Emmanuel Torquebiau *Editor*

Climate Change and Agriculture Worldwide

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LA RECHERCHE AGRONOMIQUE POUR LE DÉVELOPPEMENT

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Climate Change and Agriculture Worldwide

Emmanuel Torquebiau
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Foreword

What answer can be given to all those asking questions concerning the impact of climate change on agriculture and food security? Or to those wondering what to do, or how to help people who will be (or already are!) affected by climate change? These questions are especially vital in developing countries, where major changes in climatic conditions are expected and will affect many populations, often the poorest. Not many books deal with climate change in these parts of the world, so this one comes at a very timely moment and probes a wide range of climate change-related questions regarding agriculture worldwide.

Agriculture is both subject to and responsible for climate change, while also being part of the solution. Agricultural practices therefore have to be adapted while also mitigating greenhouse gas emissions and contributing to carbon storage. Is that possible and realistic? Ongoing negotiations in preparation for the twenty-first Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 21) in Paris in December 2015 are hinged on the debate concerning the weight that should be given to these two dimensions—adaptation and mitigation. This issue is crucial in developing countries because COP 21 aspires to seal a bold voluntary agreement on climate change that will be applicable to all countries. Developing countries are, however, reluctant to commit themselves on mitigation since they do not feel historically responsible for it. The analyses outlined in the present book are essential contributions to this debate. The authors showcase the latest ongoing research and broaden the scientific scope for the future, thus offering readers a gateway to understanding the issues involved in this adaptation–mitigation debate, in turn providing them with objective elements for decision-making.

The detailed presentation of the climate-smart agriculture concept—the equation that aims to streamline the adaptation, mitigation and food security dimensions—adds further depth to the debate. The examples given illustrate that the three terms of this equation are sometimes balanced, but not always, and that choices have to be made. Not surprisingly, climate change-driven modifications are a major concern and this book will certainly facilitate decision-making to address them. These choices apply to agriculture and forestry field practices, as well as production chains, consumption habits, public policies and economic instruments. All of these parameters will ultimately help clarify the yet to be secured place that agriculture should occupy in international climate negotiations, which is essential not only for the success of these negotiations but also for the equilibrium of tomorrow's world.

The authors highlight that solutions exist and propose plenty of options. We all need to change our habits. This is possible if we heed and apply the messages put forward in this book.

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France's Special Representative for the 2015 Paris Climate Conference
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Preface

This book reviews the linkages between climate change and agriculture in developing countries, including livestock farming and forestry, on the basis of work of the French Agricultural Research Centre for International Development (CIRAD) and the French Development Agency (AFD) and partners. We wish to show that we as researchers—and our partner farmers—have to modify many of our habits in response to climate change. The authors broaden the horizons for future scientific research while referring to the latest research on the issue. Our goal is also to help orient research towards addressing future knowledge production challenges. Notwithstanding this goal, the book targets researchers working on issues other than those addressed in different chapters, science and development officers in various agricultural and forestry sectors in developing countries, and also students and the informed public. Our hope is that the scientific content presented in this book will be readily understandable for all interested readers.

The analyses are focused on the climate change context, as outlined in documents of the IPCC[1] Fifth Assessment Report, which was published (in parts) between September 2013 and October 2014. IPCC was created to provide the world with a clear scientific view on the current state of knowledge on climate change and its potential environmental and socio-economic impacts on the basis of the latest scientific, technical and socio-economic literature. The published reports are focused on the physical science basis of climate change (Working Group I), impacts, adaptation and vulnerability (Working Group II) and mitigation of climate change (Working Group III).

The main concepts frequently mentioned in this book are defined below (from IPCC):

- Climate change: a change in the state of the climate that can be identified (e.g. by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer;

[1]Intergovernmental Panel on Climate Change, http://www.ipcc.ch/.

- Risk: the potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values;
- Adaptation: the process of adjustment to actual or expected climate and its effects;
- Mitigation: a human intervention to reduce the sources or enhance the sinks of greenhouse gases;
- Resilience: the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation.

The major climate change trends are covered in Chap. 1. The book is then structured in four main parts that link the common thread of issues explored. First, examples of responses to climate stress are presented, followed, in the second part, by examples of practices modified by climate change. The third part covers approaches for stimulating necessary change, while the book concludes in the last part with a critical review of the main current debates and their research implications. The broad scope of adaptation to climate change is thus covered mainly in the first part devoted to coping with stress. After outlining the risk concept, the stresses studied are successively heat, salinity, drought, pests and diseases. An analysis of cropping systems shows that yet unknown combinations of different stresses sometimes have to be taken into account. In the second part, which addresses the pursuit of novel practices and innovations, adaptation and mitigation share the stage—sometimes even in the same practice, such as agroforestry. This includes both experiments and farmers' innovations. In the third part, we seek ways to promote necessary changes. This includes services to provide, or tools required to induce, support and remunerate changes in practices, while also concerning public policies and regulations, including those related to agricultural product demand.

The themes selected are the subject of work carried out by CIRAD and AFD teams. They were selected for being crucial with regard to the climate change issue and when recent and original analyses were available. Some questions that do not meet these three criteria are not addressed in the book, for instance, bioenergy, forest climate policy or economic instruments for the mitigation of emissions. We focused on examples of technical options, along with political and economic instruments enabling trade-offs leading to these options or that could encourage consumers and farmers to make the proper choices.

The contributions presented in this book are undoubtedly just a mere drop in the ocean of issues at hand and for which farmers in developing countries will have to cope. We nevertheless hope they will provide fuel for these debates.

Acknowledgments

The global dimension of the climate change issue and the interdisciplinary nature of this book called for a broad range of contributions and critical viewpoints. We tried to meet this requirement by appealing to authors from complementary (yet sometimes quite distant) disciplines. We also called upon just as diverse a range of reviewers—each chapter was reviewed by two specialists of the topic. The partnership between CIRAD and AFD also gave rise to complementary viewpoints from the research and development communities. We would like to thank all of the authors (see list at the end of the book), as well as the reviewers, members of the Steering Committee and the Editorial Board, not to mention of course the patient support of the editing and translating teams. We are highly grateful to all of these collaborators.

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Research Unit Acronyms

AGAP	Genetic Improvement and Adaptation of Mediterranean and Tropical Plants
AGIRS	Animal and Integrated Risk Management
AIDA	Agro-ecology and Sustainable Intensification of Annual Crops
ARTDEV	Actors, Resources and Territories in Development
BIOS	Biological Systems Department
BioWooEB	Biomass, Wood, Energy, Bioproducts
BSEF	Tropical Forest Goods and Ecosystem Services
CIRED	Centre for International Research on Environment and Development
CMAEE	Emerging and Exotic Animal Disease Control
DIADE	Crop Diversity, Adaptation and Development
ECO&SOLS	Functional Ecology & Bio-geochemistry of Soils & Agro-ecosystems
ECOFOG	Ecology of the Forests of French Guiana
EEF	Forest Ecology and Ecophysiology
ES	Environment and Society Department
G-EAU	Water Resource Management, Actors and Uses
HORTSYS	Agroecological Functioning and Performances of Horticultural Systems
IDDRI	Institute for Sustainable Development and International Relations
Innovation	Innovation and Development in Agriculture and the Food Sector
IPME	Plant–Microorganism–Environment Interactions
ISEM	Montpellier Institute of Evolutionary Sciences
LAE	Laboratory Agronomy and Environment
MOISA	Markets, Organizations, Institutions and Stakeholder Strategies

Pests and Diseases	Risk Analysis and Control of Pests and Diseases
QUALISUD	Integrated Approach to Food Quality
Recycling and Risk	Environmental Risk Related to Organic Waste Recycling
SELMET	Mediterranean and Tropical Livestock Systems
SYSTEM	Tropical and Mediterranean Cropping System Functioning and Management
Tree Crop-Based Systems	Performance of Tree Crop-Based Systems

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Chapter 1
How Climate Change Reshuffles the Cards for Agriculture

Emmanuel Torquebiau, José Tissier and Jean-Yves Grosclaude

Nothing is permanent but change
Heraclitus

Abstract Agriculture is affected by but also contributes to climate change. Agricultural risk may be local, impacting crops, or global, impacting food security. The agricultural sector accounts for 24 % of greenhouse gas emissions. Adaptation to and mitigation of climate change are two different responses that may be reconciled in climate-smart agriculture proposals. Developing countries will have more difficulty in adapting, as the changes will have a greater impact there than in developed countries. By around 2050, the majority of African countries will experience heretofore unknown climatic conditions on over half of their arable land. Appropriate public policies, institutions and funding are needed to increase the resilience and efficiency of agricultural production systems and implement the necessary changes.

