Ensuring top quality, high quantity production
The intensive agriculture model, based on massive use of pesticides, chemical fertilizers, water and fossil fuels, widely contributed to the dramatic increase of productivity in industrialised countries. But it is currently challenged. After several decades of implementation, the impacts on the environment, human health and biodiversity are representative of the shortcomings of this production strategy in terms of sustainability.

In developing countries, which have long been familiar with intensive agriculture techniques, crop yields remain low and increased production has usually gone hand in hand with the increase in cultivated areas, to the detriment of forest and grassland ecosystems. Tropical agriculture research, like that focused on temperate areas, is being tapped to come up with ‘other ways of producing’ so as to be able to fulfil the demand of a steadily growing world population.

In natural ecosystems, biodiversity has many functions that have gradually been lost over the past decades, in connection with the drastic simplification of landscapes in industrialized countries, and the alteration of primary productivity of environments in developing countries. In both cases, the remobilization of functional biodiversity in cropping systems is unavoidable.

Cover crops or agroforestry systems, for instance, influence and activate core processes such as soil biological activity, habitat provision for beneficial insects, and local climate and water flow regulation. This is the pathway being investigated by the group of Agropolis International agronomists, with the aim of reducing the use of pesticides, fertilizers and tillage, while not overlooking the fact that cultivated systems are designed and managed for the purposes of exportation, which fundamentally distinguishes them from natural systems.

Agronomy is substantially focused on the issue of reducing environmental impacts, while systematically seeking a tradeoff with the quantitative and qualitative aspects of production, which in turn are usually the basis of economic sustainability. In this setting, studies are based on the assumption that production is the result of managing a complex biophysical system, i.e. a crop field, in which plant, pathogen and pest populations interact and share resources (water, light, habitat, etc.). It is also considered as a commercial trade item subjected to quality standards and criteria required by the industry and markets—the research challenge is thus to come up with new production strategies.

Pascal Clouvel (UPR SCA) & Jacques Wery (UMR SYSTEM)
Ensuring top quality, high quantity production

Horticultural production: promoting quality and environment-friendly cropping

The research unit (UR) **Horticultural Crops and Cropping Systems** (PSH, INRA) conducts research on horticultural crops, especially fruits and vegetables for fresh consumption (peaches, apples, tomatoes, etc.). Its ultimate aim is to contribute to the development of technical and landscape scenarios that will help promote the quality of harvested crops and environment-friendly cropping.

To achieve these objectives, research is focused on plants, their fruits and pest populations so as to gain greater insight into and model their responses to the environment and trophic ‘plant-pest-natural enemy’ relationships. Research is also carried out on a cropping system scale to understand and model plant functioning when affected by technical operations and in interaction with the physical and biotic environments. Three teams conduct this research:

- **Plant Architecture and Resource Management:** the aim is to study and model links between nutrient resource (water, carbon, nitrogen) acquisition and usage functions and the architectural development of whole plants. These ecophysiological studies are based on flow measurements and analysis of organ formation processes within a source-sink system in interactions that determine the above-ground and root architecture of plants. Modelling of growth, nitrogen nutrition on short time steps and the combined transport of water and N and C resources within the plant architecture are key areas of expertise of this team. Studying interactions between these processes and the biotic environment of crops (pest and disease constraints) is a new research focus.

- **Ecophysiology of Fruit Quality:** the aim is to describe and model processes involved in the development of fleshy fruit quality under genomic and plant control in interaction with the physical environment and technical interventions. Through the **Virtual Fruit** modelling platform, different models of the quantitative integration of physiological functions involved during fruit development and growth (cell division and multiplication, growth, sugar, acid and antioxidant compositions, etc.) may be combined.

