INRA's scientific priorities for 2010-2020: targeted research

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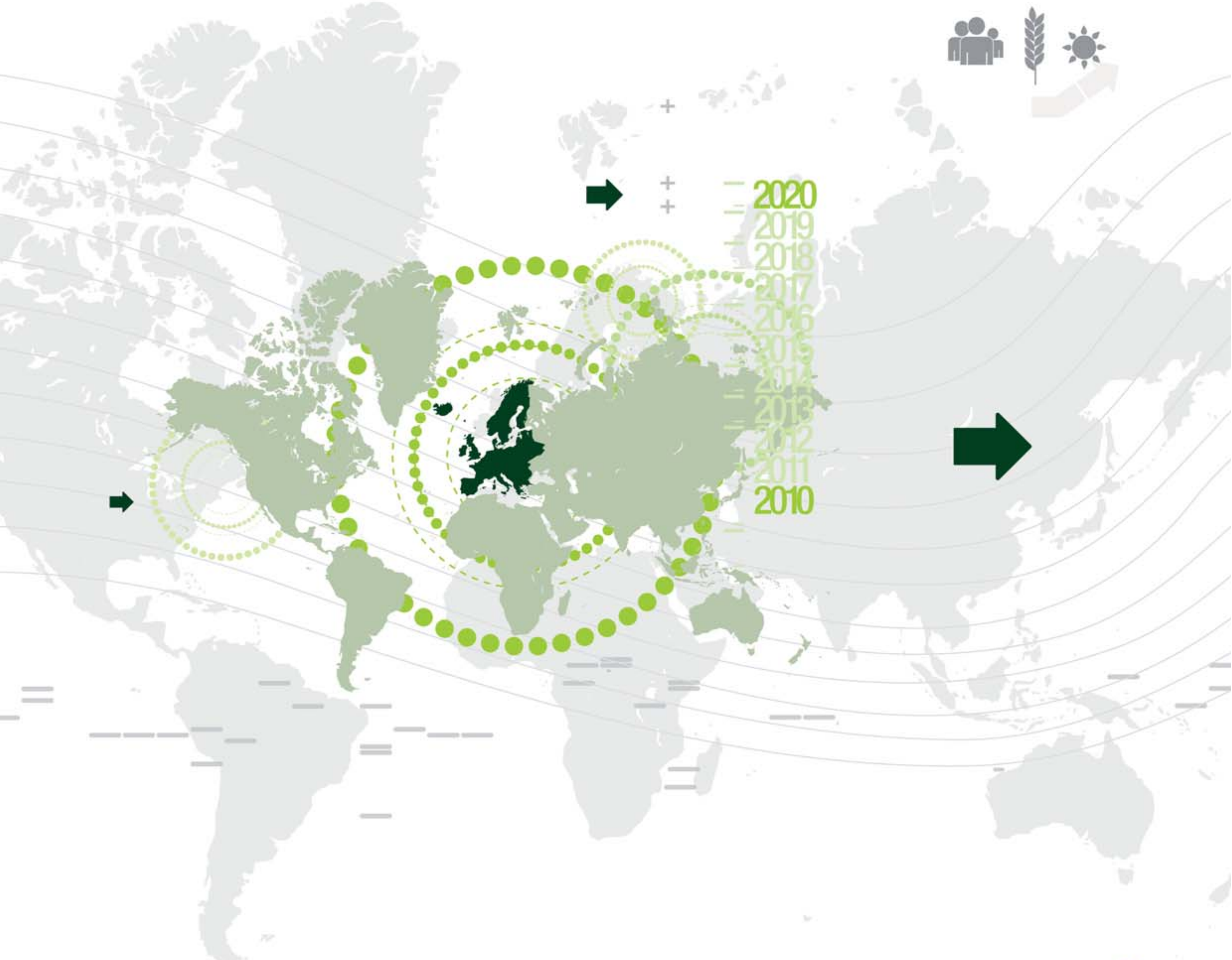


2010 - 2020
TARGETED RESEARCH

FRENCH NATIONAL INSTITUTE FOR AGRICULTURAL RESEARCH

What are the scientific challenges faced by agricultural research?

Agricultural research has two main original features.
Both in the laboratory and under real conditions, it studies **a broad spectrum of biological, ecological, technical or socioeconomic phenomena or systems** — ranging from the intimate mechanisms of living organisms, biogeochemical processes or population dynamics to the functioning of landscapes and the biosphere; from the individual behaviour of actors to that of territories, industrial sectors and markets.

Consequently, it calls upon a **vast range of disciplines**[1], mainly founded in the life sciences but also including environmental sciences, ecological engineering, ecotechnologies and biotechnologies, as well as economic and social sciences. These characteristics lead it to acquire new knowledge and then assess its importance, propose appropriate trajectories for innovation and ensure that it becomes generic. The use of model systems, however relevant they may be, can be no substitute for this approach.

In order to respond to these global issues, agricultural research must more than ever make use of **systemic approaches**[2]. It is thus strongly driven by four major challenges.

The first concerns the study of the **changes of scales and organisational levels**, such as those which lie at the heart of both integrative biology and research on ecosystems or those concerning territorial dynamics.

The second challenge resides in the **intrinsic complexity of the systems studied**: this is linked not only to the multitude of actors and factors in play and to the wealth of regulatory and interacting networks implicated in the structure and functioning of these systems[3], it also results from the diversity of their functions and the services and performances expected of them. This situation is not radically novel, but developments in investigative skills and in the analytical and digital tools available have contributed to revealing this complexity, while at the same time providing new approaches to dissect and model it.

The need for stronger **inter- and cross-disciplinary approaches** is a third challenge, fashioned by separate but complementary logics: (*i*) by reorganisation of the disciplinary landscape that has resulted in the creation of new interfaces; e.g. between physics, chemistry and biology (*cf.* plant chemistry), between biology, informatics and applied mathematics (*cf.* bioinformatics or systems biology), or between cell biology and nanobiotechnologies (*cf.* synthetic biology); (*ii*) by recognition (referred to above) of the complexity of the phenomena studied, i.e. the need to take explicit account of numerous interactions and interdependences between their biological, physicochemical, technical or socioeconomic components; (*iii*) and finally, by the need to develop approaches targeting action and the design of novel systems – for production, processing or the management of natural environments — with appropriate properties and performance, and which involve the different actors and stakeholders involved as from the initiation of research.

Finally, in a context of uncertainty, the **anticipation** of future scientific and technological changes, the trajectories and possible fates of societal contexts and the demands that may be placed upon research, is more than ever necessary. Enhancing the foresight skills of the Institute thus supposes a commitment to two complementary actions: (*i*) mobilisation of the Scientific Advisory Board so that it can regularly analyse changes in the scientific context and place INRA's orientations in perspective relative to the emergence of new scientific frontiers or technologies; (*ii*) facilitation of the management of foresight studies which will inform on the possible futures of food systems, agriculture and the environment and their connected areas (energy, urban development, etc.). Once again, national, European and international collaborative efforts will be necessary.

In parallel, the accelerated evolution of technologies in the life and environmental sciences are continuing to revolutionise **the methods used to produce knowledge.**

These changes firstly affect the acquisition of data, the diversity and output of which continue to grow in a spectacular manner, thus posing new questions with respect to the **management, sharing and analysis of data.** Different tools are thus called into question: analytical and experimental platforms as well as informatics infrastructures; the databases and scientific information systems without which the massive generation of data would have no meaning; the design of methods for meta-analysis and generalisation of their use; the extension of partnerships and the mobilisation of scientific skills and new techniques to enable capacities for data analysis that will be sufficient to cope with the intensity of their production.

Secondly, **modelling**, necessarily included in an iterative process **coupled with experimentation and observation**, is more than ever essential to determine the behaviour of complex systems and to implement the integrative approaches mentioned above. The coupling of models and data of different types is thus increasingly necessary: for example, the articulation of models and physical, biological, ecological and socio-technical data will thus be required increasingly to enable the design, assessment and guidance of agricultural practices in a context of global change[4].

Thirdly, the changes ongoing at present are of particular importance to **laboratory and observation technologies**, on the one hand, **and engineering** on the other. Whether these concern biotechnologies, nanotechnologies or sensors, *etc.*, the former first of all constitute essential tools for researchers for the acquisition of knowledge; they also offer new pathways for **innovation** in plant breeding[5], animal selection, the uses of micro-organisms or the processing and valorisation of biomass. In addition, engineering — considered here as the design, experimentation and assessment of **novel systems** to meet the demanding requirements of sustainable development — is based on an ability to assemble knowledge, techniques and know-how. Anticipation of the impacts of these technologies and technical systems (for production, processing and the management of resources and the environment) and an understanding of the conditions under which they may be adopted by actors, is itself one of the areas targeted by social and economic science research, and cannot be envisaged without its interactions with the different stakeholders concerned (farmers, industry, consumers, environmental associations, local government bodies, etc.).

1 Based on the distribution of researchers between its Specialised Scientific Committees, the skills available within INRA at present can be broken down as follows: life sciences (68%), environmental and processing sciences (12%), biotechnical disciplines (8%), economic and social sciences (8%) and digital sciences (4%). In terms of the quality and quantity of its publications, INRA ranks second in the world in "*Agricultural sciences*", according to the USDA. It shares the second place in "*Plant & animal sciences*" with University of California, Davis. But singularly when compared with its foreign counterparts, INRA is characterised by a balanced production in agricultural research and "*Molecular biology & genetics*". INRA's more modest ranking at present in the environmental sciences is nonetheless compensated for by the marked growth (140%) seen during the past ten years (source: *Essential Science Indicators* of the *WoS*, analysis of citations for 1999-2009).

