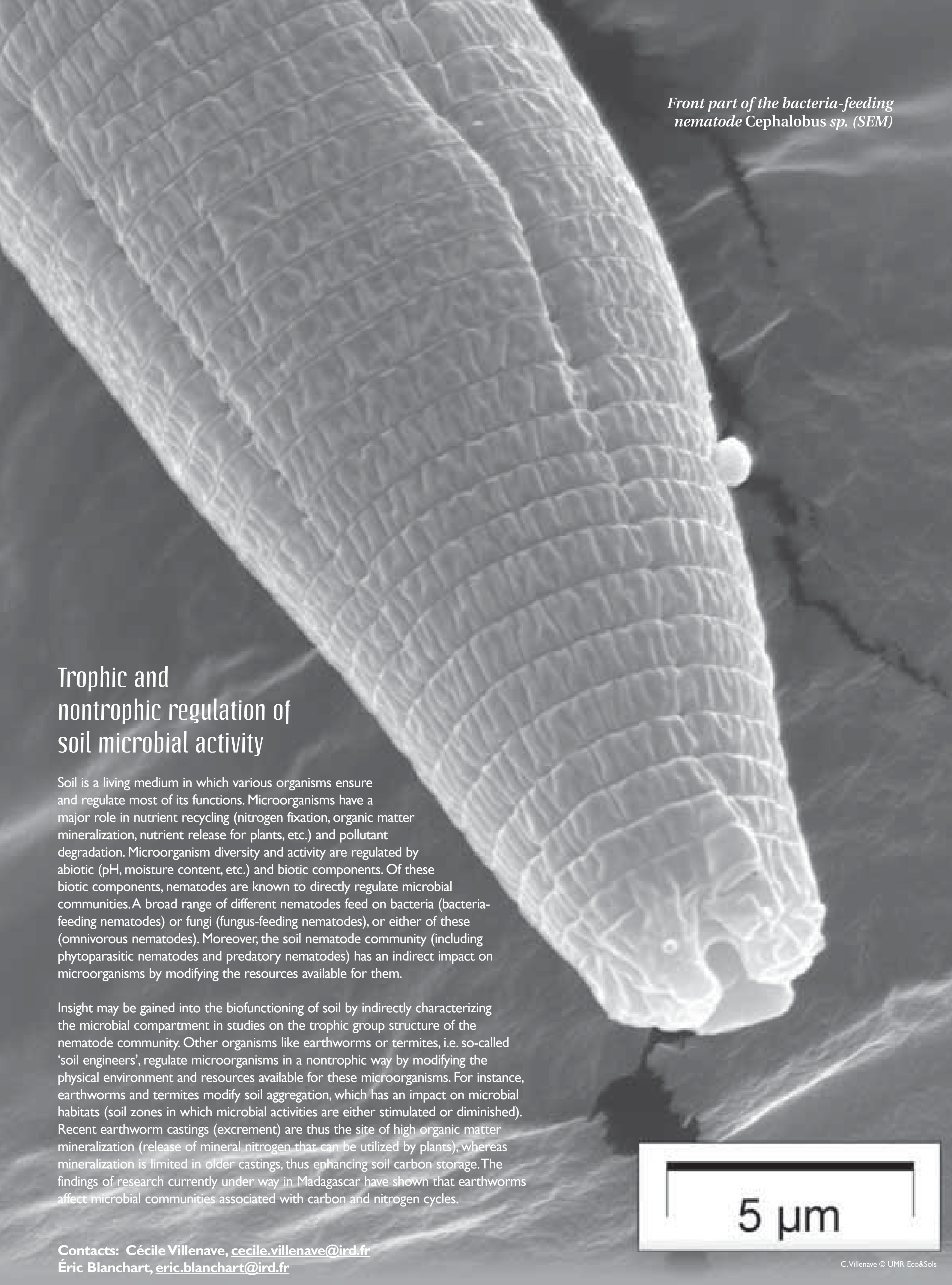
Functional ecology and soil biogeochemistry: *ecological engineering* to promote *sustainable development*

Soil is the main foundation for primary production in terrestrial ecosystems. In ecosystems affected by human activities, this plant production function has long been preserved through the management of inputs (chemical, organic) and the physical and chemical properties of soils. This strategy boosted global food production by twofold between 1960 and 1995, but it was accompanied by an almost sevenfold concomitant increase in nitrogen fertilizer inputs and an over threefold increase in phosphate fertilizer inputs.

Considering the environmental impacts of such practices, this strategy cannot provide a sustainable response to the increase in plant production necessary to cope with population growth in the coming decades. Moreover, soils and their services for society are not based solely on the production function. All services that soils provide for societies (climate regulation, water purification, etc.) have to be taken into account to preserve soil resources.

In a setting in which an increase in primary productivity and input management (chemical and organic) are essential, and global changes (climate change and land use) are under way, the scientific objectives of the **joint research unit (UMR)** ***Écologie fonctionnelle et biogéochimie des sols*** (**Eco&Sols**, IRD, INRA, Montpellier SupAgro) are to gain insight into, describe and predict biological processes involved in ecosystem services concerning the regulation of element flows in the soil-plant system, especially carbon (C), nitrogen (N) and phosphorus (P). The studies carried out by this UMR are focused on biological regulation of: (i) nutrient (N and P) bioavailability and acquisition by plants, (ii) carbon sequestration and greenhouse gas emission, and (iii) the bioavailability and ecodynamics of biological contaminants (viruses, Bt proteins, etc.).

To fulfil these objectives, UMR Eco&Sols seeks to determine the impact of soilborne organisms (plant roots, earthworms, termites, nematodes, fungi, bacteria) on flows that transit through the different compartments of soil-plant systems. The focus is placed especially on relationships such as predation, competition, facilitation, symbiosis, rhizodeposition and bioturbation by macrofauna. •••



Front part of the bacteria-feeding nematode Cephalobus *sp. (SEM)*

Trophic and nontrophic regulation of soil microbial activity

Soil is a living medium in which various organisms ensure and regulate most of its functions. Microorganisms have a major role in nutrient recycling (nitrogen fixation, organic matter mineralization, nutrient release for plants, etc.) and pollutant degradation. Microorganism diversity and activity are regulated by abiotic (pH, moisture content, etc.) and biotic components. Of these biotic components, nematodes are known to directly regulate microbial communities. A broad range of different nematodes feed on bacteria (bacteria-feeding nematodes) or fungi (fungus-feeding nematodes), or either of these (omnivorous nematodes). Moreover, the soil nematode community (including phytoparasitic nematodes and predatory nematodes) has an indirect impact on microorganisms by modifying the resources available for them.