- **Ecology of Integrated Production:** the first objective is to understand the causal chain that links cropping practices and farming landscape features with the functioning of horticultural systems defined by their constituents (plants, soil, pests, natural enemies) and with the performances of these systems: production, plant health, environmental impacts and on some populations that are involved in functional biodiversity within orchards. On this basis, the second objective is to design technical and landscape scenarios tailored to integrated production. The models are essential to our approach and make it possible to interlink knowledge from different disciplines, while facilitating in silico design steps. ***
Mango ranks fifth in terms of worldwide fruit production. Like other tropical fruit species, mango cropping is hampered by problems affecting yield and quality: alternation of flowering and production between years, variable fruit quality and ripeness, pest and disease control. The lack of knowledge on mango is a barrier to effective mango crop management. The adopted approach involves identifying factors that impact key processes in the mango life cycle and determining which of them farmers could focus on and alter to achieve regular, top quality production using environment-friendly practices. Given the complexity of the processes and many interactions involved, modelling is a preferential tool for synthesizing knowledge.

These studies revealed that in mango there are close, reciprocal, quantitative and temporal relationships between vegetative growth and flowering/fruiting processes. A mango development model is currently being developed based on the phonological features of mango trees and on endogenous and exogenous (temperature) factors affecting them. It has also been shown that fruit growth and quality development are dependent on the lighting environment and on carbon and water availability. A mango fruit grade and quality development model is currently operational.

Innovative technical operations have been developed and tested in mango orchards on the basis of these results. The two previous models could be combined to build a yield and fruit quality development model applicable on tree and orchard scales. Taking the phenological features, and thus the stages susceptible to pest attacks, into account will pave the way for further combinations with pest models, and ultimately to the development of nonchemical orchard protection techniques.

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Diagnostic methods to improve tropical tree crop productivity

In humid tropical areas, the expansion of oil palm, natural rubber, coffee and cocoa cropping to meet growing world demand raises environmental issues. It is thus essential to enhance the productivity of established plantations by targeting higher sustainable crop yields using environment-friendly cropping practices.

Researchers of the UPR Performance of Tree Crop-Based Systems are developing decision support support tools to analyse crop plots and enhance their technical management. ‘Diagnostic foliaire’ is a tool for close management of fertilization in palm orchards on the basis of leaf analyses. ‘Diagnostic sol’ is used to calculate manure requirements in coffee and cocoa plantations on the basis of soil analyses. ‘Diagnostic latex’ is used to manage latex tapping in natural rubber trees on the basis of latex analyses.

Once developed, these tools are tested, tailored to local situations and gradually improved. ‘Diagnostic foliaire’ has thus been used for a few decades on hundreds of thousands of hectares of commercial palm plantations worldwide to determine optimal fertilizer quantities to apply. It will now be combined with a second tool, i.e. ‘Diagnostic racis’. It has also been adapted for the purposes of enhancing technical advice for oil-palm smallholders in Cameroon. ‘Diagnostic sol’ has just been used to draw up a cocoa fertilization advice map for Ghana on the basis of a soil map. ‘Diagnostic latex’ which can improve the sustainable management of natural rubber plantations, is being applied in Asia (Indonesia, Malaysia, Thailand, Vietnam, China, India), Africa (Côte d’Ivoire, Ghana, Nigeria, Cameroon) and Latin America (Brazil, Guatemala). This tool is currently being developed to facilitate the selection of clones best suited for growing in marginal ecoclimatic conditions.

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The unit’s work is supported by research and technical platforms (biochemical analysis and molecular biology laboratories, culture rooms, insectary, greenhouses, tunnels and experimental orchards based at the Domaine St Paul-Avignon and the Gotheron integrated research unit). PSH has developed the Totomatix automaton to manage plant mineral nutrition on an hourly scale under controlled conditions.

A workshop zone spans an area of 70 km² in Basse Vallée de la Durance, and serves as a base for many in situ research studies, especially for the analysis of farmers’ practices and the spatiotemporal dynamics of pest populations in relation with their natural enemies and landscape components. Finally, modelling is pivotal to the unit’s research activities.

Major collaborations are underway with French and international research teams. Many studies are conducted in partnership with technical and agricultural development institutes.