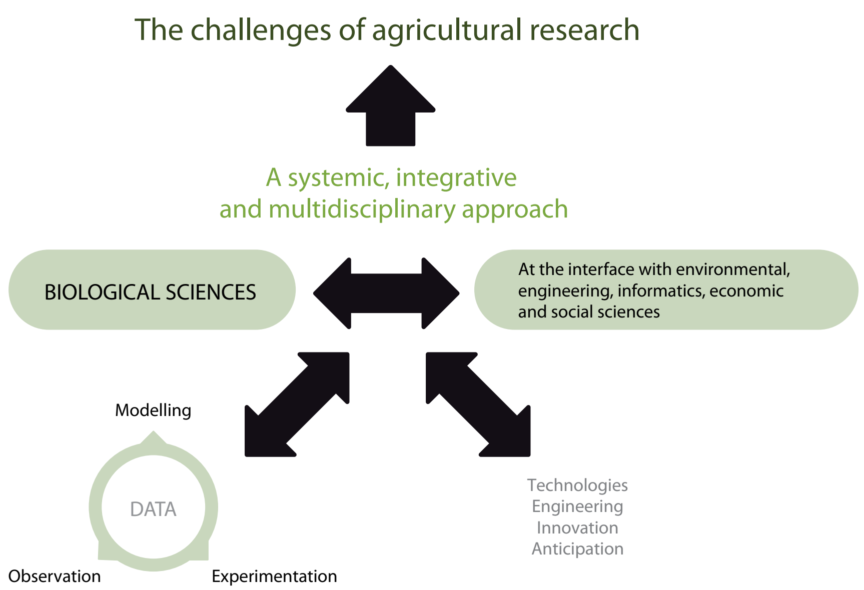
2 The debate on the new biology of the 21st century initiated by the US National Research Council agrees with this analysis. See: *A new biology for the 21st century*. 2009. Committee on a New Biology for the 21st Century: Ensuring the United States Leads the Coming Biology Revolution, Board on Life Sciences, Division on Earth and Life Studies, National Research Council of the National Academies, The National Academies Press, Washington, D.C.

3 Gene expression networks, signalling pathways, metabolic networks, trophic networks, meta-populations and meta-communities, social networks, economic markets, etc.

4 Neson et al. Climate change: impact on agriculture and costs of adaptation (IFPRI Washington, DC 2009).

5 For example: the importance of innovations in plant production was recently emphasised again by the *Royal Society* of London (*Reaping the benefits: Science and the sustainable intensification of global agriculture*, 2009).

Figure 1: Sciences of the complex at the heart of agricultural research



What are the high priority questions for INRA during the next ten years?

As a result of discussions informed by numerous foresight analyses and supplemented by broad and participative consultation (*Cf.* Annex 1[6]), INRA has chosen to focus on a limited number of priorities for the ten years to come (Figure 2). Of course, these choices will be reviewed, updated and adapted periodically in the context of upcoming assessments by the different scientific divisions and by the Institute as a whole[7].

INRA has thus identified two particular scientific projects that focus on the interfaces between different disciplines.

- The first concerns the development of predictive approaches in biology. Sometimes qualified as "**predictive biology**", this extension to integrative and systemic biology is based on the systematic exploration of living organisms at different organisational levels, and on the growing openness of biology towards modelling and digital sciences. These approaches will generate knowledge and methods that will benefit all areas of interest to INRA.
- The second concerns **agro-ecology**. While recognising that the polarisation of research on action may require consideration of its interfaces with, and extensions towards, the economic and social sciences, it is the cross-fertilisation of ecological, agronomic and zootechnical disciplines that will be targeted in the first instance as a source of new concepts and innovations. Particular attention will be paid to sustainable soil management.

Anchored within the tripod of "food and nutrition – agriculture – environment", five scientific challenges centred on major issues faced by society will drive the high priority research orientations chosen for the next ten years.

- **Integration of the economic, social and environmental performance of agriculture**, livestock farming and forestry raises novel questions regarding the understanding, assessment and modelling of these performances taken together. In a context of renewed partnerships, this will lead to the design of new production systems that are explicitly embedded in a context of sustainable development, mobilising advances in biology, biotechnologies and agro-ecology.
- In a context of food transitions of numerous origins, the **development of healthy and sustainable food systems** supposes that food production sectors must be considered globally, from the production and development of foods to their consumption, including the fate of waste and losses. In-depth knowledge is also required on all the biological and socioeconomic determinants and consequences of dietary behaviours, and on the relationships between food, nutrition, prevention and health.
- **Attenuation of the greenhouse effect and the adaptation of agriculture and forestry to climate change** require study of the interaction cascades involved in the functioning of continental ecosystems, notably in reaction to climate change, a broadening of the spatial and temporal scales studied and analysis of the adaptive mechanisms in play. The design of resilient agricultural, forest and aquacultural production systems, and appropriate methods to manage natural resources, can be expected to result from these efforts.
- **The valorisation of biomass for chemicals and energy** is motivated by the need to develop new sectors based on renewable carbon sources in replacement for fossil fuels. This will be based on developing green and white biotechnologies and biorefining, on identifying plant species appropriate for these uses and on a circular economic logic, founded on a systemic analysis of the impacts of these new sectors.
- The major challenge of **global food security under the pressure of global change** arises from the conflict between the objectives of sustainable development on the one hand, and the extent, conjunction and interdependence of crises and transitions — demographic, dietary, environmental, relative to energy or land use, etc. — both current or anticipated, on the other. The integrative nature of this challenge is thus essential: a search for territorial coherence will thus be an important objective. The globalisation of food, agricultural and environmental challenges, and their increasingly close links with the challenges faced by other fields and sectors (demographics, economics, energy, health, urbanism, etc.) further increase the need for a systemic understanding. The heterogeneity of local problems requires the consideration of multiple systems.

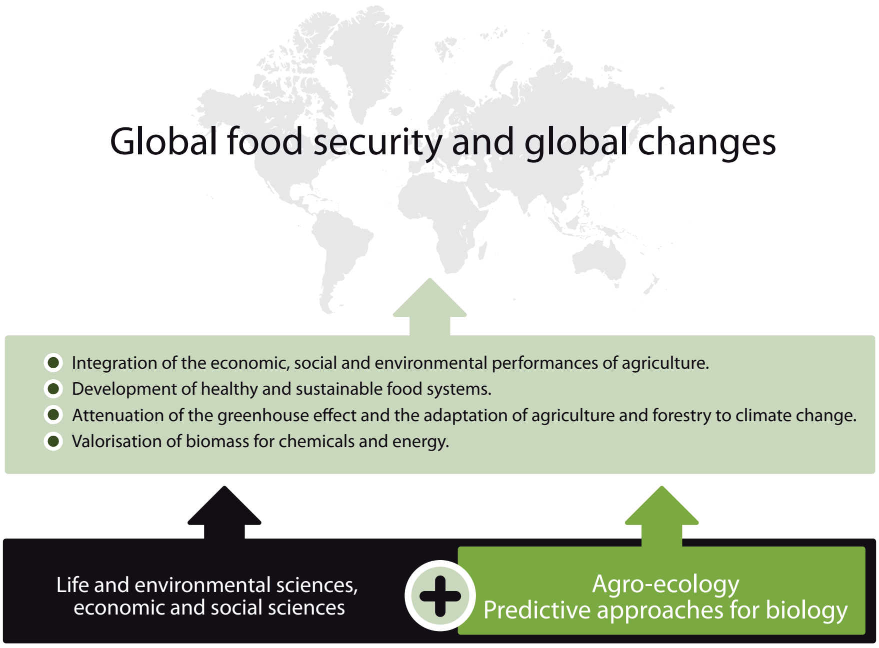
However, the importance of these challenges clearly exceeds the capacities of a single research institution. Thus the application to regions other than developed countries[8] of the research questions linked to these different challenges will require INRA to reinforce its national collaborations, to become involved in European joint programming mechanisms and to develop alliances at an international level.

[6] Annex 1: An original approach to compiling the orientation document, based on broad-based, participative consultations.

[7] International assessment of INRA: AERES Report (2009).

[8] INRA is working in practice on national sectors and territories, including those in the Overseas Departments.

Figure 2: Priorities for INRA during the next ten years



Two important and cross-disciplinary scientific projects

1. Predictive approaches for biology

Context and objectives

The conjunction of three major evolutions — a growth of investigative capacities, with a scope ranging from the molecular level to that of the living organism, or even populations and communities; the extraordinary increase in the rate of acquisition of genomic data and the opportunities offered by the development of digital sciences and technologies — has revolutionised biology. (i) It has enabled exhaustive and global approaches that favour more intense dialogue between experimentation (or, in certain fields, observation) and modelling, and generates considerable masses of data. (ii) It has renewed the study of biological systems and their complexity, making it possible to consider scientific questions at different levels: a large-scale approach to relationships between genotypic and phenotypic variations modulated by the environment and the multi-scale integration of underlying mechanisms; the study of important interaction or regulation networks; an understanding of the links between biological, physical and chemical processes at the cellular and tissue levels. (iii) It has shifted cognitive, methodological or organisational challenges by reinforcing the pivotal role of analytical platforms, highlighting the mastery of phenotyping as a major obstacle and considerably increasing the need for formal skills in the management and analysis of both data and modelling. (iv) With the development of approaches such as population or environmental genomics, these revolutions extend far beyond the framework of the biology of organisms and give rise to convergences between disciplines (for example, between genetics and ecology), around common tools and scientific objectives.