1.1 Background

Habits are hard to break. We consciously or unconsciously prefer what we know and are used to doing. The climate change the planet has experienced in recent years still has some surprises in store that will have to be dealt with. Though we know broadly what to expect, the effects are difficult to accurately predict, especially at the local level. It is not enough to say that it will be warmer. Changes in the amount of greenhouse gas (GHG) levels also affect seasonality, rainfall, biodiversity, sea level and glacier and ocean dynamics, and give rise to a complex web of interactions.

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Agriculture—no doubt the human activity most dependent on the climate—will be particularly affected. Climate change increases the frequency and magnitude of the climate hazards farmers have faced for generations. Agriculture is impacted by climate change, while also contributing to it. At the interface between climate change adaptation and mitigation, agriculture is also a part of the solution. It is the only human activity that can not only reduce greenhouse gas emissions but also sequester carbon in soil and biomass. Moreover, it can spur conservation in other sectors (energy, transport, construction) by generating products derived from agricultural or forest biomass to replace highly polluting conventional products. Agriculture will have to evolve to adapt to climate change and biodiversity loss, while also mitigating their impacts, in order to cope with the significant economic, social and environmental challenges of the 21st century and sustainably meet the needs of a predominantly urban population of approximately nine billion by 2050. We have no option but to change our habits, in this sector more than any other.

1.2 Main Thrusts of the Latest IPCC Report and the Agricultural Implications

The latest IPCC Report (IPCC 2014a) confirmed there is no possible doubt that the atmosphere and oceans are warming, snow and ice cover is decreasing, and sea levels and GHG concentrations are rising because of human activity. From 2000 to 2010, GHG emissions increased by 2.2 % per year, compared to 1.3 % between 1970 and 2000. The carbon dioxide (CO_2) concentration has risen by 40 % since pre-industrial times, mainly because of emissions from fossil fuels (energy, industry, transport) and from agriculture, forestry and land-use changes (about 24 %; Fig. 1.1).

Each of the last three decades has been successively warmer than any previous decade since 1850, and if the same trend continues, the global average land temperature may increase by between 3.7 and 4.8 °C in the course of the 21st century, whereas it rose only by around 0.85 °C from 1880 to 2012. To keep the temperature from rising more than 2 °C, GHG emissions must be reduced by 40 to 70 % by 2050 relative to 2010 levels, then to zero by 2100. In that scenario, the most optimistic one foreseen by IPCC (representative concentration pathway [RCP] 2.6; Fig. 1.2), the CO_2 concentration would reach 421 parts per million (ppm) in 2100, as compared to about 400 ppm today, with a rise in sea level of 26 to 55 cm (as compared to 19 cm from 1901 to 2010). No matter how things unfold, many changes are now inevitable. They will affect society as a whole and involve physical systems (rivers, glaciers, coastlines, etc.), natural ecosystems (biodiversity) and human activities (food production, wellbeing, health, economy, etc.). In addition, there is likely to be an increase in the variability of extreme weather events.

Many technical, institutional, regulatory and behavioural options are available to meet climate change challenges, but all are predicated on a change in our habits, and the longer we wait the costlier the response. The options are twofold, comprising

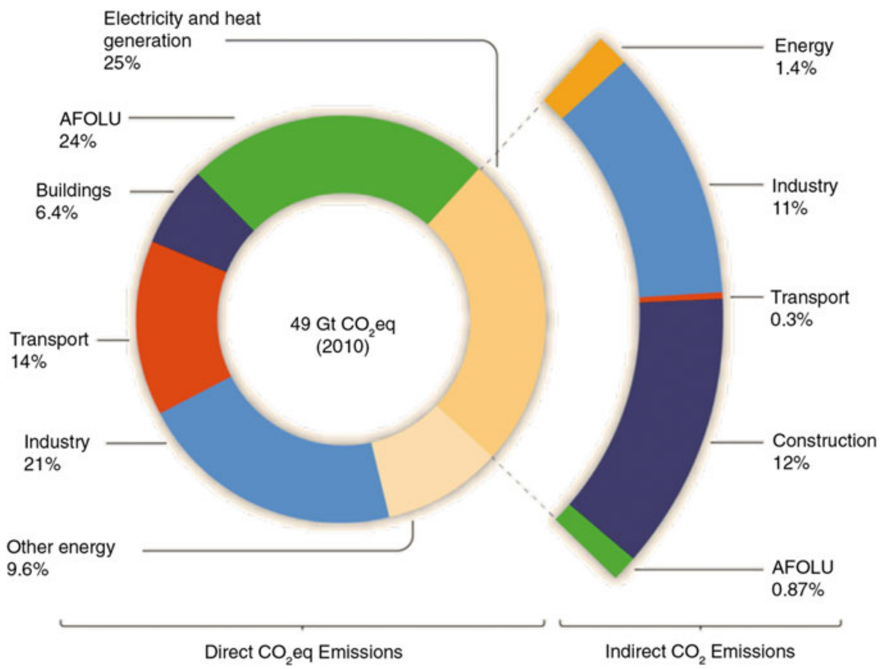

Fig. 1.1 Total anthropogenic greenhouse gas emissions (Gt CO_2-eq/year) by economic sector. *AFOLU* = agriculture, forestry and other land use (*Source* IPCC 2014a)

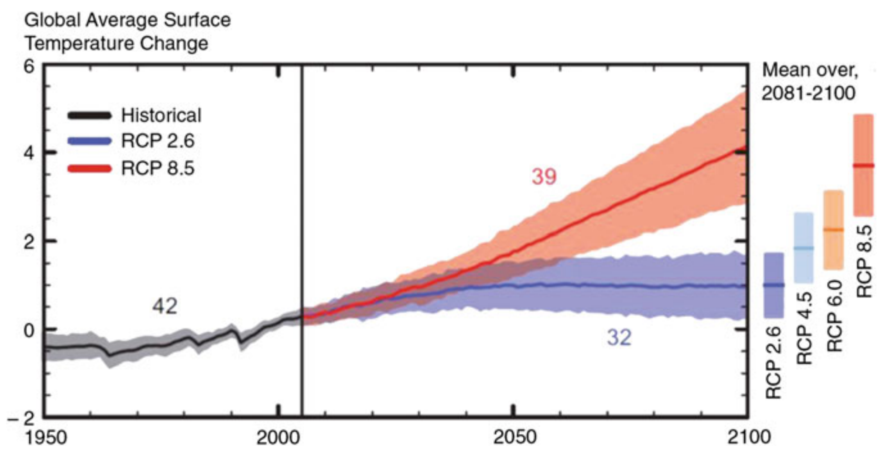

Fig. 1.2 Multi-model simulated time series from 1950 to 2100 for change in global annual mean surface temperature (°C) relative to 1986–2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The mean and associated uncertainties averaged over 2081–2100 are given for all RCP scenarios as coloured vertical bars. The number of models used to calculate the multi-model mean is indicated (IPCC 2013)

strategies for adaptation to climate change (changes in natural or human systems) on the one hand, and efforts to mitigate climate change (human intervention to reduce GHG sources or increase 'sinks') on the other hand.

Climate change has an impact on human activities by increasing risks that are dependent on three factors: exposure of an activity (e.g. its location in an area of increased drought), vulnerability of the population concerned (likelihood of being affected by the risk), and damage induced by exposure to climate hazards (for humans or the environment) on account of a particular weather event (Fig. 1.3). All three factors need to be considered in adapting to climate change, so adaptation is necessarily site-specific and no solution can be assumed to be workable in all circumstances. Complementarity between the different levels of society (from individuals to governments and international organizations) is essential for successful coping strategies, which are presently being applied in most countries. Those strategies should primarily target vulnerability and exposure to risk so as to help boost the resilience of affected human groups. Various economic mechanisms are needed to stimulate adaptation through incentives and impact forecasts.

In agriculture, the risk may be local, such as when seasonal rains fail, but global food security is an especially serious risk, since needs from the agricultural sector are expected to increase by 70–100 % by 2050 (Soussana 2012). Climate risk is of course combined with other factors, such as increased land-use, deforestation, degradation of some soils, biodiversity erosion and groundwater availability.