Annual crops: alternative cropping strategies for developing countries

The internal research unit (UPR) Annual Cropping Systems (SCA, CIRAD) conducts research on smallholder farming in developing countries. These regions are characterized by high population growth, limited land access and high dependency on increasingly irregular rainfall, fragile erosion-prone soils, difficult and volatile socioeconomic conditions and, especially, limited access to markets and credit.

The unit aims to develop cropping systems that preserve, while making sustainable use of, natural resources in tropical farming systems that boost their productivity and reduce the environmental impacts of farming. Besides the well-being of the rural people involved, the recent hunger riots highlighted the fact that local produce is crucial for feeding constantly-growing urban populations.
For these populations, the ‘ecological intensification’ challenge is to produce more, more regularly, through greater use of ecosystem services. For the unit’s researchers, processes involved in crop production must be considered from different angles in order to come up with alternative cropping strategies.

With this new approach, the ‘soil-plant-atmosphere’ unit is considered as a biological system that is favourable to limited (or even nil) application of pesticides, chemical fertilizers and irrigation. The crop field is also considered as an open social system with respect to the functioning of farms and production subsectors.

UPR SCA is organized in five research teams:

- **CARABE (Characterization and Integrated Management of Biotic Risks for Cultivated Ecosystems)** studies the effects of farming practices and cropping systems—as factors responsible for variations in the spatiotemporal availability of resources ( trophic, habitat)—on pest and disease control and regulation.

- **QUALITE (Product Quality Elaboration and Management)** focuses on agricultural product (raw and processed) characterisation and quality development processes. It also studies management of this product quality via stakeholders’ practices on field, landscape and industry scales.

- **ADEMES (Decision Support, Spatial Organization and Production Chain Economics)** complements this approach on the spatialization and organization of supply areas. These activities include fibre (cotton) and sugar (sugarcane) production, while encouraging openings in favour of energy subsectors (sugarcane and Jatropha).

- **CESCA (Knowledge and Modelling of Annual Cropping System Functioning)** aims to design and assess annual cropping systems that meet ecological sustainability, economic viability and social equity imperatives. The biophysical aspect of practices (conservation agriculture, pest regulation, livestock-crop integration, etc.) is studied in interaction with the social sciences and humanities.

- **SCRID (Sustainable Farming and Rice Cropping Systems)** conducts research in Madagascar with the aim of developing rainfed rice-based cropping systems in close collaboration with national agricultural research agencies and the Université d’Antananarivo.

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**Modelling the functioning of a tropical agrosystem: an application to banana plantations**

Modification of overall agrosystem functioning is required for cropping system (CS) innovation. A system approach to relationships between plants, pests and the environment is needed to understand and describe the functioning of these new systems, which are more complex than systems in which inputs are massively used. This system-based representation of agrosystem functioning is a model that can be customized according to the values of the studied variables. This genuine CS design support tool can also be used to represent CS functioning.

The SIMBA model simulates banana plantation functioning and performance and enables multicriteria assessment of virtual or real CSs. It can be customized according to different variables (climatic and soil data, initial parasitic nematode population levels) and enables simulation of banana growth and yield, pest development dynamics, soil moisture and nitrogen levels and the growth and effects of cover crops and weeds. Moreover, it evaluates the environmental risks of the simulated systems. It accounts for variations in the structure of banana stands during cropping cycles. Inclusion of the parasite component in the model, in interaction with the stand growth and structure, the soil status and nematicide treatments, is crucial for simulating the agroenvironmental performance of modelled banana plantations.

It facilitates studies on certain ecological mechanisms and the development and optimization of new control strategies (crop rotations, cover crop based systems, etc.).

The spatial inter- and intra-plot organization and spatialization of protection resources are key elements for pest control. Because of its moderate dispersion potential, the banana weevil is a good example for studying the effects of different CS spatial organizations on its epidemiology. The COSMOS model simulates the weevil’s movements, reproduction and mortality, in interaction with the banana tree, crop residue, cover plants and pheromone traps.