Insight may be gained into the biofunctioning of soil by indirectly characterizing the microbial compartment in studies on the trophic group structure of the nematode community. Other organisms like earthworms or termites, i.e. so-called 'soil engineers', regulate microorganisms in a nontrophic way by modifying the physical environment and resources available for these microorganisms. For instance, earthworms and termites modify soil aggregation, which has an impact on microbial habitats (soil zones in which microbial activities are either stimulated or diminished). Recent earthworm castings (excrement) are thus the site of high organic matter mineralization (release of mineral nitrogen that can be utilized by plants), whereas mineralization is limited in older castings, thus enhancing soil carbon storage. The findings of research currently under way in Madagascar have shown that earthworms affect microbial communities associated with carbon and nitrogen cycles.

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Microbial activity and nitrogen cycle in soils

Soils naturally have a low nitrogen content (0.3–3% of their dry weight), whereas this element accounts for 5–50% of the dry weight of plants. One unique feature of the nitrogen cycle is that it depends directly on the soil bacterial activity. Some legume plants are associated with symbiotic bacteria, i.e. 'rhizobia', which can fix atmospheric molecular nitrogen (N_2). Other plant species depend on bacteria to get their mineral supply, in the form of either ammonium (NH_{4+}) through ammonifying bacteria, or nitrate (NO_{3-}) through nitrifying bacteria. Direct application of chemical fertilizers in crop fields has prevailed in agriculture until present. This strategy is detrimental to the environment, leading to nitrate leaching into the water table and emission of nitrous oxide (N_2O) gas, which has a serious greenhouse effect. Note that in turn this nitrous oxide emission also depends on the activity of denitrifying bacteria communities.

Low-input, environment-friendly agriculture should be based on a more thorough understanding of the bacterial compartment. The aim should thus be to selectively stimulate bacterial communities that mineralize organic nitrogen for plants, while reducing the activity of bacterial communities responsible for nitrous oxide emission. This is a key challenge for tropical countries where fertilizers are expensive and in short supply.

J.-J. Drevon © UMR Eco&Sols

◀ *Rhizobium nodules on bean roots.*

One strategy of low-input or 'conservation' agriculture is to leave crop residue on the soil surface. This increases soil organic matter but may also boost N_2O emission. UMR Eco&Sols has been focusing substantial research on this topic and has shown that direct seeding mulch-based cropping systems (DMCs) do not increase N_2O emissions. These results suggest that N_2O emission generally depends on the quality of the organic litter layer (C/N ratio, lignin/phenol ratio).

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This ecosystem-oriented approach focused on functional communities and interaction networks is pivotal to the UMR's laboratory (on microcosms and mesocosms) and field research–with the ultimate aim being to develop ecological engineering that meshes sustainable agricultural production with preservation of soil environmental services. The stability and resilience of these functional communities with respect to climate and land use change are studied under different Mediterranean and tropical soil climate conditions, within the framework of collaborations with national agricultural research centres and universities in developing countries.

These experimental approaches are closely associated with modelling devoted to formalizing biological processes that determine soil functions and predicting flows in 'soil-plant' systems.

Microbiology and plant biology: biodiversity, *symbiotic microorganisms,* plant responses *and adaptations*

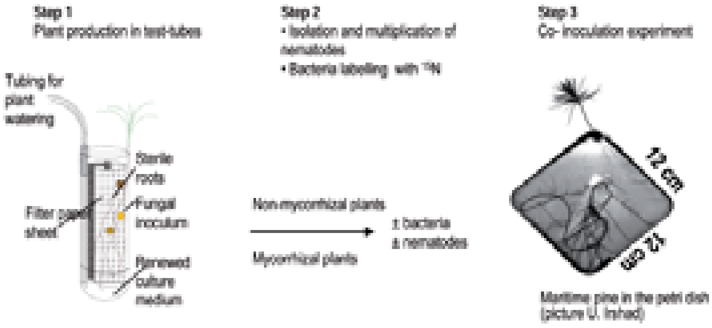
The **Laboratory of Tropical and Mediterranean Symbioses** (**LSTM**, CIRAD, INRA, IRD, Montpellier SupAgro, UM2) is a microbiology and plant biology research unit specialized in biodiversity, symbiotic microorganism function and the response and adaptation of plants to these microorganisms and to harsh environmental conditions. The laboratory's research ranges from the analysis of the biodiversity of symbiotic microorganisms to gaining insight into molecular mechanisms involved in plant/bacteria interactions.

The studies and applications are focused on Mediterranean and tropical environments in which microorganism/plant symbioses enable sustainable improvement of

Role of bacteria / bacteria-feeding nematode interactions on mineral nutrition of maritime pine

Relationships between microorganisms and their predators determine nutrient cycling rates and have a marked impact on plant mineral availability. The beneficial effects of these relationships on root growth and mineral nutrition were clearly demonstrated in annual plants. However, contrary to grass plants, little experimental data is currently available on the role of these interactions in woody plant root development and mineral nutrition. In forest ecosystems of temperate regions, tree roots systematically live in association with symbiotic soilborne fungi that form mixed organs called ectomycorrhizae.

These ectomycorrhizae host specific bacterial populations, i.e. mycorrhiza-associated bacteria (MAB), which can be isolated and reared in the laboratory. UMR Eco&Sols launched a new research topic on these trophic networks based on the working hypothesis that bacteria/bacteria-feeding nematode populations occur in the vicinity of woody plants, especially between nematodes and MABs. An initial experiment was set up in 2008 to test different coinoculation treatments between a nematode species, a *Pseudomonas fluorescens* bacterial strain, a model ectomycorrhizal fungus *(Hebeloma cylindrosporum)* and a tree of economic importance in France, i.e. maritime pine *(Pinus pinaster)*. The nematode, bacterial strain and the fungal partner were all isolated from soils and ectomycorrhizae sampled in the *Forêt des Landes de Gascogne* (France).



U. Irshad, C. Plassard © UMR Eco&Sols

Experimental design for studying the effect of trophic relationships (ectomycorrhizal fungi, associated bacteria and bacteria-feeding nematodes) on root growth and mineral nutrition of maritime pine.

The experimental design was based on ^{15}N labelled bacteria. The preliminary results suggested that nematode predation by bacteria leads to nitrogen and phosphorus release. This latter element is essential for the absorption of nitrate added to the culture medium.