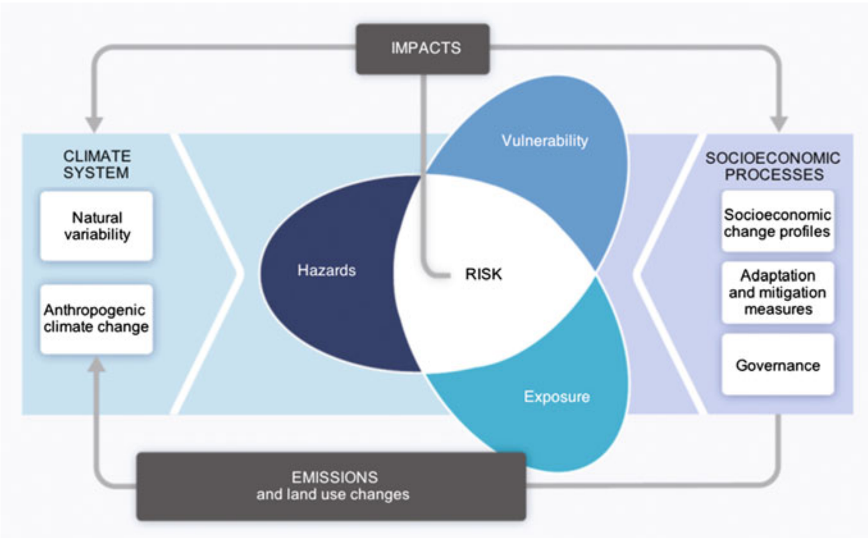

Fig. 1.3 Core concepts addressed in the contribution of Working Group II to the Fifth Assessment Report. Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems. Changes in both the climate system (left) and socioeconomic processes including adaptation and mitigation (right) are drivers of hazards, exposure, and vulnerability (IPCC 2014b)

The climate change issue as it affects agriculture is also analysed in terms of 'demand', namely whatever can be altered to reduce climate risk. Diet, foodstuff transport, agricultural product price regulation, management of pre- or post-harvest crop losses, and waste management are all factors to be taken into account.

1.2.1 *Adaptation and Agriculture*

Adaptation may involve lessening undesirable effects or taking advantage of favourable opportunities, but in agriculture, IPCC results show that negative impacts are much more common than positive ones. Lower wheat, maize and rice yields are expected if temperatures increase by 2 °C or more, thus impacting food access and use, as well as price stability. Lessening of harmful effects is a strategy very familiar to farmers—anticipating climate hazards, for example through crop diversification or changing planting dates. However, a change of strategy is necessary when the hazard occurs frequently. Then it is essential to fundamentally alter the crop management system or cultivation strategy or to start over somewhere else. Resourcefulness is needed, such as switching to a crop that is better adapted to the new conditions or moving to higher elevations to grow crops, weather permitting.

Agriculture that is adapted to climate change is said to be 'resilient', which means it allows production to continue despite unexpected disruptions. Diversity is one essential element of resilience. A farm on which monocropping is practised is less resilient than a farm where intercropping or mixed cropping prevails. A strategy that takes local biodiversity (hedges, grass strips, landscape mosaics, etc.) and agrobiodiversity (beneficial associated species, soil flora and fauna, etc.) into account enhances agricultural resilience substantially (Hainzelin 2013). Another resilience-fostering strategy is to select crops tailored to their environment, rather than modify the environment, for example through irrigation and inputs (e.g. pesticide treatments to compensate for poor plant health). Risk management can also involve insurance mechanisms, but not all farmers can afford insurance and the situation may soon become unmanageable should the targeted risk insured become widespread. What is needed, of course, is a substantial, internationally coordinated research effort—to provide farmers with plant varieties, livestock breeds and crop management systems that will be adapted to tomorrow's climate, while developing the necessary support in the form of public policy incentives or effective weather monitoring systems.

1.2.2 *Mitigation and Agriculture*

The land sector (AFOLU, see Fig. 1.1) includes direct emissions, emissions related to land use change to meet the needs of agriculture and livestock farming, and indirect emissions conventionally attributed to other sectors, such as agricultural

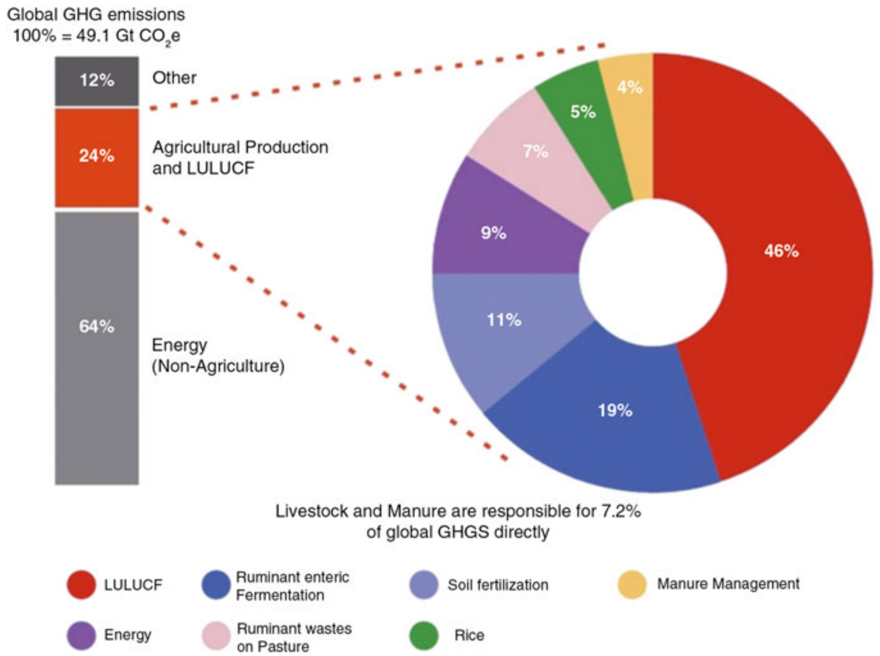

Fig. 1.4 Overall agriculture, forestry and other land use (*AFOLU*) emissions by component, 2010 (WRI 2014). *LULUCF* = land use, land use change and forestry

produce transport. GHG emissions from agriculture are increasing at a slower rate than those from other human activities (FAO 2014). Under the baseline IPCC scenario (no mitigation), while agricultural emissions other than CO_2 are increasing, net CO_2 emissions in the land sector are decreasing due to a reduction in deforestation rates and increased reforestation, but there is greater uncertainty regarding emissions in this sector than in others. The land sector should hence not be overlooked, as it accounts for almost a quarter of all emissions. These are derived from deforestation as well as agricultural emissions arising from livestock farming and soil and nutrient management. This sector is unique in that it is a domain where climate change mitigation could come via an increase in GHG capture ('carbon sinks', through carbon storage in biomass and soil) and a reduction in emissions ('carbon sources', through changes in land and herd management). Enteric fermentation, manure, synthetic fertilizers and irrigated rice are the main sources of agricultural GHG emissions, alongside emissions from farm machinery and buildings (Fig. 1.4). The primary sink in this sector is the growth of forests and trees and carbon storage in aboveground and belowground biomass. The land sector thus plays a central role in food security and sustainable development. The most cost-effective forest mitigation options are afforestation, sustainable forest management and reduced deforestation. The most cost-effective mitigation options in agriculture are the management of cultivated or grazed land and the restoration of organic soils.

There are numerous obstacles to the implementation of mitigation options in the land sector due to its nature, including the availability of funding, poverty, and institutional, environmental, technological, dissemination and transfer issues. Public policies based on sustainable development and equity principles are essential for climate change mitigation, but they assume that collective action will not be impeded by private interests. The attitude that climate change is a problem to be managed by others is rife. These policies are formulated on the basis of value judgments and ethical considerations, and economic decisions interfere with development goals. Developing countries, in particular, are often reluctant to implement mitigation policies that could hinder economic growth, as they are more vulnerable to climate change and do not feel responsible for past GHG emissions. They reject efforts by developed countries to place the onus of mitigation on developing economies. In recent discussions, however, there has been increased focus on synergy between adaptation and mitigation under the same technical and regulatory options. Climate policy design is influenced by the way individuals and organizations perceive risks and uncertainties and take them into account. The cost of mitigating climate change varies greatly depending on the selected reduction target, the zone under consideration, the technologies used and the possible positive or negative side effects. Individual behaviour, lifestyle and culture are major influences. Demand-related measures, such as dietary changes and loss reduction in food supply chains, have significant (but according to IPCC still uncertain) potential for reducing GHG emissions associated with food production.