It enables trapping optimization and proposes plantation landscaping arrangements to limit the development of weevil populations.

These new tools should help predict performances in terms of production and the properties of different emerging communities in banana plantations, e.g. their stability and resilience.

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*Banana/Neonotonia wightii (legume) association.*
Virtual Fruit—a model to gain insight into fruit quality

Fruit quality is the result of many highly interacting physiological processes that are controlled by many genes whose intensity varies with the environment and cropping practices. The genetic, environmental and cropping factors controlling the intensity of the processes and their interactions have to be understood before being able to manage this quality, which is an especially difficult task. The conventional experimental approach does not generate a sufficiently integrated image of fruit functioning. The Virtual Fruit model was thus developed. It integrates seven different submodels that describe the main aspects of fruit functioning. It can simulate fruit growth and variations in the contents of dry matter and the main fruit sugars and acids, as well as fruit ripeness levels.

The use of Virtual Fruit revealed that application of water stress after a good irrigation period would substantially reduce growth, while fruits of continuously stressed plants continue growing, thus suggesting that fruit can adapt to stress situations. Virtual Fruit also revealed that a genetic change due to a mutation disrupting sugar transport to the fruit markedly upsets its functioning.

Virtual Fruit has been combined with genetic models, thus providing a promising way for model-assisted selection and for finding ideotypes that meet consumers’ fruit quality expectations. Virtual Fruit could also be especially useful for interpreting results obtained on the basis of functional genomics approaches.

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Ensuring top quality, high quantity production

The unit conducts research in the fields of agronomy, entomology, weed science, plant breeding, biomathematics, economy and technology, with activities under way in Réunion, sub-Saharan Africa (Burkina Faso, Mali, Cameroon, Benin), Kenya, Zimbabwe, Madagascar and Brazil. It has collaborations and researcher exchanges with USA and Australia.

Direct seeding mulch-based cropping systems

The aim of ecological intensification in agriculture is to replicate the functioning of natural ecosystems in which a network of complex interactions is combined with high functional biodiversity. This complexity and biodiversity promotes expression of the natural functions of biological and biogeochemical regulation cycles.

Cropping systems have to reproduce these pathways. The goal is thus to turn agrosystems into genuine cultivated ecosystems.

UPR Conservation agriculture and engineering (SIA, CIRAD) develops and disseminates direct seeding mulch-based cropping systems (DMC) based on three interrelated principles:

- no tillage
- permanent plant cover with species that produce high biomass on and within the soil
- development of high biodiversity with multifunctional plant species and associated populations of macro- and micro-biological organisms that become established and evolve through appropriate cropping practices and diverse and abundant organic carbon resources.

These principles promote efficient expression of genetic potentials that favour pest and disease resistance and high productivity. The UPR promotes ecological intensification by adhering to these principles and studying their implementation and management.

This expertise is divided into two complementary research lines:

- Designing DMC cropping systems: this core activity of the UPR, which is applied to agricultural development, is an engineering approach to ecological intensification.
- Identifying research themes applied to gain insight into the processes involved, and leading to the development of DMC management tools and indicators.

The UPR’s field research is conducted in a broad range of different biophysical and socioeconomic settings representative of tropical environments.
The aim is to address major issues facing developing countries. Based on the scientific activities of the team operating in Brazil—the cradle of tropical DMC—these issues are dealt with throughout the unit’s geostrategic and partnership system: Central Africa (Cameroon), North Africa (Tunisia), Indian Ocean region (Madagascar), Asia (Cambodia, Laos, Vietnam, Thailand, China), and the West Indies (Guadeloupe).

Through its partnership network, the unit is setting up stations where priority research topics are investigated to gain insight into the processes and enhance DMC management, along with direct engineering applications to promote ecological intensification.