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agricultural and forestry production and restoration of endangered environments. LSTM conducts studies in the following scientific fields:

- ■ analysing symbiotic biodiversity in Mediterranean and tropical ecosystems
- ■ understanding the structure and evolution of genetic diversity of symbiotic bacterial populations (phylogenetic and genetic approaches to populations)
- ■ studying the genomic diversity of photosynthetic *Bradyrhizobium* populations, bacteria/host plant interactions and light-induced regulation
- ■ characterizing a new possible signalling pathway between rhizobia and plants of the pea family, as suggested by the absence of common nodulation genes in photosynthetic *Bradyhizobium* species
- ■ unravelling the signalling pathways of plants in response to bacteria. In addition to identifying these pathways, the aim is to understand their interactions and analyse the bacterial genes involved in their induction
- ■ studying the adaptation of symbiotic microorganisms to constraints in Mediterranean and Sahelian soils, especially water stress and high temperatures, as a function of climate change and human activities (farming and mining). These studies–particularly through metagonomics approaches–will enable comparison of the diversity of microorganisms in different agroecological zones and characterization of physiological and genetic mechanisms involved in stress adaptation of bacterial strains isolated in these soils with the aim of optimizing symbiotic functioning in these environmental conditions
- ■ studying the adaptation mechanisms of plants and associated microorganisms to extreme edaphic constraints of ultramafic soils in New Caledonia. Functional genomics approaches at different genomic levels will help determine the mechanisms involved in: (i) the resistance and hyperaccumulation of metals in plants, (ii) the adaptation of microorganisms associated with plants, and (iii) plant-microorganism interactions
- ■ transferring and promoting sustainable development technologies for developing countries so as to design methods that could foster sustainable development and interest biotechnology companies.

LSTM consists of five teams:

- ■ Ecology and molecular physiology of photosynthetic *Bradyrhizobium* species
- ■ Symbiosis biodiversity and evolution
- ■ Plant responses to microorganisms
- ■ Adaptation of plants and microorganisms to nickel
- ■ Symbiotic functioning of ecosystems

LSTM collaborates with the most competent French laboratories in this field, in addition to other local partnerships in France (Montpellier research hub). •••

Within the framework of the 'Nickel and its environment' project of the *Centre National de Recherche Technologique* in New Caledonia, the UMR is participating in setting up a joint molecular biology platform in Nouméa, in direct collaboration with the University of New Caledonia and the *Institut Agronomique néo-Calédonien.* Development links will be maintained with countries in West Africa (via the joint IRD/ISRA/UCAD laboratory in Dakar, Senegal) and the Mediterranean Basin. The UMR hopes to have a key role in setting up two laboratory networks–Mediterranean and subSaharan–in the fields of microbiology and environmental restoration.

Genomics collaborations with United States laboratories will be strengthened in liaison with *Génoscope d'Évry* and the UCLA-DOE Institute for Genomics and Proteomics at Los Angeles, USA.

LSTM is also involved in teaching many university courses and organizing university level training in biology and physiology. It provides training support through interventions and supervision of professional or research training sessions.

Study of energy cycles, water, nutrients and organic matter decomposition

The **Centre of Evolutionary and Functional Ecology** (**CEFE**, CNRS, UM1, UM2, UM3, Montpellier SupAgro, CIRAD, EPHE) conducts broad ranging research on biodiversity dynamics in terrestrial media.

Some of the main aims are:
- to assess mass and energy flows between ecosystems and their environment and within ecosystems
- to predict their responses to global changes and, especially, to take the influence of human activities into account with respect to these changes
- to assess the role of the diversity of organisms in the regulation of these flows.

To fulfil these objectives, CEFE studies mechanisms involved in several key terrestrial ecosystem functions: energy, water, carbon, phosphorus and nitrogen cycles and organic matter decomposition. Within the framework of this research, soil is an essential ecosystem function compartment.

Indeed:
- Soil is a water reservoir that compensates for the unpredictability of this resource for plants, while providing a favourable environment for microorganisms and macrofauna
- Soil is a reservoir for mineral elements and an organic waste receptor available for organisms inhabiting them
- Soil harbours a diverse range of organisms (microorganisms, macrofauna) which ensure essential functions such as biogeochemical transformation of carbon, nitrogen, phosphorus, etc.
- Soil is the site of complex sets of inter-and intra-specific interactions between organisms it hosts and is the counterpart photoreceptor of the ecosystem.

The multiscale approaches developed at CEFE enable assessment of the full complexity of ecosystem functioning:
- Local *in situ* approaches to analyse the biological diversity and to analyse and explain the functional variability of soil (study of the spatial variability of physicochemical properties of soil and its biological functioning, study of relationships between plant and microbial diversity, impact of human disturbances on this functioning, etc.)
- Approaches conducted in experimental fields or under controlled conditions (microcosms) to measure these flows and to highlight the key environmental factors determining their control, for instance: (i) by manipulating the diversity at different trophic levels (plant, animal or microbial diversity) in the studied systems, (ii) by modifying the environmental conditions (rainfall exclusion, organic matter quality, etc.) or (iii) by long-term monitoring to assess the vulnerability of certain functions with respect to extreme climatic events
- Modelling approaches (modelling energy, water and mass flows and respiration within the ecosystem).

Research on these topics involves volatile compound analysis techniques, in vitro assays to measure enzymatic activities of soil and its fungal and bacterial communities, analysis of soil and litter organic matter, and molecular typing tools to assess the taxonomic diversity of soil organisms.

Finally, Mediterranean (Mediterranean fallows, green oak forests) and tropical (tropical rainforests, etc.) ecosystems serve as biological models for this research. ■

Microorganism biodiversity in the rhizosphere

D. Mousain © LSTM

Young maritime pine plant inoculated by the symbiotic ectomycorrhizal fungus Hebeloma cylindrosporum.

Many soilborne organisms have a symbiotic relationship with plants. Soil fungi thus form mycorrhizae on the roots of over 90% of plant species. This is also the case with rhizobia, i.e. bacteria that form nodes on the roots of plants of the pea family.

These symbiotic organs have a key role in plant nitrogen and phosphate nutrition. Mycorrhizal fungi increase the soil volume colonized by root systems, while also mobilizing mineral or organic substances inaccessible to plants. Nodes on legume roots reduce atmospheric nitrogen into forms that can be assimilated by plants, thus enabling them to grow in relatively infertile natural ecosystems or in agrosystems without any nitrogen fertilizer input.