1.2.3 The Bioenergy Issue

Bioenergy production has an important role to play in mitigation, but must be carefully gauged against other potentially conflicting forms of land use. Questions remain as to the sustainability of bioenergy practices and the efficiency of bioenergy systems, including input use. GHG emissions from bioenergy cropland (due to the intensive use of inputs or mechanization), food security (competition with food crops), water resources (irrigation) and biodiversity conservation (large mono-cropped areas) are some of the obstacles to the large-scale deployment of bioenergy production schemes. Bioenergy technologies are varied and encompass a wide range of technical options and pathways, but the scientific debate on the overall climate impact of land use competition between particular bioenergy schemes is still ongoing. Available results indicate that technologies involving options with a short emission life cycle (e.g. sugarcane, *Miscanthus*, fast-growing trees and sustainable use of biomass residue), some of which are already available, can reduce greenhouse gas emissions. Forest biomass can also be used for bioenergy generation, but only biomass from sustainably managed stands or forests has a positive impact on the carbon stock.

1.2.4 Situation of Developing Countries

The third volume of the IPCC Report indicates that the models predict a strong negative impact on agricultural productivity and global food security for scenarios involving local increases of 3–4 °C or more. The risk will be higher in tropical countries because of the greater impact, widespread poverty and adaptation difficulties. In the tropics, maize and wheat yields begin declining when temperatures rise by 1–2 °C, rice yields when the increase is 3–5 °C. However, IPCC also believes that the agricultural mitigation potential could account for as much as three quarters of total agricultural emissions and that this could be achieved by managing the soil carbon stock, mainly in developing countries, not so much by reducing emissions.

By 2050, most African countries will experience heretofore unknown climatic conditions on more than half of their arable land. By 2080, there will very likely be a negative impact on yields in the tropics, regardless of the adaptation or emission scenario considered. Africa is one of the most vulnerable areas in terms of food security, but climate change will also affect crop yields, food security and local economies in Central America, northeastern Brazil, parts of the Andean region, and South Asia. Yields of some crops could nevertheless increase in a few tropical highland areas, such as rice in Madagascar. Crops such as arabica coffee will have to be cultivated at higher elevations to benefit from lower temperatures.

In current climate change adaptation conditions, at least seven climate risks in Africa are projected to be medium-high or high by 2030: biome distribution changes, coral degradation, reduced crop productivity, detrimental effects on livestock, vector-borne diseases, malnutrition, and human migration. In Latin America, there will be significant risk to water resources, coral reefs and food production, and from vector-borne diseases, while in Asia the risks will concern crop productivity, water shortages, floods and heat-related mortality. Many drivers of change in tropical regions may therefore have a negative impact on agriculture. According to the report of IPCC Working Group III, if greenhouse gas emissions are not reduced and lead to a 4 °C increase from 2080 to 2100, food security in Africa will be threatened, even if progress has been made in adapting to climate change. While the initial effects of global warming in Africa can be offset by agroecological practices, modelling studies show that in the case of maize, only new cultivars or irrigation practices will be able to counter the effects of extreme temperatures and water stress beyond 2040 (Folberth et al. 2014).

When poverty prevails, the climate change impact exacerbates other stress factors and often depreciates the wellbeing of the most vulnerable people. There is a real risk of food insecurity and the breakdown of food supply systems in the event of sharp increases in temperature, drought, flooding or high variability in rainfall extremes. Inadequate access to safe drinking water or irrigation water obviously has negative consequences, especially on farmers and herders in semiarid regions. Impacts on marine and coastal ecosystems and their biodiversity may seriously threaten fishers.

The sectors under greatest threat in developing tropical areas are: freshwater resources (significant reduction in renewable surface water and groundwater resources in dry subtropical regions); marine systems (high local extinction rates in semi-enclosed tropical seas); food (mostly negative effect of increased temperature on yields); rural households headed by women or lacking access to land, agricultural inputs, infrastructure and education; human health and population security (risks related to displacement and migration). All of these risks imply that climate change will exacerbate poverty in already poor countries. Combating climate change is therefore tightly linked to sustainable development and equity, but there may be a contradiction between necessary adaptations and some mitigation targets. Climate policies and technical solutions should therefore transcend adaptation and mitigation objectives and focus on development pathways in the broadest sense so as to sidestep that contradiction.

Many initiatives already take climate change constraints in developing countries into account, particularly with regard to adaptation, which is often linked to development initiatives such as integrated water resource management, agroforestry or coastal mangrove reforestation. Ecosystem-based adaptation sometimes includes protected areas, conservation agreements and community management of natural areas. Resilient crop varieties are adopted, in addition to the development of climate forecasts and early warning systems. Traditional environmental knowledge is increasingly put to use in adaptation efforts.

1.3 What Climate-Smart Agriculture Proposes

1.3.1 Synergy Between Adaptation and Mitigation

There are many possible interactions between adaptation and mitigation and between different adaptation options. These interactions may involve co-benefits (influence on other societal goals such as health or biodiversity), synergies (mitigation and adaptation objectives reached simultaneously) or tradeoffs (choice between mitigation and adaptation). Agricultural and forestry policies are generally more effective when they combine mitigation and adaptation. Despite the obvious links between the two approaches, most initiatives deal with them separately—mainly mitigation under the United Nations Framework Convention on Climate Change (UNFCCC) negotiations, and adaptation in the context of the Millennium Development Goals. But things are changing. Some discussions focused on the 'land sector' during the United Nations negotiations in Warsaw in November 2013 and again in Lima in 2014, thus reconciling the former negotiations on mitigation in the forestry sector with more recent negotiations regarding agriculture, which were mainly geared towards adaptation. While forests were the main focus of earlier discussions, agriculture is progressively included in the discussions. The debates highlighted the fact that agriculture (not only forests) must play a role in mitigating climate change, while linking mitigation and adaptation approaches. Mitigation can even be one of the functions of adaptation, such as when a crop management system is developed that improves productivity while increasing the stock of biomass. Technical solutions are available that can simultaneously tackle the food security, mitigation and adaptation challenges, providing a unique opportunity for agriculture to move towards more agroecological practices.

The climate-smart agriculture (CSA) concept promoted by FAO since 2010 (FAO 2013) is based on this synergy between adaptation and mitigation. CSA is focused on three objectives: sustainable food security (production), adaptation to climate change (or agricultural resilience to climate disruptions) and mitigation of climate change (emission reduction or carbon storage). The concept was developed in response to the realization that agriculture in developing countries must undergo profound transformations to meet food security and climate change challenges.

The three main features of FAO's rationale are as follows:

- some practices fulfil the definition above, but ecosystem-oriented, landscape-scale and cross-sectoral (agriculture, livestock farming, forestry, food security, etc.) approaches are essential;
- institutional support and public policies are needed to enable smallholders to make the necessary transition, which will require a massive information and coordination effort and better streamlining of agricultural, food security and climate change policies;
- available funds are insufficient to achieve that transition, so new financial arrangements must be found that combine public and private sources and are geared towards combating climate change and enhancing food security, while taking the characteristics of the various sectors concerned into account.

Hence, rather than an agricultural technique, CSA is considered a holistic approach that takes practices, public policies and financing (Lipper et al. 2014) into account. It is intended to address all three challenges (adaptation, mitigation, food security) simultaneously. Practices and enabling conditions for their implementation must hence be described concomitantly in order to promote CSA. Otherwise, these practices could merely be existing sustainable agriculture technical options (contour cropping, integrated pest management, water retention, intercropping, etc.).

The so-called Sahel Re-greening Initiative in Niger is a concrete example of CSA. Research and development operations, decentralization initiatives, and the transfer of tree ownership rights from the State to farmers have helped revive the practice of assisted natural regeneration of field trees (agroforestry). Over just a few years, there has been a spectacular increase in tree density, which has helped change the microclimate and improve soil fertility (adaptation), increase standing biomass (mitigation), and enhance farmers' incomes and livelihoods.