There are several research priorities:

- **DMC and soil organic matter dynamics**
- **DMC and soil biological activity**
- **DMC and pest, weed and disease management**, as illustrated by three examples: *Striga*, soilborne white grubs (‘Optimization of pest management by ecological mechanisms for sustainable improvement of agrosystem productivity’ research project) and rice blast (‘Agricultural management of rice blast resistance’, *Agence Nationale de la Recherche*, France)
- **DMC and plant breeding: improved rice varieties (SEBOTA)**.

Major collaborations are under way with institutions in France (*Agence Française de Développement*, *Fonds Français pour l’Environnement Mondial*, *Ministère des Affaires étrangères et européennes*) and abroad (Madagascar, Laos, Cameroon, China, Brazil, Vietnam, Cambodia, Thailand), such as the *Groupement Semis Direct* in Madagascar, Kasetsart University (Thailand), etc.

### Ecological intensification of cocoa- or coffee-based agroforestry systems

Agroforestry stands in which cocoa and coffee trees are grown alongside many different woody, forest or fruit species are complex systems with high environmental and socioeconomic value. These sustainable systems require few chemical inputs and, in addition to coffee and cocoa, they provide farmers with a range of self-consumed or marketed fruits, timber and medicinal products. They also participate in biodiversity conservation and carbon storage. There is, however, considerable potential for improving the performances of the different constituents of these systems in which interactions between the many associated species are complex.

Research carried out by CIRAD and partners, particularly in Latin America and Africa, is aimed at developing models of functional associations that take farmers’ expectations and environmental constraints into account. This implies describing cocoa- or coffee-based agroforestry systems, analysing their ecophysiological functioning, assessing their agroecological and socioeconomic performances, while also characterizing farmers’ cropping practices. The findings of this research have shed light on the dynamics of these systems, which vary differently over time depending on the local soil-climate conditions, situations and farmers’ strategies.

Further insight has been gained on agroecological and socioeconomic factors that determine the sustainability of these agroforestry systems and variations in their performances over time. The development of decision support and prediction tools based on the ecophysiological functioning of the species present also enables quantification of different complex processes (nutrient cycle, light interception, resource distribution). It is thus possible to meet farmers’ needs by proposing them the most suitable cropping practices for intensifying cocoa- and coffee-based agroforestry systems, while not reducing their high environmental value.

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The crop canopy is a site of mass and energy exchanges between the plant and atmosphere. There is high microclimatic heterogeneity in this complex environment. Many studies have shown that the grapevine canopy structure affects the yield via its effects on light interception, photosynthesis and transpiration. It also affects grape ripening and the harvested grape quality by modulating the fruit lighting and temperature conditions. In a given environment, adapting this structure to meet different wine production objectives (red wine for aging, low alcohol wine, grape must for fruit juice production, etc.) is a current major agricultural challenge.

The studies are based on 3D plant structure representation methods with the aim of developing analytical tools suitable for investigating the functioning of grapevine canopies. The TOPVINE model was developed for dynamic prediction of the formation of the leaf area and its response to water deficits in different grapevine cultivars. This leaf area is then distributed through a probabilistic description of the space explored by each branch and the position of leaves within the space. By this description, the canopy is viewed as an assembly of branches represented by ‘leaf clouds’.

These tools were tested and compared with canopy functioning indicators that are currently used by industry professionals (e.g. the illuminated leaf area) in a range of different ‘cultivar x cropping system’ combinations representative of Côtes du Rhône vineyards. The results of these initial simulations highlighted the close interaction between the grapevine architecture and the cropping system in terms of the radiation balance, which was not discernible with the indicators used to date.

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For ecological intensification, research must provide relevant solutions to two major issues, i.e. need to produce more even though farmland is decreasing, and to produce better in order to preserve the environment. The intensification of natural processes by direct seeding mulch-based cropping systems (DMC) can restore the chemical, physical and biological fertility of the soil, while enhancing expression of genetic potentials to ensure high pest and disease resistance and high productivity.