Symbiosis generally has a paramount role in ecological processes. In plant successions, legumes boost the soil nitrogen content through symbiotic fixation of this element via their nodes. In parallel, mycorrhization explains how some plant species are replaced by others. Recent studies have shown that symbiotic fungi can supply carbon to understorey plants, thus offsetting the reduction in photosynthesis due to shade cast by the tree canopy. It seems that this process contributed to the evolution of non-chlorophyll plants.

In practical terms, it is possible to isolate and specifically inoculate microorganisms to enhance plant growth, e.g. legume seed yields and protein quality, or to manage the production of edible mushrooms like truffles, saffron milk caps or ceps. However, the symbiotic efficacy varies considerably depending on the microbial partner. Research is under way mainly to analyse the genetic diversity of these symbiotic microorganisms (dozens of species are involved), study the functional significance of this diversity, gain insight into symbiotic organ function and unravel the molecular signals involved in plant-microbe dialogues.

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Archeological excavation of a block of houses built around a central courtyard (late 2nd century BC) in the harbour city of Lattara (Hérault, France).

Soils maintain *an evolutionary record of* ecosystems and humankind

Research on environments of the past are based largely on geochemical and biological indicators found in ice, lake sediments and soils. These indicators consist of minerals (e.g. nitrogen and phosphorus), isotopes or rare earths whose concentrations vary according to climatic conditions, plant covers or human uses of the environment. They also include a broad range of different biological remains, plant debris (seeds, needles, buds, etc.), pollen grains, phytoliths (silica crystals produced by plants), silica-shelled algae (diatoms) and animal remains (insects, crustaceans, mites). Their analysis generates information on the composition of past environments and enables studies on the impacts of climatic or human-induced changes on the function and biodiversity of natural or cultivated ecosystems.

Soils are of primary importance for studying past human societies and populations. We are thus surrounded by archeological soils produced through thousands of years of temporary or long-standing human occupation–for living, settling or growing crops. Soils contain the first traces of Paleolithic houses or fire places, the first forms of habitats that appeared during the Neolithic period and those of the first villages and settlements. Domestic waste of all types, dishes, stone and metal tools, small objects of daily life, plant and animal food remains (usually burnt), charcoal and bones are preserved in settlement soils (houses and roads). They provide information on eating habits, lifestyles, food economies and trade patterns of these societies. Necropoleis for incineration or burial also provide substantial information on human paleopathologies, funeral rites, forms of organization and hierarchical structuring of these societies.

Soil is an archive that paleoecologists and archeologists know how to interpret in order to unravel its history and that of plant covers and human societies that it has supported. These disciplines are now based on a broad spectrum of expertise, such as sedimentology, paleobotany (palynology, anthracology and carpology), archeozoology (terrestrial fauna and ichtyofauna), geoarcheology and physical anthropology.

Paleoecology and archeology have always focused on finding markers that could be used to draw up a highly accurate chronological chart of the evolution of ecosystems and human societies. These disciplines are now based on a palette of modern archeological dating technologies.

This research aims to gain insight into the evolution of human societies and changes that ecosystems have undergone as a result of natural processes or their human occupation. Climate changes and biological refuges since the last deglaciation 18 000 years ago have tempered the history and organization of ecological systems. Constraints concerning the soil, terrain, migration routes, and natural disturbance regime (fires, insect epidemics, avalanches, storms, etc.) have contributed to organizing and structuring current ecological systems. Human populations have settled and developed on them. Studies on of the soil's archeological archives clarify the reasons underlying these settlement patterns, the typology of the occupants, the demographical structure of the populations and their pathologies, lifestyles and agrarian innovations, the relationship between these populations and their environment as a source of habitat materials or tools, food or energy sources. Finally, the human settlement of territories has modified the natural organization of ecological systems because of the tapping of environmental resources, development of agrosylvopastoral practices and upsetting the set of constraints. The study of the mechanisms, kinetics and chronology of the anthropization of natural systems enables us to understand their reactivity and is useful for gaining greater insight into sustainable resource and land management.

The historical understanding of interactions between human societies and environments is a major current environmental, social and political challenge with respect to establishing a compatible sustainable interaction between the dynamics of social systems and that of natural constituents and their environments. By assessing these archives, it is possible to build scenarios on the historical durations, which extend much beyond a century, sometimes even a millenium. Archeology and paleoecology thus help in coming up with answers to baseline questions: Where are we from, who are we and what is our fate?

Christopher Carcaillet (UMR CBAE, CNRS/EPHE/UM2), Philippe Blanchemanche (UMR ASAP, CNRS/Culture/UM3/INRAP)

Soils maintain *an evolutionary record of* ecosystems and humankind

Changes in ancient environments *and human practices*

The ***Centre de Bio-Archéologie et d'Écologie*** (**UMR CBAE,** CNRS, EPHE, UM2, INRAP) conducts research aimed at: (i) gaining insight into how ancient environments changed over the last centuries or millenia, and (ii) determining links between human practices and environmental changes affecting ecosystem function, the organization of communities and geographical population patterns. Past environmental changes were the result of land use modifications (agriculture, resource use) as well as climatic and orographic modifications. CBAE carries out studies in regions within the Mediterranean Basin, including the Middle East, tropical regions (Africa, South America) and northern regions (Canada, Scandinavia).

To analyse these processes, CBAE implements strategies and methods based on biological and geochemical indicators in natural and archeological soils, in surface deposits such as peat, tuff, travertine, and lake sediment. These superficial formations that cover the subsoil have accumulated over the last millenia in most cases, and sometimes throughout the Pleistocene period*. Such deposits (or archives) are affected by plant cover modifications, soil fauna activities, modifications in geochemical flows in catchments, and by land use changes by human populations.

The laboratory researchers are also investigating the conditions of natural biological resource extraction and use, from the gathering of materials to their processing for domestic use. There has been a substantial increase in such studies, aimed especially at analysing the emergence of prehistoric agriculture and domestication patterns (kinetics, mechanisms). Archeological soils host a high quantity of plant remains of different types, origins and uses. These remains are the result of harvesting and transformation of plant organs for domestic uses (food crops, fuelwood, timber, etc.). Plant remains in archeological soils are studied to trace the feeding habits of societies, ethnobotanical and agricultural practices from the harvesting of crops until their processing, and in some cases to analyse cultural practices associated with human cremations and funeral burials.

The main research topics investigated by the UMR are:

- domestication and paleoagronomy
- the role of fires on terrestrial ecosystem dynamics
- the impact of agropastoral abandonment on current forest landscape structures. •••

* Modern name for the Quaternary period, which is the most recent geological period spanning around 1.8 million years.