Intermittent paddy rice irrigation (also known as 'sustainable rice intensification') is another example of CSA. Using that approach, water consumption can be reduced (adaptation) along with methane emissions from anaerobic decomposition of organic matter (mitigation), while boosting yields and quality (food security). The approach still needs to be validated on a larger scale, and could give rise to weed problems, but the initial results are promising.

Decentralized energy generation on farms is another example of CSA. This contributes to climate change mitigation (no fossil fuels used), adaptation, if this generation is based on locally available resources, and food security, by cutting energy expenditures. Support measures are needed for farm-scale energy generation and for sustainable management of the resource (wood or other biomass) and the potential impact of bioenergy generation on land devoted to food production. There are therefore many different options for the implementation of CSA principles. Land use characterization (Box 1.1) provides information on the necessary choices.

Box 1.1. Five complementary dimensions for land use characterization and awareness raising on decisions related to climate change.

Marie de Lattre-Gasquet and Chantal Le Mouël, Agrimonde-Terra foresight study

Agricultural potential: knowledge of this can facilitate decision-making on land allocation to various uses, the way the land is utilized in each case, property assessments, etc., leading to several types of classification. At the global level, the GAEZ model (global agroecological zones; Fischer et al. 2012) is often used. It distinguishes categories of land according to their agricultural usage potential: ‘very suitable’, ‘suitable’, ‘moderately suitable’, ‘marginally suitable’ and ‘not suitable’. But not all land with sufficient agricultural potential for cultivation may be available because of restricted access (see next dimension). Verburg et al. (2013) speak of the “myth of arable land”, reflecting the fact that, depending on the source, estimates and projections of arable land vary widely owing to the land use categories and methods used and the specific objectives of each study. Increases or decreases in temperature and water variations induced by climate change affect the land’s agronomic potential and hence its classification. In the past, climate change tended to lessen the agricultural potential of land, whereas it could improve it in some areas in the future.

Access to land: depends on its governance, which sets the rules, processes and structures that determine how land is used and controlled, the way decisions are implemented and enforced, and how competing property interests are managed. Unequal access to land among individuals, social groups, and men and women is a major economic stratification factor in rural and urban areas. A broad array of rights must be recognized to improve access to land. Pressure due to climate change will increase competition for land access, which could in turn result in changes to land governance.

The distribution of land among different uses: refers to where the bulk of agricultural and forest production takes place. This dimension is largely a function of market access for farmers, transport and production costs, and agricultural policies for some types of production. In some sectors and regions, processing industries are questioning the sustainability of their agricultural supplies. Future climate change will alter agricultural production locations and could lead to more land ‘relocation’.

Modes of production: are related to agricultural production systems, which in turn are characterized by combinations of crops, crops and livestock, crop sequences and the combination of different factors (land, labour, capital) and inputs (fertilizers, pesticides, water, energy etc.) used for crop or livestock production. Modes of production may, for instance, be characterized by the degree of intensification or the yield per hectare. They are heavily influenced by—but may also influence—hydroclimatic variations.

Multifunctionality of land: means that even land used for biomass production for energy or food purposes produces ecosystem goods and services. Farmers manage and help maintain the land. In a context of rapid climate change requiring alleviation or even mitigation measures, it is essential that multifunctional uses be considered on par with agricultural production itself.

CSA generally embodies approaches focused on sustainable water and soil conservation and management (moderate irrigation, water capture, erosion control, organic matter enrichment, soil biodiversity improvement, cover crops, tree cover in fields and landscapes, etc.). Carbon sequestration in aboveground and belowground parts of plants is frequently sought, especially to achieve 'sustainable agriculture' (Perfecto et al. 2009) based on the use of woody plants, cover crops, perennial grasses, roots and tubers. CSA cannot be reduced to monocropping, but instead should integrate various agricultural activities, such as combining crop and livestock farming, paddy fish farming, and agroforestry.

1.3.2 Efficiency, Resilience and Landscape Scale

Most agricultural GHG emissions arise from natural resource use (clearing and cropping new land, transforming permanent grassland into cropland, tapping water resources) or from production input use (fertilizer and energy). Enhancing resource-use efficiency (more volume produced per unit of input) should make it possible to reduce GHG emissions per output unit and slow the expansion of agricultural land by making more intensive use of it, thus helping to mitigate climate change (FAO 2013). That so-called 'land saving' approach contrasts with another approach whereby land serves both production and conservation purposes ('land sharing'; Grau et al. 2013). Under the latter approach, which is akin to CSA (see Chap. 24), sustainable agricultural intensification generates environmental co-benefits by broadly contributing to natural resource conservation (soil, water, biodiversity and agro-biodiversity).

Climate change alters the state of play, affecting current risks and adding other risks and uncertainties. The unpredictable nature of the changes makes forecasting difficult. 'No-regrets' approaches (of interest regardless of the change), such as the implementation of conservation agriculture proposals (zero tillage, permanent ground cover, tailored crop sequences), or input consumption reduction strategies (fuel, mineral fertilizers), while maintaining production volumes, reduce the vulnerability of territories and populations and increase resilience. A landscape-scale approach, which calls for a degree of heterogeneity in land use, is essential to enhance resilience and risk management. That scale is best suited for devising mechanisms that ensure synergy between adaptation and mitigation (Harvey et al. 2014; Duguma et al. 2014). At that scale, various land use modes may be pooled in multifunctional land areas to more effectively address a number of climate-change-related objectives. The landscape approach requires a sustainable natural resource management system that recognizes the value of ecosystem services provided to the different stakeholders while accounting for their sometimes widely varying strategies and objectives. It addresses social concerns regarding the necessary tradeoffs between conservation and development and takes poverty reduction objectives and food security issues into account. These interactions between ecology and society are able to develop within a given 'territory', i.e. a landscape of stakeholders resulting from a social construct and hence a governance mechanism. The territory has to be large enough for natural resources and areas to be managed at an appropriate level and for vital ecosystem services to function, while remaining small enough for concerned stakeholders to remain motivated by undertakings at that scale.

Hence, we can also refer to climate-smart landscapes and territories. A climate-smart landscape is characterized by a mosaic, or matrix of entities connected by a network of biotic and abiotic interactions, for example a mixture of fields, grazing lands, natural areas, woodlands and protected areas. Crops, species and crop management systems may be diversified within each entity. Between the various parts of the mosaic, green infrastructures such as hedgerows and drainage streams can be maintained, riparian forest (woodland along streams) protected, and grassy strips preserved on the edges of tilled plots, etc. That spatial diversity can also be managed on farms by staggering planting dates between neighbouring plots, mixing plots or diversifying rotations, installing honey plants or beehives, or maintaining a network of hedges.

A climate-smart territory is the ideal scale for collective action, where the initiatives of stakeholders pursuing the same climate-smart goals are coordinated. At the village or small region governance level, land management schemes that address climate change issues should clearly be implemented in coordination with the initiatives of neighbouring landowners, local authorities, and nature conservancy or watershed management agencies. That is the whole point of the 'cross-sectoral harmony' effort that FAO identified as being one of the essential conditions for CSA. This concerns the agriculture, forestry, nature conservancy and, of course, water management sectors, in addition to the public finance, insurance, land use planning, public works, energy, and even waste management sectors. Finally, the private sector may influence the situation one way or another by the law of supply and demand or through partnerships with the public sector.

The landscape and territory approach requires an understanding of how to meet the needs of local communities without affecting biodiversity or ceasing to provide ecosystem services. The participation of all parties is essential to curb conflicts that could arise on account of divergent visions, goals and interests regarding spatial development. Moreover, capacity building for local institutions and stakeholders (including rural communities) should be considered a way of boosting trust between stakeholders and encouraging them to work together, especially for land management. That will require the formulation of a public policy that unifies different sectoral policies governing agricultural productivity, ecosystem management, forests and improvement of community livelihoods. An enabling market environment is vital, as well as environmental legislation that recognizes the rights of rural populations. For instance, public incentives that could adversely affect biodiversity, such as subsidies on chemical inputs, which promote the use of simplified crop rotations, are better abandoned.

