Minimizing the impact of cropping on biogeochemical cycles

▲ Vascular plant inventory in an oil palm plantation.

▲ Maize grown on Vigna umbellata residue (Xieng Khouang province, Laos).
World food production has doubled over the last 50 years, thus basically compensating for the high global population growth. This so-called Green Revolution has been possible through the use of improved crop varieties and increased input applications. This trend has not taken effect in some developing countries, however, and the recent hunger riots underline the fact that agricultural production is insufficient to meet the food needs of these countries. Moreover, in recent decades, and in close connection with agricultural intensification, humans have modified ecosystems to an unprecedented extent, as highlighted by the Millennium Ecosystem Assessment. There have been clear benefits in terms of increasing agroecosystem productivity, but many other ecosystem services have been highly altered, especially biogeochemical cycles. Excessive fertilizer inputs under intensive agriculture have also had negative environmental impacts. Nitrogen, which is a major plant nutrient, can pollute groundwater by vertical transport through the soil (leaching) when the soil nitrate concentration is excessive. This can also give rise to greenhouse gas emissions (nitrous oxide). Excessive phosphorus levels in the soil can lead to surface water eutrophication following lateral transport of this mineral through erosion. In addition, the needs of a growing global population have been partially fulfilled by changes in land-use patterns, particularly through the cultivation of forests and grasslands. This results in significant loss of carbon bound in soil organic matter, thus affecting the carbon cycle and increasing the greenhouse effect via carbon dioxide emissions. Models predict an increase in the world population of around 50% by 2050. Changes that have occurred on our planet over the last 50 years are not sustainable, so the aims of the Doubly Green Revolution must now be achieved. The challenge is to further increase agricultural production worldwide at roughly the same pace, while preserving ecosystem services, and especially by reducing the negative impacts on biogeochemical cycles and biodiversity.

Studies carried out by teams in the region are aimed at meeting the necessary challenge of ecological intensification of agroecosystems, especially in Mediterranean and tropical conditions markedly affected by global change (climate and land-use changes). This research is focused on finding more efficient genotypes and inputs, developing innovative crop management sequences and cropping systems capable of achieving higher and more stable agricultural production, to cope with climate change and hazards. These practices include the use of multispecies stands (agroforestry, intercropping, etc.), or techniques such as direct seeding mulch-based cropping systems that benefit from the functional complementarity of different plant species. Numerous studies also concern the management of organic matter dynamics, in association with plant cover, microbial communities and soil fauna. In the periurban agriculture setting, recycling of diversified organic matter resources, including wastes and residual waste products, highlights the potential impacts of micropollutants such as metals contained in this organic matter. Research is thus aimed at assessing the agricultural performances and environmental impacts of studied cropping systems and techniques.

Philippe Hinsinger (UMR Eco&Sols)
Minimizing the impact of cropping on biogeochemical cycles

Understanding carbon and nutrient flows in Mediterranean and tropical agroecosystems

Primary production in terrestrial ecosystems is regulated by radiation interception and the acquisition of resources, most of which are found in soils (water and nutrients). In ecosystems affected by human activities, this plant production function has long been maintained through management of inputs (mineral, organic) and soil physical and chemical properties. Through this strategy, global food production doubled between 1960 and 1995, but inputs of nitrogen fertilizer increased by almost sevenfold, along with a more than threefold rise in phosphate fertilizer inputs over the same period. Given the environmental impacts of these practices, this strategy cannot provide a sustainable response to the need to increase crop production to fulfill the food requirements of a growing population in the coming decades.

In this setting of increased primary production, management of inputs (chemical and organic) and global change (climatic and land use), the scientific objectives of the joint research unit Functional Ecology and Biogeochemistry of Soils (UMR Eco&Sols, CIRAD, INRA, IRD, Montpellier SupAgro) are to gain insight into, describe and predict factors that determine primary production in Mediterranean and tropical ecosystems, and especially ecological processes involved in ecosystem services that regulate mineral flows—primarily carbon and nutrients, nitrogen and phosphorus—in these agroecosystems. From an environmental standpoint, research is focused on carbon sequestration and greenhouse gas emissions and, secondly, on the ecodynamics of biological contaminants (viruses, Bt proteins, etc.). This research is in line with the aims of international (Millennium Ecosystem Assessment) and French (Grenelle de l’Environnement) initiatives concerning links between ecosystem services and human well-being.