Main teams

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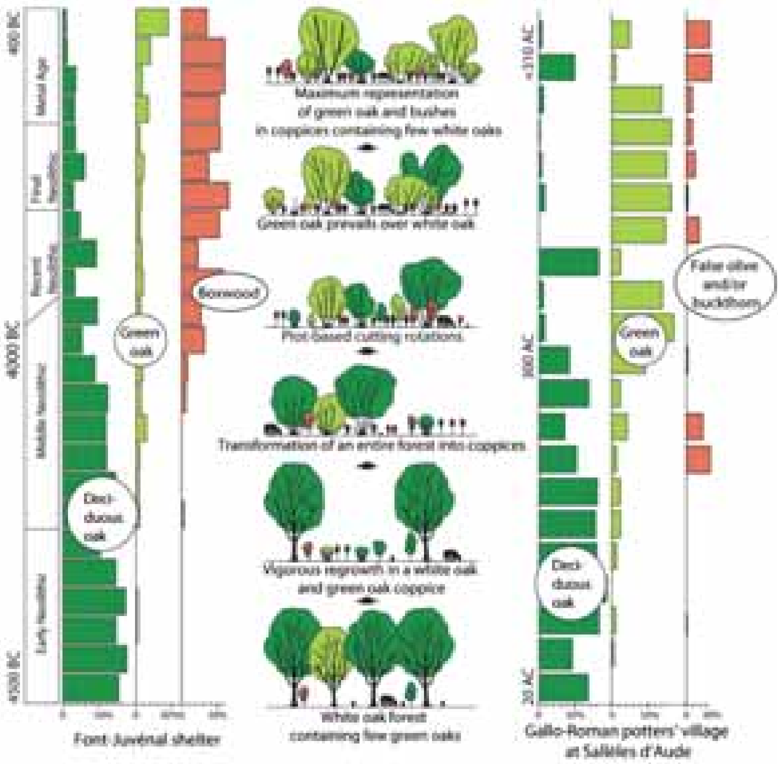
Charcoal charts the history of Mediterranean oak forests



Evolution in the proportions of the main ligneous species in charcoal sampled at two archaeological sites in Aude (France).

Current Mediterranean landscapes are the latest expression of a long historical pattern. Since the Neolithic period, wood harvesting by agropastoral and protoindustrial societies modified the vegetation structure. Cutting a forest does not eliminate it, i.e. vigorous shoots can grow from leaves, thus giving rise to a coppice. In the Early Neolithic period, primarily deciduous oak (likely white oak) forests were cut on a per-plot basis to harvest wood, grow crops in cleared areas and graze livestock in forest clearings. Subsequent shoot growth gave rise to new vigorous forests. From generation to generation, plots in these forests were cut at the pace of rotations and revolutions in agrosylvopastoral usage that took place, or for more specific uses such as charcoal production. As green oaks grow better shoots than white oaks, this species results in dominating, along with bushy species like boxwood and false olive. This effect of vegetative superiority of green oak over white oak is a reversible process, which begins when a site is first utilized by humans, with kinetics that differ according to the usage intensity. Green oak stands remained almost pure for centuries, except in cases where fires or erosion had laid the soil bare, which has had a lasting impact on landscapes.

In the last 50 years, small-scale activities involving high wood consumption and grazing are declining, and hence regrowth of white oak has been taking place to the detriment of green oak. This long history is archived in soils in the form of charcoal. This charcoal–residues of fires made for domestic or craft uses–provides an accurate stratigraphic historical record. This charcoal can be carbon-14 dated and its unaltered anatomical structure is preserved, thus facilitating identification of the woody species from which it is derived. These 'anthracological' studies thus track forest modifications that have occurred over the last millenia.

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Increased frequency of fires and soil genesis

Since 2003, CBAE has been coordinating research in the Alps to study the function of ecological systems on a catchment scale. This research is focused on long-term relationships between the plant cover, fires and the dynamics of plant communities and soils. They are based on 'soil' and 'sediment' archives, including: anthracological analyses, geochemical analyses of major elements (e.g. iron, aluminum, silica, carbonates) and rare earths, as well as the use of erosion indicators (e.g. magnetic susceptibility). This research has revealed several phases in the recent evolution of forest stands–soil development phases after deglaciation, followed by the establishment of forest systems and soil alteration (podzolisation) over a period of around 1 500 years.

Ecological accidents, associated with rapid increases in the natural fire frequency, have contributed to modifying the plant cover composition and structure. This has been followed–in a very short time span of just a few decades (< 300 years)–by an increase in erosion and changes in catchment soils, with a major feature being depodzolisation and soil genesis oriented towards brown soils. Ecosystem stability (soils and plant cover) has been very high in catchments not affected by ecological accidents. It was found that fires alone do not modify the forest and soil composition, but an increase in the fire frequency permanently alters the ecosystem. These findings come at a time when climate change is under way, which will lead to increased risks of fire in the coming decades due to the more frequent droughts expected.

Loup lake, Maurienne valley (Savoie, France).
Its sediments unravelled the history of soils, vegetation and fires over the last 11 000 years.

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Environments, territories and societies in the Lez river delta over the last six millennia

A 2nd century BC vineyard discovered near the protohistoric city of Lattara (Hérault, France). The density was about 10 000 vines per hectare, with layering trenches visible.

C. Jung © INRAP

At a distance of 700 m from the ancient town of Lattara in the Lez river delta (France), a preventive archeological excavation of Port Ariane is an example of a multidisciplinary approach that has highlighted the evolution of a 'natural' environment before the establishment of an urban site, during its settlement and following its abandonment. A stratigraphic sequence of almost 6 m revealed the functioning of the river over several millenia. Three hydrological stability episodes were identified, marked by a slowdown in sediment inputs and the development of alluvial soils. The first occurred in the Middle Neolithic period, with Chasséen settlement (4 000 BC), in line with the regional archeological data. The second began in the Final Neolithic period (2 500 BC), with settlement indices confirmed by palynological analysis highlighting voluntary destruction of the plant cover during the same period. For around 1 500 years, abandonment of the site corresponded to an already acknowledged regional abandonment. At the end of the Bronze Age (900 BC), there was a series of several different land use patterns interlaced with longer bridging phases (150–300 years).