These changes concern INRA at numerous levels: they open the way not only to a clearer understanding of different phenomena but also to the more efficient prediction of phenotypes; they encourage the development of integrative biology which forms the basis for the originality of the Institute's contribution to the life sciences; they modify our view of model species and systems, and they increase capacities for direct research on systems of agronomic interest.

Skills and areas of expertise

During the two previous Contracts of Agreed Objectives, INRA anticipated these profound changes by backing the development of high-throughput biology and supporting integrative biology approaches.

Firstly, INRA became closely involved in the national system for the coordination of infrastructures (RIO puis GIS IBiSA[9]), by basing its efforts on a small number of platforms of national importance operated by other institutions or, when more relevant, by investing in platforms or resource centres that would be open to the wider scientific community. This policy resulted in regular and sustained investments in major equipment, in the setting up of the National Commission for Collective Tools (CNOC) and in the accreditation of, and support for, some twenty structuring platforms. Supplemented by long-term incentive support for the production of critical biological resources (sequencing, genotyping and the organisation of genetic resources), this has been extended since 2007 by support for the development of databases.

Secondly, based on the recommendations of its Scientific Advisory Board (2005), INRA stimulated the development of integrative biology and modelling by mobilising complementary tools: programmed incentive actions focused on animal, microbial and plant integrative biology (agroBI programme, 2006-2008), collaborations between INRA and INRIA teams (2008-2010) and the emergence of research on complex systems (Scientific Interest Group: National Network on Complex Systems, 2006-2010); the recruitment of Associate Scientists on Contract and Young Scientist Contracts, and researcher schools in integrative biology organised in collaboration with the CNRS[10] (2005, 2007). Backed by its different divisions and supported by the commitment of teams to European or ANR[11] projects (BIOSYS, SYSCOMM and then "white" programmes), these different actions enabled some units to acquire a strong position in the field of integrative and systemic biology, and enabled INRA to carry out high-profile (although numerically limited) actions in the field of bioinformatics. More generally, and even though some heterogeneities persist between both units and divisions, these efforts have contributed to laying the foundations for the changes to which the Institute must now be committed.

High priority research questions

The development of predictive biology has raised new research questions at the interface between biology, applied mathematics and informatics.

- Regarding the modelling of complex systems, two central issues concern: the analysis, reconstruction and simulation of interaction and regulation networks and the morphogenetic processes that bring into play dynamic systems with a dynamic structure and the links between biological, physical and chemical processes;
- Regarding integrative biology, the two main questions concern the massive combinatory exploration of correlations between genotypes and phenotypes[12] and the integration of underlying mechanisms at levels ranging from the gene to the organism.

To address these questions, it is necessary to overcome the methodological and technological obstacles of the management and analysis of very large datasets, as well as the production itself of these data: the development of phenotyping strategies (definition and ontology of the traits studied and metrology); access to novel imaging techniques for living organisms and to very high-throughput sequencing and genotyping platforms. At higher levels of integration, efforts to improve epidemiological approaches, and the design of models that couple population dynamics and genetics, remain scientific priorities.

Actions proposed for INRA and extensions to national and international collaborations

As well as integrating these high priority research questions in the strategic plans for different divisions, two major programmes will be initiated in 2010 and 2011:

- the "Metagenomics of Microbial Ecosystems" programme, which in particular will try to establish links between very high throughput structural and functional approaches and prediction and engineering in these ecosystems;
- the "Animal and Plant Genomic Selection" programme, which will combine methodological research and some integrated projects focused on particular species, and include an analysis of the transformation of different sectors induced by the deployment of genomic selection.

The proposals made by the Institute with respect to dietary cohorts and green and white biotechnologies, in the context of the "Health and Biotechnologies" part of the Investments for the Future programme, will also contribute to developing predictive biology and its applications at the food/health interface, or in the areas of agricultural production and bioprocessing industries. Thus development of the diversified phenotyping of major cohorts will enable the identification of biomarkers for health and causal relationships between diet and health.

At the request of INRA's central management, the Scientific Advisory Board carried out a foresight study on "data management and sharing". Focused initially on genomic and molecular data, this study is now likely to be extended to other fields (ecology and environmental sciences, agronomy, economic and social sciences) and it will give rise to proposals concerning, firstly, informatics infrastructures, skills, organisation, partnerships or ethical practices, and secondly, research questions relative to the representation of knowledge, the integration and large-scale analysis of data, data mining and meta-analyses.

Depending on an analysis that is still to be carried out, the strengthening of systemic biology and its extension to synthetic biology may give rise to some specific operations designed to structure facilities around a small number of sites and lead teams and/or the initiation of a major programme. In terms of broader integration, modelling of the dynamics and functioning of populations and communities will be supported in the context of major programmes focused on adaptation to climate change and the integrated management of plant and animal health.

Among INRA's most important national and international partners in this area, mention should be made of: INRIA[13] and the BBSRC for systems biology; CEA[14] and the Beijing Genome Institute for metagenomics; international genomics consortia and the USDA-ARS and CGIAR[15] for animal and plant genomic selection, respectively, and CNRS and ESFRI for data management and sharing.

9 RIO: Réseau Inter-Organismes (Inter-Institution Network); GIS IBiSA: Groupement d'Intérêt Scientifique: Infrastructures en Biologie, Santé et Agronomie (Scientific Interest Group: Biology, Health and Agronomy Infrastructures).

10 CNRS: Centre National de la Recherche Scientifique (French National Centre for Scientific Research)

11 ANR : Agence Nationale de la Recherche (French National Research Agency).

12 For example, in association genetics and genomic selection, in research on predictive biomarkers through the coupling of genotyping, phenotyping and metabolomics approaches in very large cohorts, or the interface between green and white biotechnologies to optimise the links between the structure of biomass and its biotransformation in a context of plant chemistry.

13 INRIA: Institut national de recherche en informatique et automatique (National Institute for Research in Computer Science and Control).

14 CEA : Commissariat à l'Energie Atomique et aux Energies Alternatives (French Alternative Energies and Atomic Energy Commission).

15 CGIAR: Consultative Group on International Agricultural Research.

2. Agro-Ecology

Context and objectives

In a context of degraded or increasingly rare natural resources, of society's demands for a reduction in the use of plant health products and veterinary medicines, of fluctuating trends in demand and upcoming modifications to the Common Agricultural Policy, it is necessary to overcome the historical cleavage between agronomy and ecology in order to reinforce the conceptual bases of agricultural research, to develop its capacities for critical analysis and its ability to make useful proposals so that it can attain the quantitative and qualitative objectives of agricultural production under conditions, and using resources, that meet the criteria of sustainable development.

While in the past the prime objective was to reach maximum production potential, today more emphasis is laid on resilience in the face of unforeseen events (economic, climatic or health, etc.) and on development synergies between agriculture and its environment. This supposes an extension to spatial and temporal scales and consequently more emphasis on broader levels of organisation (population, community, ecosystem, landscape). Ecology studies these levels of organisation, but classically targets subjects that differ (ecosystems little affected by human activities and with a high degree of biodiversity) from those of agronomy. **The first objective thus concerns the appropriation by agronomy of the concepts and methods of ecology, and their application to man-made ecosystems managed by agriculture and livestock farming.** The application and/or adaptation of the laws of ecology to these particular systems, and their combination with agronomic knowledge, constitutes a promising area of research both in terms of its potential for academic advances and its short and medium-term applications.

A crop or herd can be seen as a population whose genotype is partially controlled by domestication and which interacts with communities of species assembled within the agro-ecosystem: macro- and micro-organisms decomposing the soil, pests, auxiliaries, mutualistic or competitor organisms. The cultivated plot and its annexes (borders, improvements, etc.) correspond to an ecosystem integrated in a landscape. Agro-ecology thus supposes that account is taken of biological diversity at all its organisational and functional levels so as to understand the dynamics of living organisms and its role in the ecological services rendered by agro-ecosystems, notably in terms of productivity, and in the resilience of these ecosystems. The integration of knowledge on ecological processes at the scale of a landscape mosaic requires the combined study of processes (biotic and abiotic), transfers and biogeochemical cycles as a function of the spatial and temporal organisation of agricultural activities and territories.

Many of the mechanisms involved in interactions between a landscape matrix, farming practices, biodiversity and the functioning of and services rendered by ecosystems, are poorly understood or have not been quantified with sufficient accuracy. It is therefore necessary for us to improve our ability to evaluate ecological services, anticipate their evolutions and master them.

Particular attention will be paid to the ecology and sustainable management of soils (including technologies for the restoration of soils that have become unfit for cultivation). Indeed, at the human scale, soil is a resource that it is difficult to renew, and its loss in quantitative (erosion) or qualitative (loss of organic matter, pollution, salting, compaction, etc.) terms now appears to be rapid and a major concern. Furthermore, although the development of agro-ecology encourages greater focus on the biological and ecological functioning of soil so that we can better understand and manage agricultural production systems, our knowledge in this area is still too limited. Analysis of the impacts of inputs and farming practices on the quality and ecological status of soils and freshwater aquatic environments is thus an additional objective, which requires in particular an increase in research on ecotoxicology.

The purpose of developing knowledge in agro-ecology and sustainable soil management is to encourage the introduction of innovative farming systems that combine economic, social and environmental performance (cf. Scientific Challenge I). This will offer particularly valuable support for methods to design and assess agricultural and sylvicultural systems, and for approaches designed to optimise the development of these systems at the scale of a landscape or territory.