1.4 Designing and Implementing Appropriate Public Policies

Climate-smart agriculture proponents consider that appropriate public policies, institutions and funding are essential to enhance the resilience and efficiency of agricultural production systems and enable the necessary changes to be made. Agricultural development funding requirements in developing countries are sizeable and still generally unfulfilled. Those needs will likely increase in the future because of climate change, with underfunding becoming much more acute if new funding is not made available. Private stakeholders—mainly farmers—account for most investment in agriculture. Public stakeholders can, however, play a strategic role by creating an environment conducive to private investment, particularly in land management, large-scale rural infrastructure (roads and rural trails, irrigation schemes, etc.) and agricultural research, in close liaison with agricultural extension services. It is also important to help farmers overcome innovation constraints that hamper their acceptance of change. Securing access to land is thus fundamental, and the guidelines set out by FAO (Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the Context of National Food Security) are a very valuable tool.

The approach taken must be systemic and, for example, address the need, beyond farms, for extension and supply network that are accessible to all farmers, together with a marketing system that can include newly created products. Improving the efficiency and resilience of agricultural systems will require integrated governance at all levels (local, national, regional and international), involving all stakeholders (farmers, manufacturers, traders, retailers, consumers and public authorities).

Climate-smart agriculture should not be viewed as a system or a set of techniques or practices to be promoted, but rather as a new approach to "developing the technical, policy and investment conditions to achieve sustainable agricultural development for food security under climate change."[1] CSA proponents propose an integrated approach whereby climate change is taken into account at the global level but its consequences, and hence any adaptation measures, are defined mainly at the local level. Finally, food security must be addressed both globally and locally. On 23 September 2014, the Global Alliance for Climate-Smart Agriculture was launched at the UN Climate Summit. The objectives of the framework document, signed by many public and private partners, are threefold: knowledge building and information sharing, mobilization and improved effectiveness of public and private financing, and creation of a favourable policy environment. On the African continent, the Africa Climate-Smart Agriculture Alliance was formed in 2014 under the auspices of the New Partnership for Africa's Development (NEPAD). These bold initiatives are meant to make climate-smart agriculture a reality.

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Part I
Coping with Climate Change

Chapter 2
Hazards, Vulnerability and Risk

Olivier Gilard

Abstract The hazards and vulnerability concepts are introduced after a brief review of the definition of risk. Hazards are essentially associated with any natural phenomenon investigated, while vulnerability is primarily a socioeconomic parameter influenced by other drivers of change such as demography. The risk concept derives from these two parameters. Given that there is no such thing as a zero risk situation, it is essential to introduce the idea of an acceptable level of risk which must be determined through a participatory process set in motion by society. Knowledge regarding these two risk components is dependent on the methods used to assess them and associated levels of uncertainty. The impact of climate change on hazards is hard to quantify because, under a constant climate, it is generally an order of magnitude below the natural existing uncertainty. Conversely, vulnerability is not well understood and few rigorous methods are available to quantify this factor. Clarifying hazards thus may seem to enhance the risk assessment but this is illusory since the less understood vulnerability factor is overlooked, which may lead to too much attention being focused on the hazards factor to the detriment of vulnerability management. This may also apply to other climate risks such as drought, although flooding risk is better understood. These considerations may be useful for the agricultural community which, besides its production function, could offer society other services of territorial scope, encompassing different areas, while in return benefitting from support measures that would make the risks more acceptable.

2.1 Brief Review of Cyndinics—The Science of Risk

In the field of cyndinics, especially for natural disaster experts, from a conceptual standpoint, hazards and vulnerability elements are distinguished when analysing risk (Gilard 1998b). Under this conceptual rationale, hazards are random factors

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resulting from natural phenomena that cause a danger when they arise. Hazards are characterized by a relatively well known probability law. They are mainly dependent on ‘natural’ factors that human interventions can help change via development projects or by the impact of certain practices (e.g. runoff on sealed surfaces). Conversely, from this conceptual standpoint, vulnerability is viewed as a socioeconomic factor that characterizes foreseeable damage when a phenomenon occurs (Goutx 2012; Veyret and Reghezza 2006; Weiss et al. 2011), without any presumptions regarding the probability of occurrence of the phenomenon. For both concepts, the spatial distribution is heterogeneous and differs from one plot to another. They can be extended to different spatial scales depending on the targeted analysis accuracy and use. These concepts are illustrated hereafter on the basis of examples regarding natural climate-related phenomena.

The first example is from a flood risk analysis. On a given piece of land, floodwater intrusion resulting from a river overflow is the considered hazard. It can be quantified by a series of physical characteristics, combining water level, current velocity and flooding duration, with a probability of occurrence assigned to each of these three factors (l, v, d) (Gilard 1998b). Although this hazard can best be described by a probability value because of its progressive and continuous nature, a hydrometeorological measurement network, with long-term monitoring data, is required to obtain accurate knowledge on such phenomena. The same plot of land can be characterized in terms of its vulnerability to the flood phenomenon. The susceptibility of the plot may differ depending on its use—a plot with an agricultural use will not have the same vulnerability as that with an urban use. Different crops do not have the same susceptibility to flooding, i.e. perennial crops are generally less susceptible than annual crops, at least for short-duration floods. Similarly, in urban environments, the vulnerability of a school is not identical to that of a residential area, industrial zone or recreational area, etc. Construction regulations may even modify the vulnerability of a given building or piece of land —a house with a mezzanine is less vulnerable than one at ground level. Independent plots can thus be characterized by a specific level of vulnerability. Risk is usually defined as the product of a hazard (probability of occurrence) and a vulnerability (estimated cost of foreseeable damage). This definition mistakenly always generates a positive result, thus tending to minimize the risk in the illusory quest for a risk-free situation. The risk concept can however, be defined differently through an additive combination of hazards and vulnerability levels (Gilard 1998a, b), whereby the risk may be positive or negative, and therefore acceptable when the hazards level is consistent with the vulnerability level, or unacceptable in the reverse situation (Figs. 2.1 and 2.2).

The same type of analysis could apply to drought risk. Here again, hazards caused by a shortage of water can be described by a rainfall probability distribution, generally with a seasonal adjustment. The duration parameter is crucial to determine the drought severity. The vulnerability in turn reflects the potential impact of this lack of rain on the use of a given plot, irrespective of the probability of occurrence of the phenomenon or the crop cycle period concerned by the hazard. The extent of the risk depends on the relevance of these parameters. By the acceptable risk

Fig. 2.1 Flooded street, Hanoi (© O. Gilard)

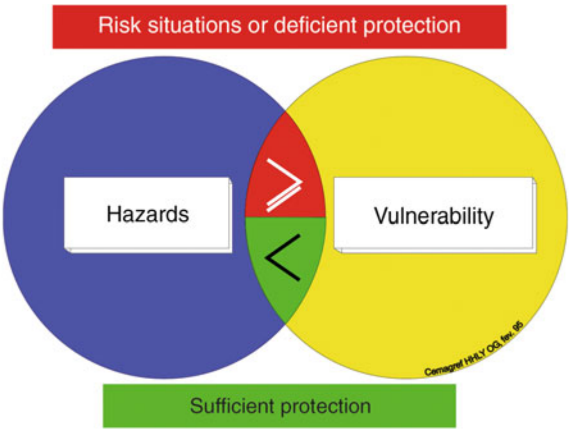


Fig. 2.2 Risk—a combination of hazards and vulnerability (Gilard 1998a, b). In *red*, unacceptable risk situations when hazards are greater than the vulnerability and, in *green*, acceptable risk situations when hazards are less than the vulnerability. This comparison may be made for each territorial unit

concept, the risk occurrence could be offset by other regulation or compensation mechanisms (e.g. through an insurance scheme covering the agricultural impact of the risk).

Let us now consider the often overlooked principle that zero risk situations do not exist! Regarding the flood example (Vinet 2010), a flooding river does not have a maximum value, i.e. a flood could be more intense and therefore more infrequent than previously monitored floods. When a dike is built, despite the low probability, a flood that would overflow the dike could occur at any time. Similarly, with regard to droughts, a drought could last longer and be more intense than previously observed. These natural phenomena are not 'bounded'. We thus conclude that there are no zero risk situations and full protection against any phenomenon is impossible. So it is essential to set an acceptable risk level, which could in turn be used to determine exactly what could be managed by development projects or infrastructures, or by other measures, such as insurance schemes, crisis management, etc. Clearly, this acceptability notion is by necessity delineated collectively, while also including economic, sociocultural and psychosociological considerations, as we shall see later with the more precise definition of vulnerability.