The impact of the founding of Lattara harbour in the 6th century BC was reflected by traces of agricultural development in the vicinity. This is further illustrated by the vineyard of around 2 ha that was set up in a hydromorphic setting at the end of the 3rd century BC. After the Gallo-Roman settlement was abandoned, a Lez river flooding phase began and lasted until the 6–7th century, which induced a major change in the hydrosystem. A third stable period, marked by intense development of medieval water development projects, succeeded a hydroclimatic degradation phase during the Little Ice Age. One of the main outcomes of this operation was that the land has been permanently used over the last six millenia despite constraints related to the rapid, profound modifications that the environment underwent.

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Measurements of soil physical properties revealed that their infiltration capacity was higher in elevated hill soils than in other soils, thus reducing runoff and in turn erosion.

D. McKey © UMR CEFE

Pre-Colombian elevated fields in a coastal savanna region of Guiana

In the Amazon, like other intertropical regions, some so-called 'natural' habitats are actually landscapes that were modified by humans during the Prehistorical period. Pre-Colombian farmers transformed coastal savanna floodplains in the Guianas by building elevated fields, sometimes ridges, whereby the soils remained above the water level during the rainy season. According to available archeological data, most of these structures were built and used during the Araucan period (600 to 1 300 AD).

To explain how these complexes of elevated hills have remained in the landscape after more than 10 centuries under tropical climatic conditions (3 000 mm annual rainfall) and how they influence the current functioning of Guianese savannas, research carried out within the framework of the 'Amazonie' programme (CNRS) is coordinated by CEFE in collaboration with its French (UMR Archéologie des Amériques, University of Nanterre), German (Soil Physics Department, University of Bayreuth) and English (Archeobotany and Paleoecology team, University of Exeter) partners. This consortium is thus developing interdisciplinary approaches that include archeology, archeobotany, paleoecology, ecology, soil science, remote sensing, etc.

The archeobotany findings revealed that maize was cropped intensively on these elevated hills. During what period, by whom and how were they cultivated? Why were they abandoned? The soil and ecological data suggest that these structures have remained functional over time via feedback phenomena–the heterogeneity caused by humans is thought to have caused heterogeneity in the biological functioning of the soils (concentrated activities of natural soil engineers, i.e. social insects, earthworms, plants) and feedback effects on the self maintenance function of these structures.

It is essential to study 'socioecological systems' such as these elevated fields to gain insight into the resilience of the ecological systems, the dynamics of the activities and feedbacks of ecosystem engineers (including humans) and, finally, to promote sustainable development, combining food production and biodiversity conservation.

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Other teams focused on this topic

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An educational information system for the storage, promotion and effective use of soil data:
an example in Languedoc-Roussillon region (France)

Soils have developed over a long evolutionary period as a result of many interacting natural and human factors. It is therefore not surprising to note that soils may vary markedly in landscapes. This is especially true in Mediterranean regions marked by a complex geological evolutionary history and early settlement and use by humans.

Soil scientists have always analysed this variability and presented it in forms accessible to potential users. Until the 1980s, this information was disseminated in the form of soil maps printed on paper, accompanied by an instruction leaflet. There is currently high demand for soil data for agroenvironmental management. It is thus urgent to reissue the information from these hardcopy maps in a well organized form to ensure their preservation and effective use.

The Languedoc-Roussillon soil database developed by UMR LISAH is a successful example of a portal to information contained in soil maps on a regional scale. Users thus have access to three overall types of data:
■ A soil study directory inventories studies that have been carried out in this field (220 studies in Languedoc-Roussillon, France)
■ A regional soil reference repository proposes zoning and characterization of 'soils and landscapes' based on soil-landscape divisions, at 1/250 000 scale, meeting the specifications of the *Inventaire, Gestion et Conservation des Sols* (IGCS) programme
■ Per-site soil data consists of descriptions and physicochemical analysis findings characterizing the different identified soils.

A website *(Sol et paysage du Languedoc-Roussillon)* was developed on the basis of information contained in this database and a photo library. It provides a broad range of non-soil science specialists with access to the features of soil covers of their region and briefly outlines basic soil science and landscape analysis concepts.

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For further information on the Languedoc Roussillon soil database: http://sol.ensam.inra.fr/BdSolLR

For further information on the IGCS programme: www.gissol.fr/programme/igcs/rrp.php

For further information on the 'Soils and landscape of Languedoc-Roussillon' site: www.umr-lisah.fr/Paysages

Study of Mediterranean societies and their *environments from* the Prehistorical period *to the Middle Ages*

The **joint research unit *Archéologie des Sociétés Méditerranéennes*** (**UMR ASM**, CNRS, French Ministry of Culture and Communication, UM3, INRAP), based at Lattes (Hérault, France) consists of six research teams that are all devoted to studying societies and their environment in the Mediterranean Basin, from the Prehistoric period to the Middle Ages:
■ Mediterranean and African prehistory
■ Mediterranean protohistory
■ Nile and Mediterranean Egypt
■ Archeology of environments and resources
■ Production and consumption techniques
■ Territories, interactions, culture.

These teams are multidisciplinary and multiskilled, while also calling upon soil science (geoarcheologists, sedimentologists), physical anthropology and paleobotany (palynologists, anthracologists, carpologists) specialists. Archeozoology (terrestrial fauna and ichtyofauna) is also focused on for the purposes of investigating food economies.

The main lines of research concern house forms and functions, funeral practices and material cultures**. Structures remaining in soils can be studied to gain insight into the first types of houses in the Paleolithic period, and the first villages, urbanism of early communities and the construction materials used (raw earth, wood and stone). Domestic waste of all types, dishes, stone and metal tools, small objects of daily life, plant and animal food remains (usually burnt), charcoal and bones are preserved in settlement soils (houses and roads). They provide information on eating habits, lifestyles, food economies and trade patterns of these societies. Necropoleis for incineration or burial also provide substantial information on human paleopathologies, funeral rites, forms of organization and hierarchical structuring of these societies.

The focus is especially on indigenous societies and their relationships with their Mediterranean partners from the end of the Bronze Age (around 900 BC) to the Augustine period (1st century AD). The population dynamics and production techniques used from material extraction (stone, clay, metal) until the trade and consumption networks are research issues also covered by the laboratory.

Society-environment interactions is a transversal research theme. The Bas-Languedoc coastal region (France) is an especially unstable interface environment. These environmental changes can be monitored through lagoon and fluvial morphosedimentary dynamics, vegetation changes and land development patterns (traces of plantations and crops, ditch networks, livestock production). The UMR is also striving to compare population forms and dynamics as well as land use patterns during the second half of the Holocene period (from 4 500 BC) with active paleoenvironmental processes under way. ■

** Includes all objects that have been shaped, modified or used by humans.

Topics covered by *the research teams*

(May 2009)

Research units and teams are mentioned on the following chart in order of appearance in this document.