Skills and areas of expertise

INRA benefits from internationally recognised expertise in the study of soil and the disciplines required in agronomy, livestock farming and forestry (soil sciences, plant and animal sciences, bioclimatology, etc.). Until now, the ecological approaches developed by INRA mainly concerned environments that were little affected by human activities (forests, grasslands and aquatic environments). Two structuring operations during the period 2006-2009 contributed to initiating agro-ecological research: in Avignon on "Integrated Fruit and Vegetable Production" and in Dijon on "Agro-Ecology of the Cultivated Plot". However, few studies have focused on ecological services, restoration strategies or ecotoxicology.

High priority research questions

Integrative study of biotic interactions in agro-ecosystems

The diversity and complexity of biotic interactions involving cultivated plants and domestic animals need to be understood in a more integrated manner by focusing not only on "positive" interactions (complementarity, facilitation, nutrient recycling, symbioses, pollination, parasitoid organisms, beneficial organisms, etc.) but also on "negative" interactions (competition, weeds, pests, etc.). Cultivation practices and livestock management methods act on the life cycle on numerous species present within an agro-ecosystem. Research will focus in particular on determining non-linearities, threshold effects in the structuring of communities and trophic networks and interactions with the physical environment that can cause a loss of biotic regulation within agro-ecosystems. In return, efforts will be made to mobilise "positive" biotic interactions, particularly in the context of production systems designed to achieve a high level of environmental performance.

Agro-ecology of the landscape

At the scale of a landscape mosaic, numerous spatial processes condition the long-term fate of agro-ecosystems. These processes are affected by the intrinsic characteristics of the environment (topography, soils, hydrology, etc.) and by the spatial organisation of production workshops and connected spaces that are little managed or not at all. Integrative study of these spatial processes will notably enable an understanding of the economies of scope that can result from diversified production systems – whether this concerns a diversification of land use, mixed-livestock farming or agroforestry – that could better utilise resources, encourage nutrient and carbon recycling and enable high levels of biological diversity. Studies will focus in particular on determining whether the characteristics of the landscape matrix can compensate for locally intensive management methods.

Multicriteria assessment of agro-ecosystems

The multicriteria management of agro-ecosystems in a long-term perspective that integrates arbitration between short and long term timescales and gives importance to the properties of resilience and adaptability, is another priority. Efforts will be made in particular to advance knowledge on management methods that in the long term either reinforce or, on the contrary, limit, the maintenance of ecological services, whether these are services in support of biotic regulation (pest control, entomophilous pollination, etc.), production services that contribute to farm income (stability of production) or non-commercial services (conservation of common biodiversity, water savings, soil carbon storage). This approach will require methodological developments regarding the quantification of ecological services, and will also include a socioeconomic dimension relative to innovation strategies and an adaptive management of agro-ecosystems that is designed to reduce uncertainties over time.

Sustainable management of numerous soil functions

The aim will be to stimulate approaches that combine physicochemical (structure, composition, modelling of biogeochemical cycles), biological (soil microfauna and macrofauna, microflora, rhizosphere, microbial communities, ecotoxicology) and socioeconomic (study of practices, economic evaluation of ecological services, incentive tools for sustainable management) methods. Emphasis will be laid on characterising the different functions of soils and evaluating the ecological services they render (supply of both marketable goods and ecological non-marketable services) and on taking account of long time steps (via Environmental Research Observatories (ORE), in particular). Priorities will also concern the impacts of agricultural practices in terms of the transfer of pollutants and xenobiotics, and the consequences for ecotoxicology linked to toxicology. Thus preference will be given to studying combinations of pollutants and to methods for the diagnosis of ecological status and the restoration of soil quality (including when they have become unfit for cultivation) and of freshwater aquatic environments. This research on the sustainable management of soil and water resources will in particular target improvements to the control of the long-term cost-benefits and cost-efficiency of management procedures and of environmental risks.

Extensions to national and international collaborations

The scientific challenge of agro-ecology will be taken up in the context of the "Agro-ecology and Soil" thematic group, managed jointly by INRA and CIRAD within the AllEnvi Alliance. It will also form part of the research programmes of several Scientific Interest Groups (GIS) coordinated by INRA, with partners from different sectors.

At the European level, research in agro-ecology is being developed under European FP7 programmes coordinated by INRA, such as REX[16] ENDURE[17] and the SOLIBAM[18] project. At a more global level, this theme is being covered by the international "Agrobiodiversity" programme run by DIVERSITAS[19].

Actions proposed for INRA

As well as work on this area included in the strategic plans of different divisions, a major INRA programme on agro-ecology and the services rendered by ecosystems will be entering its incubation phase. In addition, a regional approach to the theme of agro-ecology has already started with the identification of new clusters in the regions of Paris (Saclay–Grignon), Rennes (agro-ecology of the landscape), Toulouse (agro-ecology and mixed farming systems) and Theix (agro-ecology of grazing-based livestock farms).

16 REX: Réseau d'Excellence Européen (European Network of Excellence)

17 ENDURE: European Network for the Durable Exploitation of Crop Protection Strategies.

18 SOLIBAM: Strategies for Organic and Low-Input Integrated Breeding and Management.

19 http://www.diversitas-international.org/

Water, agriculture and continental ecosystems

Water is a major factor in the productivity and functioning of cultivated or natural continental ecosystems. In return, different land uses and farming practices have a considerable impact on water resources and aquatic environments in terms of both quantity and quality. Mastery of this situation implies the development of water-saving production systems and a reduction in pollutant emissions. It also means that agriculture must be associated with resource management systems that can regulate competition for use in a context of collective approaches to territorial development. Climate projections, European regulatory timetables, the growing intensity of water use conflicts in large parts of the world mean that the investment of agricultural research in these important challenges is a high priority.

INRA is contributing by taking the lead in French scientific output on water. These efforts will be sustained in response to several of the scientific and thematic challenges described in this document. Integrative biology and plant selection (Scientific Project 1) and Agro-ecology (Scientific Project 2) should supply the cognitive foundations for the design of production systems that consume fewer resources, optimise resource valorisation and contribute to the better ecological status of water bodies. The impact of unexpected hydrometeorological events, which are now occurring with increasing intensity and frequency (droughts, heavy rainfall, catastrophic surface run-off and floods), is one of the principal factors driving ecological and socio-technical adaptations to climate change. These adaptive processes will be one of the most important objectives of Scientific Challenge III. A direct link can also be made with Scientific Challenge V, because of the crucial importance of water and irrigation to global food security. An integrated approach to these issues will be supported by INRA in its proposals for the programmes of the "Territories and Natural Resources" Thematic Group of the AllEnvi Alliance.

Five scientific challenges focused on major stakes for society

1. Integration of the economic, social and environmental performance of agriculture

Context and objectives

Despite considerable advances in recent years, convergence of the economic, social and environmental performance of agricultural and forestry practices and systems requires significant research efforts to enable major changes to the functioning of these systems. The complexity of the dual insertion of agricultural and forestry activities, both vertical (in the production, processing, distribution and consumption sectors) and horizontal (in territories and areas of employment and housing), must be taken into account. Major changes are necessary and should include the diversity of natural resources and environments in which agriculture, livestock farming and forestry are operated, as well as the variability of economic (viability of farms), social, regulatory and institutional contexts.

The principal objective of this challenge is thus to develop research that will contribute to defining practices, systems, sectors and agricultural and forestry territories that combine economic, social and environmental performance. Taking up this challenge will require the design with all actors of a new trajectory for scientific, technological and organisational progress and transfer. The combined mobilisation of numerous disciplines in the context of integrated and systemic approaches should not be limited to the spheres of science and research alone. This ambition requires a reinforcement of the Institute's skills in research engineering, organisation and transfer-development, at the same time as the cooperation of all partners in the system for agricultural research, training and development (RFD).

Skills and fields of expertise

This challenge concerns a large number of disciplines (biology, genetics, agronomy, ecology, economic and social sciences, mathematics and informatics, etc.) and thus many, if not all, of the INRA research divisions. In practice, the Institute benefits from recognised expertise in these different disciplines, and is desirous to explore a broad diversity of agricultural and production systems. However, these skills are often deployed for segmented research programmes and projects focused on distinct and insufficiently coordinated scales of functioning. For this reason, several Scientific Interest Groups have been set up in recent years in the areas of both plant sciences (PICLeg[20] for legume crops, GC-HP2E[21] for arable crops) and animal sciences (Elevages demain).

High priority research questions

The research priority is therefore to **develop integrated and systemic analyses of practices, farms, sectors and agricultural and forest territories.** These analyses will be of an integrative nature, taking full advantage of the breadth of skills available within the Institute, in the context of projects developed jointly with all actors and partners involved in both the questions addressed, the methodology, and the results anticipated. These analyses will be systemic because the development of sustainable agricultural and forestry activities at the scale of farms, sectors and territories requires that these entities be considered as a focus for the interaction of physical, biological, technical, economic and social processes. This challenge will also open the way to more ambitious and longer term research projects.

At present, an initial opportunity for the coordination of research is developing through the **design of integrated management strategies for plant and animal health which limit the use of plant health products and/or veterinary medicines while remaining as technically and economically successful as the protection methods currently employed.** Indeed, the protection of plants and animals, the prevention of health events and the rapid and efficient management of their effects if they occur, are three key elements of sustainability, the importance of which will increase in view of firstly, the growing globalisation of economies and trade, and secondly, climate change. Without excluding the use of novel bioactive compounds, studies will make use of predictive epidemiology in order to optimise biological or ecological control methods, the creation and management of spontaneous or induced resistance in different breeds or varieties and study of the spatial and temporal diversity of products and production systems.