2.2 How Does This Apply to Climate Change?

Quantifying hazards—what does that mean? A brief update on a few operational hydrology facts will help differentiate intrinsic climatic variations from the impact of changes in the same climate. Climate change, resulting from the impact of a rise in temperature due to greenhouse gas build-up, leads to modifications in climate-related hazards, particularly all hydrometorological phenomena. These modifications are nevertheless very hard to predict since the phenomena involved are inherently highly variable, both spatially and temporally. They are generally described in terms of a 'regime' (rainfall, flow rates, low flows, etc.), i.e. a probabilistic representation of the overall range of possibilities, with a margin of uncertainty, in a recognized stable climate setting. The impact of climate change should be determined in terms of modifications in the regime (Renard et al. 2006). This is just a secondary factor as compared to the primary variability in the measured phenomena.

To gain a clear understanding of the above and draw relevant conclusions, it is useful to briefly outline a few baseline operational hydrometeorological principles. Hydrometeorological phenomena are monitored by available relevant networks that measure different parameters such as rainfall and river flow rates. Just measuring the different parameters is in itself a difficult task. For rainfall, we actually only know how to measure a quantity of water over a given time step. Similarly, water level at a given time enables us to determine a flow rate on a rating curve (which is hard to plot and a source of uncertainty, especially for measured flood and low flow extremes). The flow of a flooded river is currently determined with a margin of uncertainty of over 10–20 %[1] (Alliaud et al. 2013; Chastan et al. 1993; Gilard and Mesnil 1994). Progress has been achieved in recent years on normal river flow measurements based on radar and Doppler effects, but these methods are generally impractical during major floods, so we have to rely on indirect estimation methods with their associated margins of uncertainty. The same problem arises when assessing severe low flow events, which are very hard to accurately measure.

The rainfall regime is characterized by three main parameters, i.e. the intensity, duration and frequency, at least for small time steps (e.g. daily). More integrative parameters may also be considered, such as decadal rainfall rates (useful for agriculture) or seasonal rainfall patterns (useful for estimating available resources), etc. The point-specific nature of these measurements is somewhat problematic—a rain gauge records local characteristics of a rain storm whereas spatial variability in the rainfall pattern is often noted. Have we not all crossed a rainy area and then come upon an adjacent area that is still completely dry? Rain gauges therefore have to be well distributed throughout the concerned area to encompass this spatial variability, while also accounting for orographic factors such as the terrain. Recorded data may now be supplemented with indirect radar measurements, thus improving the representativeness of point measurements obtained. The descriptive accuracy of the rainfall regime depends on the duration of the time series measurements, especially for integrating so-called extreme events in the probability distributions of these parameters, which is essential for gaining full insight into potentially associated risks. Longer series enable more reliable estimates of the 'natural' frequency of these events, while in addition enhancing the capacity to consider them when making development decisions (size of hydrological structures, estimating agricultural production failures, etc.).

The hydrological regime of rivers is also characterized by three main parameters, i.e. flow, duration and frequency (Galéa et al. 2000; Javelle et al. 1999; Mar et al. 2003). The most relevant parameter should be defined according to the phenomena studied, i.e. the water volume when available quantities are sought (e.g. the mean monthly volume over a given month) or the flow rate when studying the intensity of a phenomenon (e.g. maximum instantaneous flow to characterize the flood intensity). The relevant parameter is not monitored directly but instead is obtained by processing baseline measured data. However, the prediction quality of the models used is degraded by the many measurement uncertainties (Renard et al. 2006; Sauquet et al. 2012).

Climate change, the effects of which have already been observed on the temperature variable, inevitably has an impact on other climate variables such as rainfall, and consequently river flow (Redaud et al. 2002), etc. But it is complicated (Sauquet et al. 2012), if not impossible, to assess these changes due to the

[1]The 1992 historic flood of the Ouvèze River at Vaison-la-Romaine (France) is edifying in this respect—it was not possible to reduce the assessment range (found to be between 800 and 1200 m^3/s) even after a year of research (Chastan et al. 1993; Gilard and Mesnil 1994). Similarly, inclusion of a single especially dry year in the 1986 Niger River flow record prompted a review of all probabilistic flood frequency estimates for this large river.

complexity of the prevailing phenomena. Such assessments have to take into account the overall rainfall and hydrological regimes and local features (geology, orography, land cover, etc.), which in turn may independently undergo changes.

This scenario can be illustrated by assessing the impact of climate change on the centennial flood of the Seine River in Paris (France). Such assessments are, however, complicated by changes related to control dams and their management, by changes in runoff and flow conditions, etc. If it were necessary to decrease the return period from 100 to 80 years due to climate change, would that fundamentally alter the centennial flood hazard?

2.3 What About Vulnerability?

2.3.1 What Are the Current and Future Adaptation Margins?

Vulnerability is far more complex to characterize, and especially to quantify, than hazards because a full set of economic, social, cultural, psychological, etc., factors have to be taken into consideration. This characterisation and quantification is multi-levelled and involves individual to political perceptions. The latter ultimately determine the operational choices made by a country or society to ensure protection from foreseen risks which, as already noted, must be defined by a level of acceptability. Moreover, to be effective, this vulnerability assessment should be spatialized on a scale that is suitable for fine-tuned land management. This is the only way to obtain sufficient leeway to minimize the impacts of the most exceptional events, which certainly will both technically and financially exceed the structural protection resources at our disposal.

It is only in the last 20 years that vulnerability analysis studies (Veyret and Reghezza 2006; Weiss et al. 2011) have been under way in some developed countries. Moreover, the topic has still far from been thoroughly investigated regarding some natural risks. Vulnerability quantification is thus still highly tentative. However, working on this risk component increases the leeway for making it acceptable (Goutx 2012). Concerning the flood risk, infrequent floods could be acceptable in some urban areas if they are of limited duration and if houses are built with a sufficiently elevated mezzanine. Moreover, concerning floods, for rare flood events, decisions could be made to flood agricultural areas in order to reduce the risk in urban areas, but financial compensation would have to be arranged for this 'risk exchange', thus making it possible to reduce the size of protective structures. In urban areas, it could be acceptable that some roadways and recreational zones are temporarily flooded in order to better protect hospitals and fire stations, etc. Drought risk to agricultural activities could be made acceptable by selecting resistant crop varieties and setting up insurance mechanisms that are less expensive than building water infrastructures (which could also fail in the event of exceptional droughts).

Fig. 2.3 Market near a flooded road after heavy rain, Cameroon (© L. Parrot/CIRAD)

Support measures could be effectively identified by focusing studies on enhancing vulnerability assessment and management. This could help gain further insight into the risk, to come up with non-structural solutions that do not involve infrastructures and that indirectly boost the efficiency of structural measures, while drawing up land use plans that take all of these risk factors into account (Figs. 2.2 and 2.3).