Studies on these processes and their management provide the foundations of engineering applied to ecological intensification. This involves implementing all DMC diagnostic, development, assessment and management methods to address major issues concerning development in tropical countries. UPR SIA, through its diversified partnership network, is implementing DMC principles and promoting the reintroduction of functional biodiversity, through studies on:

- rehabilitation of degraded tropical soils
- ecological intensification of rainfed food and cash cropping systems, flooded rice cultivation under poor water management, and tree-crop based systems
- development of biological tools to support environment-friendly system functions, such as soil detoxification, pest control, carbon sequestration and the development of DMCs that meet organic agriculture specifications.

These new cultivated ecosystems are valuable for both humans and the biosphere. The engineering approach is based on systems research, which enhances thematic research and in turn integrates thematic research advances. This approach favours biological modelling, which recreates—*in situ* and *in vivo*—all interactions and interfaces required for the intensification of natural processes so as to better understand, control and manage them.

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▲ Rice cropped on *Stylosantes guianensis* mulch (Xieng Khouang province, Laos).
Ensuring top quality, high quantity production

A 100 ha agroforestry plot can yield as much as a standard 140 ha crop field. In agroforestry systems, trees and crops are grown together in agricultural plots. Current experiments, supplemented by computer simulations, have confirmed the high productivity potential of temperate agroforestry systems. Mixed poplar–cereal crop plots produce 40% more than plots of the same area in which trees and crops are grown separately. The complementary needs of trees and crops is one of the keys to this success—late deciduous trees such as walnut, associated with early winter crops, such as wheat, are ideal combinations, with light, water, nitrogen being more efficiently used than in pure crop systems.

This boosted productivity could also be explained by other more subtle mechanisms. The plasticity of tree root systems can overcome competition with the crop by growing deeper, thus also enhancing their resistance to summer water stress. Trees also provide climatic protection for crops, therefore reducing heat stress, which is increasing with global warming. Other interactions between trees and crops involve the biodiversity that the trees reintroduce in the plot. Wild flowers that grow under the tree rows attract beneficial organisms that, in turn, help control cereal aphids. Several thousands of hectares of agroforestry plots are now planted yearly in France and in around 10 other European countries.

A hectare of agroforestry plot stores around 2 t more carbon a year than a standard crop plot. Due to the annual mortality of fine tree roots, a significant share of this involves long-term carbon storage. Agroforestry systems are a typical example of ecological intensification, whereby productivity is maintained while generating environmental services to benefit everyone.

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Changing relationships between sugarcane growers and industrial stakeholders to improve sugarcane quality

Agroindustrial subsectors represent a significant income source for farmers in both developed and developing countries. Farmers and agroindustrial processing units interact in supply areas to manage physical flows of agricultural raw materials, information flows and incentive instruments implemented to regulate and pay for deliveries in quantitative and qualitative terms. Their relationships depend on the physical and biological characteristics of the raw material, the degree of supplier atomization and value sharing strategies between stakeholders involved in the supply chain.

CIRAD is helping industrial operators and sugarcane growers in South Africa and Réunion explore new types of relationships with the aim of increasing the total value produced within sugarcane supply areas. This support is based on the development and use of two simulation tools (MAGI® and PEMPA®). These tools, which are implemented on a supply area scale, are used to compare different strategies for managing cane flow between growers and sugar mills, and quality-based cane payment schemes. These scenarios fuel discussions between growers and industrial operators on decision making with respect to flow logistic organization, investment in production, haulage and processing capacities throughout the chain, and sharing the excess value generated by the most promising innovations.

The approach can also be used to investigate new organization strategies, including new payment systems tailored to changes in industrial products (energy production, green chemistry).

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MAGI® and PEMPA® simulation tools downloadable at: http://agri-logistique.cirad.fr

A newly planted agroforestry plot with walnut trees and cereal crops.
Harvesting latex in a natural rubber plantation (Indonesia).