The contributions of the two scientific projects will also be important to meeting this challenge.

Thus in a transversal manner, and benefiting from INRA's area of excellence, particular attention will be paid to **the contribution of genetics to the sustainability of agricultural and forest systems.** The potential for progress in science and innovation offered by genomics, post-genomics, biotechnologies and predictive biology will be exploited in order to take account of new and more numerous selection targets, to develop high throughput genotyping and phenotyping and ultimately to create new genetic materials that will contribute to the sustainability of agricultural and forestry systems. Efforts in terms of genomic selection will focus in particular on: (a) taking simultaneous account of several traits in selection targets, including aptitude for downstream valorisation, (b) the genetic control and variability of these traits, and (c) the analysis of genotype-environment interactions in the diversified and fluctuating contexts of productive and environmentally-friendly agro-systems.

Alongside the efforts announced in the context of Scientific Project 2, **agro-ecology** will also be mobilised with the dual objective of understanding the functioning and management of man-made agro-systems, including their dimensions in terms of territories and actors. Emphasis will notably be placed on aspects relative to innovations (design and adoption), the adequacy of productive and territorial structures in a context of sustainable development, the valorisation of environmental benefits (higher prices) by the market and/or by taxpayers (public support policies), the role of agricultural advisors and systems for stakeholder organisation.

Extensions to national and international collaborations

The research that needs to be developed in response to this thematic challenge forms a natural continuum with the Grenelle de l'Environnement (Environment Round Table) and its results, and with the Ministry of Agriculture plan entitled "Objectif terres 2020: pour un nouveau modèle agricole français" (Towards a new Model for French Agriculture).

This research also finds its natural extension in the different French Scientific Interest Groups (GIS) (referred to above) that associate French partners in agricultural research, development and training, and in the Groups currently being set up (for vines and wine, fruit crops and fish products). These vertical GIS (sectors) share the same general objectives, which are to integrate economic, social and environmental performance, but they also have practical, operational aims, i.e. the development, adoption and dissemination of innovations oriented according to the principles of sustainable development. They are all linked to the "Relance Agronomique" Scientific Interest Group, which has the triple ambition of ensuring the overall coherence of research and development actions targeting the renewal of practices and agricultural systems, the pooling of databases and, more generally, knowledge in this field, and finally the development of appropriate training and advisory systems. This research will also benefit from the existence of two Scientific Interest Groups that target plant and animal genomics (GIS GENOPLANTE[22] and AGENAE[23], respectively), and from the wealth of infrastructures, facilities and tools for observation, experimentation and demonstration operated by the Institute and its French partners (environmental research observatories, experimental units, experimental farms, etc.). In this respect, efforts will focus on the European dimension for two purposes; firstly, the openness of French facilities to European partners, and reciprocally, the use by French researchers of facilities in other Member States in order to broaden the scope of observation, experimentation and demonstration.

In addition to European and international collaborations driven by different researchers and teams, it is mainly through the programmes that target this challenge that INRA will be able to pursue its ambition as a leader in Europe (e.g. by continuing to coordinate the ENDURE network) and in the world (e.g. by participating in the "Wheat Genetics, Genomics and Breeding" programme of international agricultural research centres).

Actions proposed for INRA

In addition to the elementary disciplinary research that will be carried out by specific divisions in the context of their strategic plans, often interacting with others, three transversal, multidisciplinary, integrated and systemic programmes will contribute to taking up this challenge: the first, launched in 2010, concerns the integrated management of plant health, while the other two will be initiated in 2011 and will concern respectively the integrated management of animal health and genomic selection (animals and plants). A fish-farming programme is also under discussion with the CIRAD, IRD[24], IFREMER[25] and other actors in the sector.

[20] Scientific Interest Group on "Integrated Production of Legume Crops".

[21] Scientific Interest Group on "Integrated Arable Production Systems with High Economic and Environmental Performance"

[22] Scientific Interest Group on "Plant Genomics".

[23] Scientific Interest Group on "Analysis of the GENome of Farmed Livestock".

[24] IRD: Institute for Research and Development.

[25] IFREMER: French Research Institute for Exploitation of the Sea.

2. Development of healthy and sustainable food systems

Context and objectives

Food systems to feed humans, defined as all production, trade, processing, distribution and consumption activities, are currently undergoing unprecedented change at the global scale that affects both developed and emerging countries. This revolution, which includes changes to food supply, consumption and their consequences in terms of health and quality of life, is particularly important because it has occurred so rapidly and profoundly and been accompanied by evolutions in human lifestyle and pathologies. The underlying causes and consequences of these changes are not yet fully understood. The complexity of food systems, their interconnections with environmental factors and the consequences of globalisation are another facet of this change. Their sustainability is being called into question by global climatic and demographic changes and the availability of raw materials and energy.

The challenge is to describe and understand the evolution of food systems (causes, consequences and mechanisms) in all their dimensions and in a wholly integrated manner, so that opportunities for improvement can be proposed that will favour the health and quality of life of populations while complying with the principles of sustainability and with economic and societal constraints. For this reason, this challenge first of all involves health issues; notably the control of health risks and the conditions necessary for a healthy diet that will contribute to limiting pathologies linked to over-nourishment or malnutrition. Secondly, it involves challenges linked to the impacts – and the dependence of systems – on the availability of raw materials, water and energy, and the social importance of access to food, characterised today by marked social inequalities. An approach throughout the food chain must be developed, linked to issues concerning production systems. In geographical terms, the scope of these studies will correspond to the food systems of developed countries; it may be informed by specific cases in emerging or developing countries, depending on the collaborations that are established.

"Sector" and "species" groups at INRA: optimum interfaces for expertise

The "Plant Sector Groups" and "Animal Species Committees" at INRA are discussion forums focused on the production sectors for plants (sugar beet, cereals, forage, fruits and vegetable, ornamental horticulture, oilseed and protein crops, etc.) and animals (cattle, sheep, goats, pigs, rabbits, poultry, fish and equines). They have permanent responsibilities for watch, the mapping of skills, synthesis and foresight, and thus contribute to dialogue between, and agreements with, different partners. Made up of INRA researchers and engineers, these multidisciplinary groups include plant or animal geneticists, physiologists and pathologists, agronomists or livestock specialists, technologists and economists, and can also invite personalities from outside INRA from technical institutes or professional organisations. Depending on the socioeconomic and scientific contexts, and by generating overviews of the results of research and innovations produced by INRA, they contribute to the orientation partnership and enhance the Institute's mission relative to transfer and dissemination.

One major project currently under way is trying to analyse the environmental impacts of agriculture in terms of the technical solutions designed or studied by INRA, so as to improve the environmental performance of farms without jeopardising their viability or that of their sectors. The combined and synergistic functioning of study groups in the plant and animal fields provides an opportunity to address questions at the interface of several subjects (mixed farming with livestock) and at larger scales (territorial dimensions). In the future, the role of these groups in the Institute's partnership policy will be reinforced so that they can establish links with research structures (GIS, RMT[26]) and capitalise on the discussions and findings of these groups (active library).

[26] RMT: Réseau Mixte Technologique (Joint Technology Network).

Skills and areas of expertise

The assets already acquired in terms of skills concern biological, economic and social approaches to dietary behaviour, but these are relatively distinct and do not cover large population samples. Numerous expert studies are available concerning the physiology of nutrition and the impacts of nutrients on the main bodily functions. However, study of the effects of the overall complexity of diet and foods (composition, structure and matrix) on these functions is still little developed. It is hoped that the metabolomics and metagenomics of the intestinal microbiota, alongside genomics approaches, will make a major contribution to progress in our understanding of the interactions between food and health. The science of foods, study of their properties related to the raw materials used, their engineering and that of the different processes involved, provide solid foundations for the study of food supply, but integrative approaches, notably involving nutritional physiology, are still limited. Few studies have been performed on the sustainability of food systems, but a foresight study carried out in collaboration with CIRAD is under way to identify high priority research questions. More generally, importance must be given to the combined mobilisation of disciplines that target different aspects of both food demand and food supply, insofar as these two dimensions interact with, and contribute to, each other.

High priority research questions

To identify and master the characteristics of foods and the vulnerability of their production methods in order to design products better suited to a changing environment.

A knowledge of foods, and preparation methods that favour not only their hedonic, health, nutritional and environmental properties but also the economic characteristics targeted, must contribute to improving their adequacy for food transitions. Clearly, this development concerns not only health issues but also access to food for populations suffering from inequalities. The priorities consist in:

- Specifically studying the impact of food matrices on the characteristics of foods and their physiological effects, particularly in the digestive tract.
- Developing eco-design methodologies and innovations that will improve both the flexibility and robustness of processes, thus ensuring better accessibility and adaptation to environmental constraints.
- Analysing and modelling the consequences of changes to the characteristics of raw materials and to the functioning of upstream markets (availability, modifications to inputs and their uses, price volatility, etc.) on the quality and availability of foods.

• Analysing company strategies, organisational methods, the localisation of activities and public policies to adapt the architecture of food systems to global change.

To study, understand and act on the determinants of food consumption.

Food consumption results from interactions between the demands of consumers and the supply of production systems. For this reason, any analysis of food transitions, their determinants and means of intervention, must focus simultaneously on these two facets and study their interactions. Priority must be given to:

• Better understanding the mechanisms and determinants of dietary changes. We must improve our understanding of consumer behaviour and practices (foods for weight-loss diets, uses, supplies, etc.) by focusing on and integrating social, economic, biological and psychological determinants.