To achieve these objectives, UMR Eco&Sols conducts studies to determine the impact of plants and soilborne organisms (plant roots, earthworms, termites, nematodes, fungi, bacteria), as well as interactions between them and with their environment in biogeochemical cycles within agroecosystems. This ecosystem-oriented strategy is focused on functional communities and interaction networks and is pivotal to laboratory (microcosms and mesocosms) and field research approaches geared towards the development of ecological engineering to reconcile sustainable agricultural production objectives and the preservation of agroecosystem... continued on page 22
Environmental impacts of human societies are mainly associated with the food function. Understanding and, if possible, quantifying relationships between modes of production and food consumption and their environmental impacts (climate change, ecotoxicity, eutrophication, water use, etc.) are essential for making the necessary changes. Streamlined comprehensive assessment tools are required for environmental labelling of products consumed in France, as stipulated under the Loi Grenelle 2 (domestic or imported products), or for increasing the ecological performance (impact per produced unit) of production systems in developing countries.

The life cycle analysis (LCA) method (ISO 14040-14044, 2006) is a powerful conceptual framework for overall environmental assessment of different functions necessary to humans, based especially on the function (and functional unit), life cycle of a function (see figure below) and multicriteria evaluation concepts. However, using it for agricultural and food product systems in the tropics is very recent and poses many methodological and scientific challenges. CIRAD’s PERSYST department has decided to devote research to meeting this new challenge, and biomass-energy subsectors, tree crops, agrifood production, organic waste recycling in agriculture, irrigated crops such as rice, animal and horticultural production are now the focus of ambitious LCA projects aimed at developing specific methods for this new scope of application.

In this setting, the HortSys research unit focuses studies on environmental impacts associated with implementation of the nutritional function of fruits and vegetables. This function is crucial for balancing peoples’ diets in industrialized and developing countries. A research initiative is currently being set up on vegetables (case study on tomato) and tree products (citrus and mango). The goal is especially to develop methods that take the nutritional quality of products into account when defining functional units, that provide reliable estimates of direct emissions in the field, and that can assess the water footprint and toxicity, and the error range in results.

Contacts: Claudine Basset-Mens, claudine.basset-mens@cirad.fr
Thierry Tran, thierry.tran@cirad.fr
Cécile Bessou, cecile.bessou@cirad.fr
Anthony Benoist, anthony.benoist@cirad.fr
Tom Wassenaar, tom.wassenaar@cirad.fr
Sylvain Perret, sylvain.perret@cirad.fr
& Jonathan Vayssières, jonathan.vayssieres@cirad.fr

Comprehensive environmental assessment of agricultural and food products—a case study of fruit and vegetables

Environmental services. The stability and resilience of these functional communities to climate change and altered land-use patterns are studied in different Mediterranean and tropical soil-climate conditions, in collaboration with national agricultural research centres and universities in developing countries. These experimental approaches are closely associated with a modelling approach devoted to formalizing biological and biogeochemical processes that govern soil-plant interactions and to predicting flows in agroecosystems.

The UMR is based in France (Montpellier) and in several tropical countries in West Africa (Senegal, Burkina Faso), Central Africa (Congo), Madagascar, Southeast Asia (Thailand) and Latin America (Brazil, Costa Rica). The main agroecosystems studied include cereal and legume cropping systems, and tree crop stands for forestry (eucalyptus and maritime pine), agroforestry (coffee) and latex (natural rubber) production.

Annual and perennial legumes are introduced and managed in mixed-species stands under a range of different soil-climate and agricultural conditions, especially in low input systems. ***
Rhizosphere—a suitable scale for assessing the phytoavailability of trace elements?

Plants are key constituents of agroecosystems, so it is essential to study soil-plant transfers (phytoavailability) of trace elements (TE) in contaminated agricultural soils. Some TE such as arsenic (As) can accumulate in plants, with a high subsequent risk of contaminating the food chain. Other TE like copper (Cu) are mainly phytotoxic and affect crop yields. Research teams are assessing these risks by focusing on the rhizosphere, i.e. a thin soil layer (a few hundreds of micrometres to a few millimetres thick) in contact with roots and whose physicochemical properties are highly affected by root activities. Rhizospheres can be studied in situ by collecting soil attached to roots, but experimental laboratory tests, such as the RHIZOtest, which is based on the physical separation of soil and roots, can be used for a more in-depth analysis of the impacts of rhizosphere processes on TE phytoavailability.