1. Soils generate food and clothing for people
2. Soils regulate inland water flow
3. Soils regulate biogeochemical nutrient and pollutant cycling
4. Soils are living environments that harbour multifunctional organisms
5. Soils maintain an evolutionary record of ecosystems and humankind

Unit	1	2	3	4	5
BRGM Montpellier - Service Géologique Régional Languedoc-Roussillon Marc Audibert		•			
Centre LGEI - Laboratoire Génie de l'Environnement Industriel et des risques industriels et naturels (EMA) Miguel Lopez-Ferber		•	•		
CMGD - Centre des Matériaux de Grande Diffusion (EMA) Yannick Vimont		•			
UMR ASM - Archéologie des Sociétés Méditerranéennes (CNRS, French Ministry of Culture and Communication, UM 3, INRAP) Pierre Garmy					•
UMR CBAE - Centre de Bio-Archéologie et d'Écologie (CNRS, EPHE, UM 2, INRAP) Christopher Carcaillet					•
UMR CEFE - Centre of Evolutionary and Functional Ecology (CNRS, UM1, UM2, UM3, Montpellier SupAgro, CIRAD, EPHE) Jean-Dominique Lebreton	•	•	•	•	
UMR Eco&Sols (INRA, IRD, Montpellier SupAgro) Jean-Luc Chotte	•		•	•	•
UMR G-EAU - Water Resource Management, Actors and Uses (AgroParisTech/ENGREF, CEMAGREF, CIHEAM/IAM.M, CIRAD, IRD, Montpellier SupAgro) Patrice Garin		•	•		
UMR LISAH - Laboratoire d'étude des Interactions Sol, Agrosystème et Hydrosystème (INRA, IRD, Montpellier SupAgro) Marc Voltz		•	•		
UMR - LMGC - Laboratoire de Mécanique et Génie civil **Team 'Couplages en Milieux Hétérogènes' (CMH)** (UM2, CNRS) Moulay El Youssoufi		•			
UMR LSTM -Laboratory of Tropical and Mediterranean Symbioses (CIRAD, Montpellier SupAgro, UM2, IRD, USC INRA) Bernard Dreyfus				•	
UMR SYSTEM - Tropical and Mediterranean Cropping System Functioning and Management (CIRAD, INRA, Montpellier SupAgro) Jacques Wery	•	•	•	•	

Ferralitic andosol from the Antsirabé highlands, Madagascar

B. Jaillard © INRA

Unit	1	2	3	4	5
UPR - Direct Seeding and Cover Crops (DMC) (CIRAD) Francis Forest	•		•		
UPR - Dynamics of Natural Forests (CIRAD) Sylvie Gourlet-Fleury	•				
UPR - Environmental Risks of Recycling (CIRAD) Hervé Saint Macary		•	•		
UPR - Functioning and Management of Tree-Based Planted Ecosystems (CIRAD) Jean-Pierre Bouillet	•	•	•		
US - Water, Soil and Plant Analysis (CIRAD) Alain Aventurier	•	•	•		

Agropolis International partner research units

Unit	1	2	3	4	5
UMR EMMAH - Environnement Méditerranéen et Modélisation des Agro-Hydrosystèmes (INRA, UAPV) Liliana Di Pietro	•	•	•	•	•
UR - Plantes et Systèmes de culture Horticoles (PSH) (INRA Avignon) Michel Génard	•				

Agropolis International training and education

in the Soil Science field

Agropolis International proposes a complete training-education programme provided through its member institutions (universities and engineering schools, as well as vocational training institutions).

The training-education programme includes more than 80 diploma courses (from Bac +2 to Bac +8: technician, engineering degree, Master's, PhD), as well as vocational training modules (existing or developed upon request).

The tables below outline the training-education courses related to this domain. They specify the diploma levels, a description of the training and the institutions where the training is provided.

Training-education programme

Level	Degree	Title	Institution
Bac +3	***Licence*** **(BSc)**	Earth and environmental sciences	UM2
		Earth and environmental sciences	UPVD
	Licence professionnelle **(BSc with professional scope)**	Sustainable agriculture	Montpellier SupAgro, UM1
		Sustainable viticulture	Montpellier SupAgro, UM3
		Chemical analysis applied to the environment	UM2
		Maintenance applied to pollution treatment	UPVD
		Dismantling, waste and depollution management professions	UM1, Université de Nîmes
Bac +5	***Master recherche*** **(Research MSc)**	Earth and environmental sciences	UM2
		Biology, Agroresource, Earth science, Environment (BGAE), focus 'Biodiversity, ecology, evolution' (BEE), 'Natural and cultivated ecosystem functioning' (FENEC), 'Microbial systems' (SM)	UM1, UM2 Montpellier SupAgro
		Prehistory, Paleoenvironment, Protohistory (PPP)	UM3
	Ingénieur **(Engineering)**	Agricultural engineering, specializations 'Water, cultivated habitats and environment management' (GEME), 'Sustainable crop production' (PVD)	Montpellier SupAgro
		Forestry engineering, specialization 'Environmental management of tropical forests and ecosystems' (GEEFT), option 'Rural and tropical forestry' (FRT)	AgroParisTech-ENGREF
	Master professionnel **(Professional MSc)**	Agriculture, Agronomy and Agrifood (AAA) – Specializations 'Agricultural production system management and assessment' (CESPA), 'Tropical farming systems and development management' (SAT) 'Environmental management of tropical forests and ecosystems' (GEEFT)	Montpellier SupAgro, CIRAD, AgroParisTech-ENGREF
		Biology, Agroresource Earth science, Environment (BGAE), focus 'Territorial development and integrated management' (DAIT), 'Georisks'	UM2
	Master européen **(European MSc)**	Sustainable agricultural development / *Développement agricole durable* (AGRIS MUNDUS)	Montpellier SupAgro 5 European universities
		Sustainable tropical forestry / *Foresterie tropicale durable* (SUTROFOR)	AgroParisTech-ENGREF 4 European universities