• Elucidating how different behaviours develop, the impact of cultures, early learning and education, and the actions that can be taken to change these practices.

• Studying the conditions for the appropriation of changes to food characteristics.

• Analysing the sources of losses and waste linked to different practices, and how they can be reduced through behaviour and/or changes to supply.

• Specifically studying populations suffering from inequalities and ageing populations.

To analyse and understand the causal relationships between diet and health.

Environmental factors that impact human metabolism – and particularly diet – are major determinants for the health and quality of life of populations. However, the complexity of the relationships between diet and health requires new approaches that will involve the use of high-throughput and integrative methods alongside the traditional methods used by biology; one of the objectives is thus to determine, validate and combine novel biomarkers that are predictive of health, which forms part of the much broader field of predictive biology. To achieve this, it will be necessary to:

• Participate, coordinate and, if necessary, set up longitudinal cohort studies that include biological, socioeconomic and environmental characterisations in order to lay the foundations for an integrative approach.

• Develop biobanks and biomarkers that are relevant not only at the largest scale (population) but also at the smallest scale (finesse of biological genotyping).

• Assess the biological effects and health risks and benefits (toxicological, microbiological and nutritional) of consuming different foods, considered at different scales (restricted diets, foods, nutrients).

• Identify any transmissible metabolic effects and the socioeconomic determinants of dietary behaviour and health.

• Alongside events linked to over-nourishment (plethora), study malnourished populations and the impact of specific diets on target populations (vegetarian diets and other restrictive or exclusion diets).

• Finally, integrate advances in knowledge of the metagenome of the intestinal microbiota in the phenotyping of populations and seek to determine specific relationships with health.

Extensions to national and international collaborations

At a national level, longstanding collaborations with INSERM[27] will be reinforced by integrating these questions in the Multi-Agency Thematic Institute (ITMO)[28] on "Circulation, metabolism and nutrition" which is part of the AVIESAN Alliance. Covering these areas in the "Food and Nutrition" thematic area of the ALLEnvi Alliance will facilitate additional academic collaborations. Bilateral or even trilateral arrangements in three high priority areas, already under way with the WUR[29] (Netherlands) and IFR[30] (UK) will be pursued. But particular efforts will be made regarding European multi-institution developments linked to new instruments (JPI, KIC) and as an extension to our contribution to the "Food for Life" platform. As for partnerships with industry in France, these should increase thanks to the "Qualiment" portal[31] set up on the subject of the nutritional and sensory quality of foods, and should operate in a way similar to the Instituts CARNOT.

The consolidation and structuring of facilities (cohorts, platforms, CRNH[32] and clinical centres) in support of research work on the relationships between food and health will be favoured, linked to regional (campus), national (SNRI) and international dynamics. The European and international leadership of projects on the metagenomics of microbial systems in the digestive tract will be pursued.

Actions proposed for INRA

Two strategic programmes for INRA concern this challenge: (i) "The Metagenomics of Microbial Ecosystems" programme linked to the scientific project on predictive approaches for biology, and more directly (ii) "The Determinants and Effects of Dietary Behaviour" programme, scheduled for 2011. It should soon be possible to define a programme devoted to sustainable food systems, covering the food chain in a more general manner and based on the conclusions of the foresight study that is currently under way (duALIne[33]).

27 INSERM: Institut national de la santé et de la recherche médicale (French National Institute for Health and Medical Research)

28 ITMO: Instituts Thématiques Multi-Organismes (Multi-Agency Thematic Institutes).

29 WUR : Wageningen UR (University & Research Centre).

30 IFR : Institute of Food Research.

31 http://www.qualiment.fr/ .

32 CRNH: Centre de Recherches en Nutrition Humaine (Research Centre on Human Nutrition).

33 DuALIne: INRA-CIRAD workshop on sustainable food supply systems: "DUrabilité de l'ALImentation face à de Nouveaux Enjeux" (Sustainability of Food Supplies faced with New Challenges).

Short marketing channels: a growing demand

Convergences in the evolution of food consumption models throughout the world means it is possible to establish three dimensions (temporal, spatial and technological) that separate the consumer and foods. In parallel, "new" consumption behaviours are developing; although they remain marginal at a quantitative level, they constitute an emerging political approach in numerous countries, notably at the scale of regional government. These new food consumption behaviours take different forms: organically-farmed products, associations in support of the maintenance of peasant farming (AMAP[34]), or short marketing channels, both in France and following a similar trend in other countries. Their common characteristic is that according to different methods, and to different degrees, they reflect the need of at least part of the population to "resume responsibility" for their diet. These new food consumption behaviours correspond to new types of supply of agri-food products which, in most cases, reflect a desire to implement more environmentally-friendly practices and low-input systems, including with respect to transport and marketing. These new commercialisation and production modes question agricultural research at many levels, from the analysis of determinants for new consumption behaviours to the development of varieties and species that are adapted to these specifications. As an example, INRA is coordinating the European SOLIBAM research programme with 22 public and private sector partners, involving ten European countries, two African countries and an international research centre. The aim is to improve the performance of organic farming relative to yield and sustainability, crop diversity and product quality. More generally, these evolutions require multidisciplinary research efforts so that supply and demand aspects can be integrated in coherent analytical frameworks that will broaden the partial vision of research focused on a particular obstacle.

[34] AMAP : Association pour le maintien d'une agriculture paysanne (Association for the Maintenance of Peasant Farming)

3. Attenuation of the greenhouse effect and the adaptation of agriculture and forestry to climate change

Context and objectives

Agriculture contributes about 14% to global greenhouse gas (GG) emissions. Agriculture and forestry also play an important role in variations in carbon stocks in the soil and above-ground biomass. Between 1990 and 2005, French agricultural GG emissions fell by 11%, and the sinks related to land use markedly increased. The agriculture and forestry sectors made a more than proportional contribution to reducing total emissions in France, but we cannot be sure that this trend will continue. It is therefore necessary to reinforce research on reducing the contribution of these industries to the greenhouse effect.

The 2007 report by the IPCC[35] indicated a rise in temperatures that would remain moderate (at around 2°C) during the current century if global GG emissions were reduced between now and 2015, but this rise would exceed 4-5°C if current trends continued. This global warming would be accompanied by an increase in climate variability and in the number of extreme climatic events (heatwaves and summer droughts, intense winter rainfall and storms), the impacts of which are likely to be accentuated during the next few decades. A cascade of repercussions needs to be envisaged with respect to the effects of climate change on land use, water needs, soil quality, pest pressure, input and energy requirements, and on the origin, quality and typicality of products, analysing in particular the adaptations and retroactions needed with respect to GG emissions, natural resources and biodiversity, and finally the consequences this would have for food production.

Climate change will interact with other changes and pressures on agro-systems (increase in atmospheric CO_2 concentrations, atmospheric nitrogen deposition, the introduction of new species, changes to land use and agricultural practices, etc.). It is therefore necessary to study the combined effects of these different modifications. In addition, adaptive strategies will generate external costs (positive or negative) that must be clarified.

This scientific challenge can be broken down into four complementary objectives:

- knowledge of GG emissions and absorption by agriculture and forests,
- study of the potential to attenuate greenhouse gases and increase carbon storage in these sectors,
- analysis of the impacts of climate change and increased climatic variability,
- study of the adaptation of agriculture and man-made ecosystems to climate change.

Skills and areas of expertise

At present, research on climate change is mainly focused on the mechanisms of greenhouse gas emission or absorption and on the impacts of climate variability and change. By comparison, relatively few studies have addressed the issue of adaptation to climate change, the external costs induced and the costs and benefits of adaptation.

High priority research questions

To take up this challenge, efforts during the next ten years must concern a relatively broad range of research regarding:

- Knowledge of carbon and nitrogen cycles and the quantification of GG emissions and absorption by agriculture and forests;
- Potential for the attenuation of GG emissions and for increased carbon storage in soils and forests;
- The development of methods to estimate the GG balance and the carbon footprint of agricultural production systems;
- The development of strategies to manage the risks and opportunities associated with changes to climatic variability and extremes;
- Assessment of the regional impacts of climate change on agriculture and man-made ecosystems;
- An understanding and mastery of the effects of climate change on the dynamics of biodiversity (areas of distribution, genetic resources, interacting species, communities) and on the functioning of and services provided by ecosystems;
- Effects on the quality of agricultural products and their compatibility with criteria fixed downstream (technological aptitude);
- The adaptation of cultivated or domestic species, agricultural practices, production systems and sectors to modifications to the climate and to the composition of the atmosphere;
- The development of innovative technologies and/or systems and new sectors;
- Identification of the costs and benefits of measures to enable the adaptation and definition of collective modes of organisation in the face of climate change;
- The interactions and synergies that need to be found between attenuation of the greenhouse effect and adaptations to climate change.

Extensions to national and international collaborations

This scientific challenge constitutes an extension to the ANR Foresight Workshop "ADAGE[36]", led by INRA, and the thematic group on "Global and Climate Change" of the AllEnvi Alliance. The aim is to structure the research undertaken in the context of several ANR projects coordinated by INRA (notably projects supported by the ANR "Vulnerability, Environments, Climate and Societies" programme and a dozen or so European projects under FP7). The European Joint Programming Initiative on "Agriculture, Food Security and Climate Change", the secretariat of which is assured by INRA and the BBSRC, will amplify the actions undertaken in the context of this challenge.