In Southeast Asia, the high availability of As derived from irrigation water in flooded rice field soils boosts the risk of high As phytoavailability. However, in these soil reducing conditions, rice favours the formation of a matrix of iron oxyhydroxides on the surface of roots, which tend to sequester As in the rhizosphere and reduce its phytoavailability. In Languedoc-Roussillon region (France), studies on rhizosphere processes are also helping to gain insight into the development of Cu phytotoxicity in durum wheat in some former vineyard soils. In very acidic soils, plants reduce Cu phytoavailability by highly alkalizing its rhizosphere. Conversely, in calcareous soils, root exudates released by the plant into its rhizosphere exacerbate Cu phytoavailability, thus promoting its phytotoxicity. These two examples highlight the importance of conducting studies focused on rhizosphere processes to assess TE phytoavailability.

Contacts: Matthieu Bravin, matthieu.bravin@cirad.fr
Emmanuel Doelsch, doelsch@cirad.fr & Philippe Hinsinger, hinsinger@supagro.inra.fr

Development of tropical tree crop-based production systems

The internal research unit (UPR) Performance of Tree Crop-Based Systems (CIRAD) focuses research on agronomic aspects of tropical tree crops, e.g. oil palm, natural rubber, cocoa, coffee and coconut, while dealing with technical agricultural production systems on different scales: cropping system, production system, farm, commercial plantation, agroindustrial site, processing unit supply area, agroecosystem, etc.

Sustainable increases in income and agricultural production are required to meet the challenges of this new millennium, but in a setting of shrinking cropland, growing populations and global warming. The unit aims to fulfill these needs, while taking the environmental and social impacts of recommended systems into account for both family smallholdings and agroindustrial plantations.

In response to these challenges, the unit is striving to sustainably increase the productivity of tropical tree crop-based production systems. It is thus developing a multidisciplinary scientific project, with research focused simultaneously in the fields of physiology (plant functioning), ecophysiology (plant interactions with biophysical and climatic environments), agronomy (optimization of cropping practices and effective use of genetic gains), ecology (environmental service impact assessment) and socioeconomics (conditions in which stakeholders adopt systems, farm functioning).
Overall, the unit aims to develop knowledge and tools that will ultimately help farmers streamline their production systems on the basis of combined sustainability criteria:  
- agronomic (technical-economic optimization of production)  
- socioeconomic (economic profitability and social acceptability)  
- environmental (ecological impacts and services).

The unit carries out its targeted research activities in partnership with public and private sectors. Research is undertaken in collaboration with research units of CIRAD, INRA and IRD, universities, national agricultural research structures partner developing countries and private partners (farmers’ groups, agroindustrial groups).

Engineering and expertise operations are also conducted to meet the demands of private and institutional operators, thus generating substantial autonomous resources for the unit and CIRAD. These expertise-consulting activities account for around seven senior scientist full-time equivalents a year. The unit plans to continue its activities in the coming years, while focusing its project on two main lines of research:  
- Line 1: Agroecological performances of technical production systems  
- Line 2: Environmental and social performances of technical production systems.

Environmental impact indicators in oil palm plantations

It is essential to understand and measure the environmental impacts of agricultural production in order to optimize cropping systems and thus ensure sustainable production. This is becoming a crucial issue with respect to oil palm cropping. The growing global demand for oil palm is rapidly increasing pressure on natural resources. Since 2004, CIRAD has been developing agroenvironmental indicators to help growers reduce their environmental impact by modifying their cropping practices. Indicators of the INDIGO® method have been adapted for oil palm. These indicators were designed through the modelling of emissions and potential impacts, and validated by comparison with field data. A scoring system, developed on the basis of scientific knowledge and field expertise, is used to classify practices on a scale of 0 (high environmental risk, change practices) to 10 (optimal situation, no risk), with 7 being set as the sustainability threshold.

These classification systems, which are already operational for the first four indicators (nitrogen, fertilization, pest and disease control, organic matter and soil cover), were pooled for calculation in a database with a user-friendly graphic interface, i.e. the Ipalm software package. Growers who adopt Ipalm can already obtain an environmental assessment of their plantation and determine how to improve their cropping practices via simulations. Upstream research is under way on the functioning of agroecosystems to enhance the development of new indicators and validate them under different conditions (climate, soils, agricultural practices, etc.). The team is also focusing specifically on the production of indicators of the impact of practices on biodiversity and water quality by broadening its environmental assessment approach to the landscape scale. In the longer term, socioeconomic impact indicators will potentially be integrated to address the many sustainability issues.

Example of Ipalm (‘pest and disease control’ indicator of the Ipalm method) indicator results.