Level	Degree	Title	Institution
Bac +6	***Master spécialisé CGE*** **(CGE Specialized MSc)**	Tropical agricultural development (DAT), option 'Agronomy and innovation in rural environments' (AGIR)	Montpellier SupAgro-IRC
		'Forests, nature and society', Tropical option	AgroParisTech-ENGREF
	Ingénieur spécialisé **(Specialized Engineering)**	GREF engineering, extended specialization 'Forests, nature and society', Tropical option	AgroParisTech-ENGREF
		Tropical agronomy engineering, option 'Agronomy and innovation in rural environments' (AGIR)	Montpellier SupAgro–IRC
	Formation spécialisée **(Specialized Training)**	Environment and security, option mining security and environments (training offered only to foreign professional stakeholders)	CESMAT / EMA

Short training-education programmes

Institution	Title
Montpellier SupAgro	Biological functioning of soils (4.5 days)
CIRAD	Agricultural and environmental impact of the management of organic matter in tropical environments (5 days)
	Racinsitu: *in situ* analysis of root development of annual and perennial crops (5 days)
	Water and solute transport in soils: a biogeochemical transport model (HP1, combined Hydrus and Phreeqc models) (5 days)
CIRAD/ Ponta Grossa State University, Brazil	Direct seeding on plant cover (3 weeks)
EMA	Legal training on polluted sites and soils (3 days)
	Basic environmental chemistry (4 days)
	Servitudes (1 day)
	Polluted soils (3 days)
	Metrology of polluted water and soils (5 days)
	Diagnostic tools (3 days)
	Groundwater monitoring and pollutant behaviour (2 days)
	Industrial wastewater treatment (4 days)
	Practical approach to quarry inspection (5 days)
	Hydrology-Hydrogeology (5 days)
	Impact of quarries on water resources (4 days)

Agropolis International training and education

Graduate school focused on soil issues

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Sampling the soil solution under a nitrogen atmosphere in a rice field in northern Thailand

A PhD diploma is obtained after 3 years of laboratory research. PhD students are de facto attached to a PhD institution. PhD institutions host research units and laboratories working on major themes. Their mission is twofold: 1) to ensure direct scientific support for PhD students; 2) to provide additional training throughout the 3 years.

The purpose of this additional training is to improve the scientific education of the PhD students and help them prepare their professional future.

Only one graduate school focuses on the 'Soil' theme:

Graduate school « Systèmes Intégrés en Biologie, Agronomie, Géosciences, Hydrosciences, Environnement » (SIBAGHE)

The SIBAGHE graduate school is affiliated with UM2 for social and earth sciences. It has joint accreditation with Montpellier SupAgro, AgroParisTech and the Université d'Avignon for Agricultural and Environmental Sciences, with the universities UM1 and UPVD for genomics, botany, microbiology and parasitology.

The SIBAGHE graduate school hosts around 390 PhD students and is supported by 45 affiliated research units, 350 training supervisors and several associated external research teams. Every SIBAGHE PhD student must successfully complete two scientific training modules and two professional introduction modules. The graduate school manages thesis registrations, PhD student supervision, ensures that the thesis charter is respected and organises thesis courses and professional guidance. It is assisted by a council and managed by an office.

Contacts

Graduate school 'Systèmes Intégrés en Biologie, Agronomie, Géosciences, Hydrosciences, Environnement' (ED SIBAGHE)

(UM2, Montpellier SupAgro, Agro ParisTech, Université d'Avignon, UM I, UPVD)

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www.sibaghe.univ-montp2.fr

1. Training session on soils, Burkina Faso, Zabré region

2. A joint French-Thai research team enjoying life in the field

3. Training Thai students on soil profile description (northeastern Thailand)

4. Training session on soils, Brazil

List of acronyms *and abbreviations*

BRGM	*Bureau de Recherches Géologiques et Minières* (France)
CEMAGREF	*Institut de recherche pour l'ingénierie de l'agriculture et de l'environnement* (France)
CIHEAM/IAMM	*Centre International de Hautes Études Agronomiques Méditerranéennes/ Institut Agronomique Méditerranéen de Montpellier* (France)
CIRAD	Agricultural Research Centre for International Development (France) / *Centre de coopération internationale en recherche agronomique pour le développement*
CNRS	National Center for Scientific Research (France) / *Centre National de la Recherche Scientifique*
CORUS	Programme of Cooperation for Academic and Scientific Research (France) / *Programme de coopération pour la recherche universitaire et scientifique*
DMC	Direct seeding mulch-based cropping system
EMA	*École des Mines d'Alès* (France)
ENGREF	*École Nationale du Génie Rural des Eaux et Forêts* (France)
EPHE	*École pratique des Hautes Études* (France)
INRA	National Institute for Agricultural Research (France) / *Institut national de la recherche agronomique*
INRAP	*Institut national de recherches archéologiques préventives* (France)
IRD	*Institut de recherche pour le développement* (France)
ISRA/UCAD	*Institut sénégalais de recherche agricole/Université Cheikh Anta Diop* (Senegal)
UAPV	*Université d'Avignon et des Pays de Vaucluse* (France)
UCLA-DOE	University of California, Los Angeles - Department of Energy (USA)
UM1	Université Montpellier 1 (France)
UM2	Université Montpellier 2 (France)
UM3	Université Montpellier 3 (France)
UMR	Joint research unit / *Unité mixte de recherche*
UPR	Internal research unit / *Unité propre de recherche*
UR	Research unit / *Unité de recherche*
US	Service unit / *Unité de service*

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- *Suds en ligne, dossier thématique de l'IRD* (in French): www.mpl.ird.fr/suds-en-ligne/sols/index.html
- *Editions Quae, 'Le sol',* paperback in French (eds. Pierre Stengel, Laurent Bruckler, Jérôme Balesdent) www.quae.com

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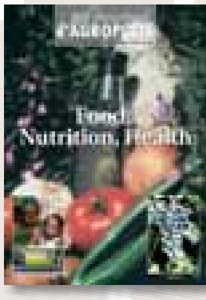

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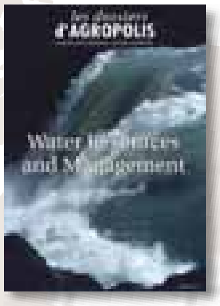

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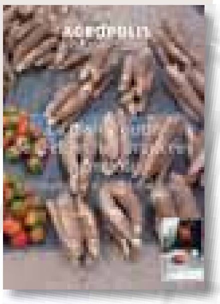

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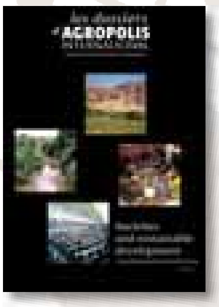

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