At an international level, this scientific challenge will be reinforced by the Global Research Alliance regarding the attenuation of greenhouse gas emissions by agriculture (initiated by New Zealand and for which INRA is jointly leading a working group). Furthermore, links have been established with agricultural research institutions for development in the context of the "Challenge Programme on Agriculture and Food Security (CCAFS)", the future "Mega-Programme" on climate change backed by the CGIAR.

Actions proposed for INRA

In addition to the work carried out in the context of divisional strategic plans, a programme on "Adaptation to Climate Change by Agriculture and Forestry" will be starting in 2010. A project on the attenuation of greenhouse gas emissions and on carbon sequestration in the agriculture and forestry sectors will be entering its incubation phase.

35 IPPC: Intergovernmental Panel on Climate Change

36 ADaptation au changement climatique de l'AGriculture et des Écosystèmes anthropisés (Adaptation to Climate Change by Agriculture and Man-made Ecosystems)

4. Valorisation of biomass for chemicals and energy

Context and objectives

Both developed and emerging countries are confronted by four major and connected challenges: (*i*) to control, limit and reduce greenhouse gas emissions into the atmosphere; (*ii*) to develop products that will replace fossil hydrocarbons (and their derivatives), the reserves of which, for a given cost, are limited and will become increasingly rare; *(iii)* to contribute to the development of bio-agro-industry and new value chains, and *(iv)* to improve energy independence at the regional scale.

The concept of sustainable development means that it is possible to address the necessary changes to industrial systems that will meet our basic needs in terms of habitat, clothing, hygiene and transport, the expression of which depends on the level of development. Renewable carbon is the recurrent theme of this challenge, and its changes in chemical state form an important part of a circular economy at both the global and regional scales. The globalisation of trade means that we must consider not only all potential sources of biomass but also the dissemination of technologies.

The scientific challenge is to develop the **green chemistry of renewable carbon** which must be articulated with complementary and competing natures of different land uses (agricultural and forest land) and the need to preserve ecological equilibriums. The issue of bioenergies and green chemistry goes far beyond simply increasing the volumes of biomass available for use by existing technologies, the sustainability of which still needs to be proven.

Skills and areas of expertise

Current skills cover the fields of green and white biotechnologies, structural biology, mixed production systems (dual purpose: food and green chemistry) and those dedicated to biorefining and more generally to process engineering. Activities in this area remain insufficiently developed when set against the opportunities opened up by both the recent findings of biology and the uses that are now technically possible for products derived from renewable carbon. Finally, these efforts do not sufficiently integrate the knowledge generated by the different disciplines concerned – which can range from the biological sciences to social sciences – to obtain a clearer understanding of these new systems, and to identify interrelations with food and energy systems. A particular problem is the need to take account of new temporal and spatial scales in order to meet the demands of sustainability and – because of the globalisation of trade – to meet local needs in the context of carbon cycles. It will therefore be necessary to go beyond assessing the effects of technological systems on their specific characteristics to consider the consequences they are likely to have in the more or less long term with respect to other objects or systems.

High priority research questions

The first area concerns the concepts and tools of green and white biotechnologies, in order to design high-performance and specific methods and technologies for use in a sustainable context. The priorities are:

- to generate more knowledge on biosynthesis pathways, their regulation, associated physicochemical mechanisms and metabolism (transport, targeting and storage), particularly for storage substances (oils, sugars) and lignocellulosic cell walls, including morphological aspects, and more data on the effects that will result regarding the major physiological functions of plant growth and development;
- to understand the factors that limit biomass and lipid yields, which goes back to the general issue of integrative biology;
- to develop tools for high-throughput structural and functional phenotyping; these will be essential if we are to benefit from the opportunities offered by advances in genomics;
- for micro-organisms, to develop synthetic biology and nanobiotechnologies as exploratory fields of interest.
- It is in this area that new approaches which call upon high-throughput methodologies and linked to the "Predictive approaches for biology" project, are anticipated.

The second area concerns the study of plant species adapted to the production of biomass on all agricultural land, including that currently neglected (derelict land, etc.). The target species for temperate countries are straw cereals, oilseeds (rapeseed, linseed, sunflower), ligneous plants (poplar, Robinia, pine, eucalyptus). These studies need to be broadened to phytoremediation, which has the dual advantage of increasing potential agricultural land areas and solving local pollution problems. The priorities are:

- to implement holistic approaches to all plant species and transformation processes in order to design more sustainable biorefineries that can use plants with optimum qualities for processing as well as agricultural yields. In this context, it is important to optimise the performance of complementary biotechnological (enzymes and fermentation) and physical and chemical (fractionation agents) processes in order to meet the need for products, molecules and bioenergy sources. The breaking down of plant organs by biorefineries needs to be reviewed in order to preserve plant structures and the functionalities of bioproducts at the correct scale and facilitate their subsequent valorisation for technical uses;
- to transpose the knowledge acquired on the metabolism of plant minerals and lipids to other biological systems of interest (micro-algae, cyanobacteria);
- to better understand species that can grow on derelict land and be used for food purposes;
- to develop databases that constitute an inventory of plants (cultivated or not) that can produce molecules (precursors) of interest, with systematic phenotyping of these plants and an international structure for biological resources that can be mobilised as a function of local conditions.

The third area focuses on agricultural and forest production systems and technological and use systems in the context of a circular economy. Energy and chemical production systems involve different steps that maintain multiple relationships between each other and with other sectors (notably food) and with the environment: no independent, sectorial approach is possible, even for second generation biofuels. The consequence is that these complex systems cannot be optimised by simply adding operations that have been separately optimised. The innovations expected are firstly of an organisational nature, and will be based on tools to analyse the impact of innovations before they are introduced. The priorities are:

- to ensure that the needs of the chemicals industry correspond to the resources offered by biomolecules, based on structure versus use function relationships, assembled in the framework of a knowledge management tool initiated by the ANR foresight workshop VégA[37],
- to constantly update **foresight**, initiated by Véga, in order to identify both **future systems at equilibrium** and the **transitions** that will enable this achievement;
- to identify and rank critical points, and notably those which concern the technical mastery of production, control of the sector, adaptation to the environment and spaces, environmental services associated with the sector and the different environ-

mental impacts that may result: soil (organic matter, fertility, erosion), water, greenhouse gases, biodiversity, resources necessary (nitrogen, energy, etc.) and competitiveness;

• to develop methodologies for eco-design and ensure that the assessment methods used (multicriteria tools, life cycle analyses) are adapted to specific or mixed systems, to contribute to these new sectors by extending the agricultural land available for biomass production, to ensure the diversification of landscape mosaics, and to design governance methods and public policies in support of integrating these systems in regionalised sectors (associations, mosaics). Criteria for the labelling of products will be proposed in order to contribute to developing the regulations that will underlie a bio-economy;

• to analyse company strategies, including with respect to intellectual property, organisational methods, the location of activities and public policies to adapt the architecture of energy and chemicals systems in harmony with food systems and ecological equilibriums. It is necessary to take account of international scenarios to ensure the representativeness of these studies, combining issues of technical and economic feasibility, ecological sustainability and social acceptability. It will thus be possible to understand the effect of changes to technical innovations on the "economic machine", and how economic regulation might hamper the dissemination of innovations;

• to ensure the hybrid modelling of sustainable sectors in an open platform, combining: *(i)* the insertion of bioproducts in current energy and chemicals production systems, with the recycling of products (plastics) and the valorisation of waste; *(ii)* economic parameters such as the availability of capital, levels of domestic demand and relative pricing systems; *(iii)* individual and collective behaviour with respect to consumption styles, urban living and territorial development, without neglecting the opinions of citizens, and *(iv)* the nature of systems at the local, national and global scales, the availability of land, degrees of autonomy and interdependence and the margins for manoeuvre allowed by the inertia of current systems.

Extensions to national and international collaborations

At the national level, integration of these questions in the ANCRE and AllEnvi Alliances provides an opportunity to combine strong and complementary skills with those available within INRA.

Partnerships with industry will be developed thanks to the "Bioénergies, biomolécules et biomatériaux végétaux du CArbone Renouvelables (3Bcar) (Bioenergies, Biomolecules and Plant Biomaterials for Renewable Carbon) portal, operation of which will be based on that of the Instituts Carnot, with the objective of accreditation in the short term.

This corpus of research will be based on selective research efforts in the disciplines present at INRA, as well as involving close collaborations with other French higher education and research institutions (CNRS, CIRAD, IFP[38], INSAT[39], AgroParisTech, Montpellier SupAgro, etc.). As a corollary, clusters with high international visibility will be proposed in response to different calls for proposals by the Investments for the Future initiative.

At the international level, CIRAD should be a strong partner both regarding an understanding of the equilibriums to be sought between developed and emerging countries, and to extend knowledge to sugar cane, sorghum, oil palm and cotton in tropical regions.

Actions proposed for INRA

Two areas of study to be targeted by different INRA divisions concern this challenge: (i) synthetic biology and nanobiotechnologies and (ii) the sustainability of systems based on renewable carbon.

Regarding the Investments for the Future programme, two proposals on green and white biotechnologies will be developed jointly in the context of broadened and renewed partnerships, and participation is envisaged in Institutes of Excellence on renewable energy. In recognition of the need for **technological research** as described in the Juppé-Rocard report, partnerships with industry need to be based on **pilots** and **demonstrators**. These will undoubtedly raise research questions that require study, and will enable the restriction or validation of models developed at the scale of the laboratory, field or pilot. Because of the relative importance of the findings specific to this theme, and in light of their strong prospects for development, investment in Research-Training-Transfer will be an option to be explored.