Contacts: Jean-Pierre Caliman, jean-pierre.caliman@cirad.fr  
Aude Verwilghen, aude.verwilghen@cirad.fr  
& Cécile Bessou, cecile.bessou@cirad.fr

Landscape and land use.
Minimizing the impact of cropping on biogeochemical cycles

Direct seeding mulch-based cropping systems (DMC) and carbon sequestration

Soils contain more carbon than terrestrial vegetation and the atmosphere combined. They hence represent a critical carbon sink that is closely dependent on land-use patterns. Agricultural practices contribute to the depletion of organic carbon resources. At the plot level, the decline in carbon stocks is attributed to three processes: 1) oxidation due to the loss of soil cohesion, thus exposing carbon to temperature and humidity variations, 2) transfers such as leaching and translocation of dissolved organic carbon or particulate organic carbon, and 3) water and wind erosion. It is thus essential to increase soil organic carbon levels so as to ensure sustainable agricultural management.

DMC with high annual carbon inputs can rectify degraded agricultural soils, restore their fertility and promote overall diversity (production, soil macro- and micro-fauna). In humid tropical conditions, regeneration of the organic matter and physical and biological properties of soils can be as substantial and rapid as losses due to continuous intensive tillage. Between 10 and 15 t/ha/year of dry matter residue must be input into the system, depending on the extent of chemical fertilization, to maintain a stable carbon balance. The best DMC produce between 15 and 28 t/ha/year of dry biomass, thus enhancing organic matter regeneration, improving the physical (aggregation, infiltration), chemical (cation exchange capacity, nutrient recycling, buffering capacity) and biological (macrofauna and microbial population diversity) features. These systems which are founded on high annual biomass production and increased functional diversity (even in the dry season) have higher carbon sequestration capacities than the conventional systems.

Contacts: Lucien Séguy, seguyl@wanadoo.fr & Florent Tivet, florent.tivet@cirad.fr

Recycling organic matter and waste through agricultural practices

The internal research unit (UPR) recycling and risks (CIRAD) develops solutions for recycling organic matter and waste using agricultural practices while controlling the agroenvironmental risks and making effective use of the cleansing potential of soil and plants. It addresses this issue by investing in research topics ranging from studies on biophysical organic matter and waste transfer and processing systems to the modelling and the integrated management of organic matter stocks and flows from the plot to the territory.

The UPR is organized along two main lines of scientific research:

- Line 1. Management of above-ground and territorial residual organic waste (from workshop to territorial scales)
- Line 2. Studies on residual waste-soil-crop interactions (from molecular to plot scales)

It is also supported by analytical and experimental platforms at each of the main sites.

The research topic ‘Modelling and analysis of mass flows on a territorial scale’ (Line 1) is focused on developing models to simulate agricultural production systems in which recycling has been used and to assess them in terms of sustainable development objectives, while taking two organization levels into account: farms (individual management) and organized groups of farms (collective management). The research topic ‘Interaction dynamics between residual organic waste, soil and crops’ (Line 2) is aimed at studying the dynamics of interactions of trace metals and nitrates with cropping systems and different types of soil on three different scales: regional, experimental plots and laboratory (rhizosphere and molecular).

In Réunion, the UPR is closely collaborating with local authorities and above all with the Région de La Réunion. In Montpellier, it has forged innovative partnerships with private companies, especially Phalippou Frayssinet, the leading organic fertilizer manufacturer in France.

Funding is mainly provided by the public sector and additional French national resources (Agence nationale de la recherche, ministries other than the Ministère de l’Enseignement supérieur et de la Recherche, Ministère de l’Outre-mer, Agence de l’Environnement et de la Maîtrise de l’Énergie). Funding associated with the unit’s research activities in Réunion is provided by the European Community and local authorities. Funding from the private sector and consulting missions also contributes to the unit’s financial balance.

Growing cover crops to restore degraded soils (Yunnan province, China).
Integrated modelling of cropping practices and biomass flows in agricultural production systems

The ‘Mafate’ approach was developed for modelling and analysing mass flows on farm and territory scales, and designed to represent farmers’ practices and test management strategies. It involves four steps: (i) acquisition of knowledge on practices, (ii) their conceptual representation (action models, typologies), (iii) construction of simulation models, (iv) use of these models to evaluate the functioning of targeted production systems. Several models have been developed with the same representation and goals, i.e. to simulate mass transfers between production units represented by stocks, linked by flows, which in turn are controlled by actions:

- ‘Magma’ was designed to simulate effluent management on livestock farms in Réunion. It was also adapted to represent family farms in Vietnam which include pig rearing, crop growing, fish farming ponds and biodigesters to process manure.
- ‘Biomas’, which was developed in partnership with the Université de La Réunion, simulates effluent transfers between farms with surpluses and farms with shortages within territories. It was parameterized in the territory of Petit-Grand Tampon in Réunion.
- ‘Comet’ has been used to study pig slurry supplies to processing units in Réunion (Grand Ilet, Saint-Joseph).
- ‘Approzut’ has been used to study pig slurry supplies to processing units in Réunion (Grand Ilet, Saint-Joseph).
- ‘Gamede’ (developed by J. Vayssières during his PhD research at CIRAD’s UPR Livestock Systems and Animal Product Management), simulates overall nitrogen flows on cattle-dairy farms in Réunion.

Ongoing research is focused especially on environmental assessment of simulated production systems and representation of farmers’ activities.

Contacts: François Guerrin, francois.guerrin@cirad.fr, Jean-Michel Médoc, jean-michel.medoc@cirad.fr & Jean-Marie Paillat, jean-marie.paillat@cirad.fr

Sharing major nutrient resources and uptake facilitation in intercropped cereal-legume systems: a case study on phosphorus

In light of the importance of ecological intensification in agro-systems, the phosphorus issue is especially worrisome because of the finite nature of natural phosphate resources, which is the main source of phosphate fertilizers. The shortage of these fertilizers will be a major problem within a few decades, so solutions are urgently needed. Among the promising innovations, UMR Eco&Sols has launched an extensive research programme on the benefits of intercropping, as compared to monocropping, in making more effective use of soil nutrient resources. Many previous studies have revealed that cereal-legume intercropping increases productivity, while also enhancing the quality of cereal production (protein contents) and nitrogen use, especially atmospheric nitrogen through more efficient symbiotic fixation. This is one factor behind the success of such cropping systems in developing countries and China, where intercropping systems are used on an area of around 25 million ha.

The hypothesis put forward is that, in addition to nitrogen, soil phosphorus could be better used by intercropping cereals and legumes than by separately monocropping these species. Studies carried out by UMR Eco&Sols have shown that legumes (various tested grain legumes) and cereals (durum wheat) tap different soil phosphorus pools (organic/inorganic). Both species make more effective use of soil resources via this functional complementarity. Studies—especially long-term phosphate fertilization trials (40 years in 2009) carried out at INRA in Toulouse (France)—have also revealed nutrient uptake facilitation processes between intercropped species, i.e. the legume seems to be able to increase phosphorus availability in the associated durum wheat rhizosphere. Research is currently aimed at gaining insight into the underlying processes in order to come up with the best crop associations, especially under minimal phosphate fertilizer application conditions.

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Contact: Philippe Hinsinger, philippe.hinsinger@supagro.inra.fr
Minimizing the impact of cropping on biogeochemical cycles

In Madagascar, direct seeding mulch-based cropping systems (DMC) have been developed as an alternative to conventional systems based on soil tillage, which are unable to effectively meet the major challenges of land conservation, environmental preservation and food security. DMC systems combine no tillage and organic matter management (crop residue left on the ground in the form of mulch, or live cover crops). Carbon sequestration in the soil and the reduction of emissions of greenhouse gases such as methane and nitrous oxide depend on management choices. Many studies, including those conducted by UMR Eco&Sols, have highlighted the high carbon storage potential of DMC systems. Regarding greenhouse gases, it is essential to gain insight into the mechanisms involved in nitrous oxide (N₂O) emission and quantify changes induced by management strategies, since the global warming potential of this gas over the next 100 years is 300-fold greater than that of carbon dioxide.

To assess the impact of management strategies on N₂O emission, UMR Eco&Sols conducted studies at research sites located in the highland region of Madagascar set up by its local partners, i.e. URP SCRiD (Sustainable Farming and Rice Cropping Systems, CIRAD - FOIFA - Université d’Antananarivo) and the NGO TAFA (TAny sy Fampilandoan'i Terre et Développement). The research included in-situ monitoring of gas emissions and soil parameters that could regulate key processes responsible for these emissions. The findings revealed very low N₂O emission, its relationship with limited nitrogen stocks in ferrallitic soils, and especially a lack of difference when comparing DMC and conventional tillage systems.

Contacts: Lydie Chapuis-Lardy, lydie.lardy@ird.fr
Jacqueline Rakotoarisoa, j.rakotoarisoa@cirad.mg
& Tantely Razafimbelo, tantely.razafimbelo@ird.fr

Nitrous oxide emission dependent on soil cover management in agroecosystems in Madagascar

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△ Measurement of CO₂ flows emitted by soil respiration under eucalyptus plantation in Brazil.