37 ARP VégA: "Quels Végétaux et systèmes de production durables pour la biomasse dans l'Avenir ?" (Which plants and sustainable production systems for biomass in the future?)

38 IFP (French Institute for Petroleum): IFP Energies nouvelles (new energies)

39 INSAT : Institut National des Sciences Appliquées et de Technologie (National Institute for Applied Sciences and Technologies)

5. Global food security and global change

Context and objectives

In the context of the global challenges of the 21st century, recalled briefly at the beginning of this document, world agricultural systems will be required to produce more and in other ways, and not only other products (marketable goods and services to ecosystems). Food systems will have to enable more consumption (where undernutrition prevails) and of better quality (in cases of malnutrition). For this purpose, major changes from the past are necessary in terms of research and innovation, individual consumer behaviour, the strategies of private enterprises and government policies.

This growing demand in an uncertain context will also require INRA to intensify its efforts in terms of anticipation, understanding and providing information for public decision-makers, economic actors and civilian society: the pursuit of foresight and collective expertise studies, the development of targeted studies similar to "Ecophyto R&D", the renewal of dialogue with stakeholders on different research themes and a review of policies on the dissemination and communication of the results of its work to public and private decision-makers and the general public.

This situation also means that the research carried out under the two scientific projects and the four scientific challenges must be placed in the systemic and global context of food, agricultural, energy, environmental and social challenges at the scale of our planet. It will also lead to the proposal of a fifth challenge; i.e. the development of dedicated research with the general aim of generating certified knowledge on global food and nutritional security assessed in all its different dimensions and in relation to other planetary challenges.

Skills and areas of expertise

INRA benefits from numerous and reputed skills in this disciplinary area which must be mobilised at the service of global food security by providing scientific expertise in the three areas of agriculture, food and nutrition and the environment, and at their interfaces, and by carrying out systemic and multidisciplinary research on the closely intertwined issues of agriculture and different types of land use, diet and lifestyles, energy and energy consumption modes, and finally the environment and the management of natural resources. However, it is clear that the Institute will not be able to achieve these ambitions on its own. Collaboration with other disciplines that are not present in-house; for example with climate or energy sciences, geography or urban planning sciences, and with other national and international institutions, is essential. Nevertheless, in view of INRA's targeted missions, the aim is not to develop agricultural research for development, or more specifically for eponymous countries.

High priority research questions

- The first priority is to endow the Institute, its partners within Agreenium and more generally the French scientific community with an ability to understand, analyse and model the question of global food and nutritional security in connection with other planetary challenges. As well as pursuing the CIRAD-INRA foresight project "Agrimonde" on future food and agricultural systems for the world at the horizon of 2050, research efforts will focus in particular on: (i) coupling biophysical, biotechnical and economic models that will necessarily integrate aspects external to the sphere of food, agriculture and forestry alone (climate change, supplies of and demands for different types of energy, urbanisation dynamics, etc.), (ii) the geographical nesting of models developed at different spatial scales, (iii) the integration of innovation, continuity and/or change dynamics, (iv) taking account of uncertainties, risks and the behaviours of actors faced with risk, and (v) the explicit modelling of public policies. It is within this framework that it will be possible to adopt a coherent approach to questions such as: (a) the breakdown of land between food and non-food crops, grasslands, forests, wet zones and urban areas, (b) the intensification and extensification of agricultural and forestry practices, (c) the role of animal production, (d) changes to food systems and consumption patterns, (e) changes to the energy and/or chemicals contexts, (f) losses and waste at different stages of production, processing, distribution and consumption, and (g) the international trade of agricultural, agri-industrial and agri-food products. These approaches will involve both biotechnical sciences and human and social sciences. They will also require methodological developments in informatics, mathematics and statistics, together with investments and collaborations in order to acquire the necessary data and information systems.

- The second research priority concerns indicators for sustainable development and methods for impact assessment. Indeed, any analysis of future food and agricultural systems at a global level in the three dimensions of sustainability will require knowledge and an explicit representation of the physical, biological, economic and social processes to which research developed in the context of the aforementioned projects and challenges can contribute. This also supposes the availability of robust and reliable methodologies to assess the impacts of processes and their evolutions, once again in three dimensions: economic, social and environmental. For this purpose, research efforts will focus in particular on: (i) indicators for sustainable development, (ii) multicriteria analyses (notably their aspects relative to the aggregation, weighting and potential incompatibilities of different criteria), and (iii) methods to assess the impacts of physical, biological, social and/or economic processes (with particular attention to the methodology used for life cycle analyses (LCA) in order to exceed certain limits).

- The third research priority aims to analyse the territorial consequences of global changes and, inversely, to study the dynamics of territorial development and their interactions with global evolutions. Particular attention will be paid to: (i) the impacts of global changes on the economic performance of agricultural and forestry activities, on upstream and downstream industries, on the prospects for the diversification of income resources for farms (multiple activities by farming and forestry households, demand for local products, supply of non-food goods, supply of ecosystem services, etc.), on evolutions affecting the farming profession and the demands of permanent or temporary residents in different regions (local agricultural products, public and private services, etc.); (ii) the roles of agriculture, forestry and the agri-food industry in the dynamics of territorial and regional development in the context of new town-country relationships, and (iii) the organisational and consultation processes necessary for actors present in the same territory.

Extensions to national and international collaborations

INRA will not alone be able to take up the challenges of world food security and global change. As well as CIRAD and other partners in Agreenium, academic collaborations with specialists in the sciences of energy, climate, geography or urbanism will need to be reinforced and/or developed[40]. At the European and international levels, work will benefit from the participation of the Institute (in its capacity as a founder member of the French node) in the Knowledge and Innovation Community on climate (KIC Climat) set up in early 2010, and its role as a leader in the Joint Programming Initiative on "Agriculture, Food Security and Climate Change". The efforts and research organised in response to the challenge of food security will also be ensured in collaboration with different institutional partners, and notably the French Ministries for Agriculture and Ecology, ADEME[41], ONEMA[42], AFD[43] and OIE[44]: several institutional partners have already declared their interest in setting up a platform for research, studies and expertise on the issue of land use linked to the development of biofuels and their potential impact, greenhouse gas emissions by agriculture and forests, or the role of animal production systems and related questions raised by certain groups in view of the rarity of available land.

Actions proposed for INRA

In addition to extending the life of the Agrimonde ® foresight platform, improving and developing quantitative tools that can be mobilised in this context and broadening the circle of interested stakeholders in the form of an extended "Partners' Club", this scientific challenge will be the subject of scientific debate on the general issue of land (availability, potential competition between uses for food or non-food production or for environmental purposes, the impacts of global change on land availability and use, tax policies and land prices, etc.), with the possible initiation of a programme at the end of 2011. Furthermore, the third part of the "Pour et sur le développement régional" project (For and On Regional Development", PSDR III), developed in partnership with CEMAGREF, CIRAD and the Regional Councils of ten French administrative regions, will be completed at the end of 2011; it will then be necessary to decide on the future of this programme in the context of territorial development according to a dialectic ranging from the local to the global, and vice versa.

40 Such collaborations are starting to be developed and structured; for example, in the context of the dynamic around the Plateau de Saclay Campus.

41 ADEME : Agence de l'Environnement et de la Maîtrise de l'Energie (French Environment and Energy Management Agency)

42 ONEMA : Office national de l'eau et des milieux aquatiques (French National Agency for Water and Aquatic Environments)

43 AFD : Agence française de développement (French Development Agency).

44 OIE: Organisation mondiale de la santé animale (World Organisation for Animal Health)

A dearth of land?

Does Earth lack land? The leap in agricultural and food prices seen during 2007 and early 2008, and the hunger riots that resulted, caused a resurgence of Malthusian fears as to our planet's inability to meet the food needs of the world, today and even more tomorrow, when in 2050 there will be more than 9 billion inhabitants. These fears have been reinforced by the concomitant development of non-food uses for agricultural goods (particularly to produce biofuels) and the need to reform agricultural production systems; these issues raise questions as to our ability to increase or (even just maintain yields) in a context of greater respect for natural resources.

Land is available to grow crops without encroaching on forests and protected areas, even if account is taken of land lost because of rising human occupation. However, these land "reserves" are limited and very unevenly distributed: almost absent in South Asia, the Near and Middle East and North Africa, they are much more substantial in Latin America (Argentina, Bolivia, Brazil and Colombia) and Sub-Saharan Africa (Angola, Democratic Republic of the Congo and Sudan). But in these regions, the efficient use of land for cropping comes up against several obstacles linked to their lower intrinsic fertility, a lack of water, a difficult topography (sharp slopes, distant from habitations), problematic logistics, the deficiencies of local laws on property or exploitation and political crises or instabilities.*

So the outlook is not catastrophic, but vigilance is essential. Even if Earth does not lack land, we must not forget that it remains a rare resource. The question of competition between different uses for land is an economic notion. Ultimately, it is the prospect of a positive outcome that determines the cultivation of a hectare, and it is a comparison of the marginal profitability of different markets that defines the allocation of land between its possible uses: agricultural food and non-food production, forests, recreational or urban spaces, etc. For this reason, the issue of "land use" lies at the heart of the priorities in this orientation document, notably in the context of the challenge relative to global food security.

** This artificialisation of land is modest at a planetary scale: it is more significant in developed countries such as France and more generally the Member States of the European Union (EU), notably because it affects fertile land at the periphery of urban zones.*