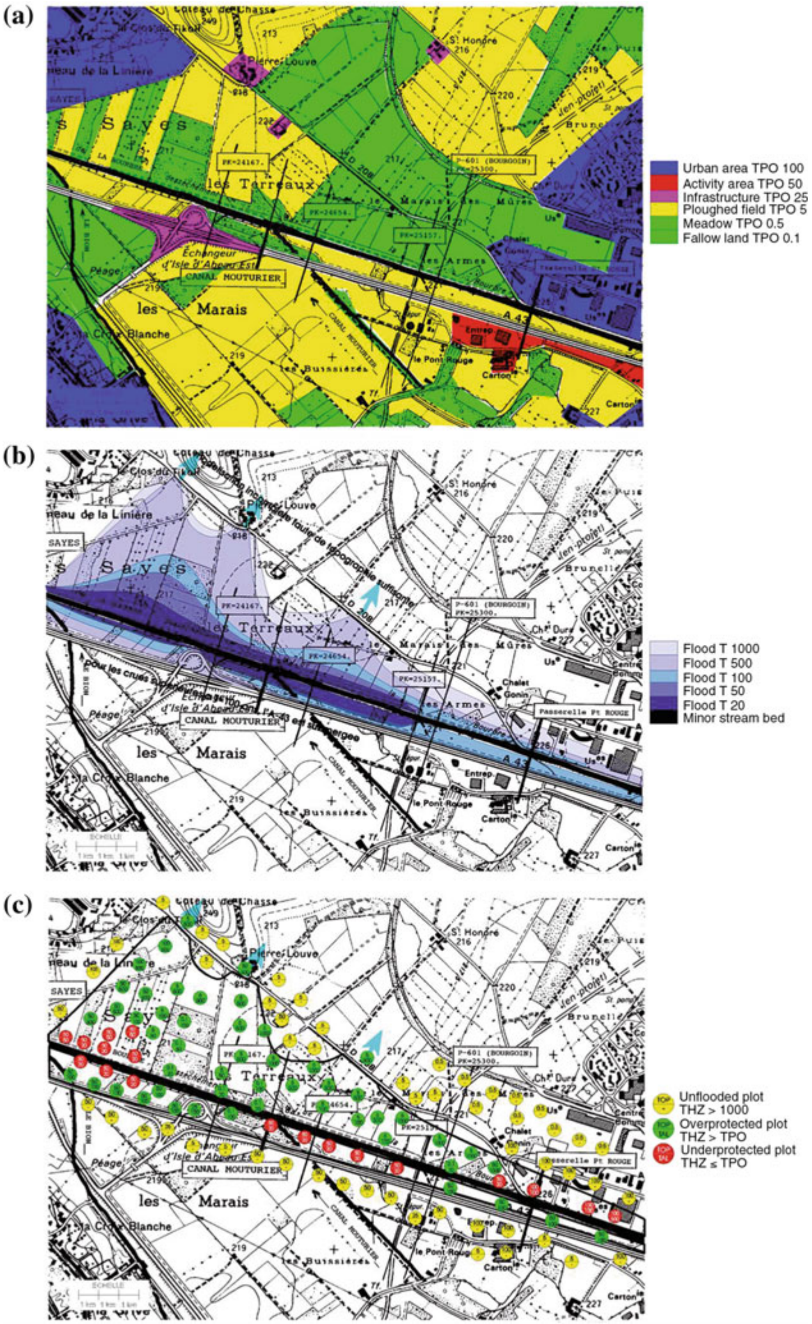
2.3.2 *To Avoid Addressing the Issues Inefficiently*

A few conclusions could be drawn on taking climate change into consideration in natural risk analyses related to climate change.

The vulnerability assessment uncertainty is an order of magnitude greater than that of hazards. The risk resulting from looking simultaneously at these two parameters (Gilard 1998a, b) is thus estimated with an even greater uncertainty, which could be summed up by the following equation:

$$\mathrm{Risk}(\pm\mathrm{uncertainty}) = \mathrm{hazard}(\pm\mathrm{uncertainty}) - \mathrm{vulnerability}(\pm\mathrm{uncertainty})$$

As the impact of climate change on the hazard parameter is an order of magnitude lower than the uncertainty regarding knowledge on this parameter, the risk


(a)
Urban area TPO 100
Activity area TPO 50
Infrastructure TPO 25
Ploughed field TPO 5
Meadow TPO 0.5
Fallow land TPO 0.1
(b)
Flood T 1000
Flood T 500
Flood T 100
Flood T 50
Flood T 20
Minor stream bed
(c)
Unflooded plot
THZ > 1000
Overprotected plot
THZ > TPO
Underprotected plot
THZ ≤ TPO

◀ **Fig. 2.4** Vulnerability (**a**), hazards (**b**) and risk (**c**) maps for the same area. The vulnerability spatial distribution is based on a tailored quantification method that includes economic and sociological factors. The hazards distribution is based on hydrological and hydraulic modelling of the studied river regime. The risk map shows plots with acceptable or unacceptable levels of risk, where the former offer leeway for tailored development projects (Gilard 1998a, b). T = *return period*, THZ = *return period of the hazard,* TPO = *return period of the protection objective;* the figures represent years

assessment is not fundamentally improved by taking the impact of climate change on the hazard factor into account, which is a complicated task (Renard et al. 2006; Sauquet et al. 2012):

$$\Delta\text{Risk}(\text{CC}) = \text{hazard}(\pm\text{uncertainty} \pm \Delta\text{CC}) - \text{vulnerability}(\pm\text{uncertainty})$$

where ΔCC < hazard uncertainty $\ll$ vulnerability uncertainty and ΔCC = assessment of the impact of climate change on the hazard factor.

Costly studies that focus on hazards factor without concomitantly addressing the vulnerability factor are not useful in the quest for tailored solutions. They might even channel research towards structural measures associated with hazards instead of measures that could ultimately be more effective—even though they would likely be harder to implement—especially those related to land-use management. Risk maps are thus based on associated vulnerability and hazards maps, which enable simulation of development projects geared towards modifying either of these two parameters (Fig. 2.4).

Showcasing climate change induces a distorting prism focused on hazards, while diverting attention from the demographic factor which otherwise would clearly increase the vulnerability overall. This demographic change should be accompanied by land-use planning to manage these risks. Such planning is not directly associated with climate change, with the noteworthy exception of coastal areas which are directly susceptible to the temperature parameter and to the impacts of the rise in average sea level.

2.4 What Relevance for Rural Areas?

Natural climate-related risks can only be managed on a tailored territorial scale—rivers for floods and a wider region for drought, especially if water resources are required that are not locally available. This territorial scale includes different types of urban or rural land use, each subject to different possible climate hazards, especially floods and drought. Collective management of these risks by society could generate opportunities in agricultural areas which, in exchange for services (in addition to the production function), could in turn benefit from compensation from other society members, thus potentially enabling them to boost their efficiency, including production efficiency (Fig. 2.5).

Fig. 2.5 Vegetable gardening adapted to a flood zone, Inle Lake, Burma (© O. Gilard)

Regarding the drought risk in agriculture, these concepts could be applied when seeking to reduce crop vulnerability by using varieties or cropping systems that are less vulnerable to drought, such as conservation agriculture, rather than trying to reduce hazards by expensive irrigation investments requiring more water, a locally rare resource. Public funding should also be directed towards vulnerability management rather than investing in hazards reduction.

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Chapter 3
Rice Adaptation Strategies in Response to Heat Stress at Flowering

Tanguy Lafarge, Cécile Julia, Alpha Baldé, Nourollah Ahmadi, Bertrand Muller and Michaël Dingkuhn

Abstract The adaptation of flowering processes to heat is crucial for maintaining yields in rice growing systems. In the Senegal River valley, high temperatures cause sterility, a situation that has prompted the development of crop management sequences and predictive models that account for the ability of plants to escape (early anthesis time), avoid (panicle cooling through transpiration) or tolerate (presence of genes of interest) heat at flowering. Avoidance and tolerance are the main genetic improvement pathways, whereas cropping practices are adjusted to ensure escape and take advantage of suitable thermal periods.

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3.1 Background

Rice spikelets become sterile in response to heat when flowering occurs at a panicle temperature of over 29.6 °C for IR64 (*indica* variety adapted to favourable environments) and over 33.0 °C for Azucena (*japonica* variety tolerant to water stress) (Jagadish et al. 2007). A detailed analysis must be conducted in order to integrate this adaptation process in growth models, including the panicle temperature, which could differ from the air temperature (Matsui et al. 2007), and the varietal diversity in temperature sensitivity. Climatic and agronomic factors affecting the organ temperature have to be considered, especially if the time when these processes occur varies during the day (Jagadish et al. 2007). Conventional crop models, such as CERES-Rice (Yang et al. 2014), ORYZA 2000 (Bouman et al. 2001) and SarraH (Sultan et al. 2013), simulate growth, development and yield of the crop in response to soil-plant-atmosphere dynamics. The heat sensitivity of flowering is eventually taken into account based solely on simple empirical functions so as not to overload the model with parameters. The RIDEV rice phenology model (Dingkuhn et al. 1995) is designed to predict the cycle length and sterility rate of plants according to temperature and photoperiod parameters, with the meristem temperature simulated as a function of the water and air temperature and the meristem position on the stalk. This model is thus structured to take the panicle temperature determinism into full account. We present pathways of escape (early anthesis time), avoidance (panicle cooling through transpiration) and tolerance (presence of genes of interest) of rice spikelet fertility to heat based on real situations encountered by farmers in the Senegal River valley, along with the modelling integration of these processes.

3.2 Sterility Risks—Changes in the Climate and Cropping Practices

In the Senegal River valley, extreme temperatures (high and low) hamper irrigated rice production by causing spikelet sterility (Dingkuhn 1992). There are two successive growing seasons, i.e. the February–March to June–July dry off-season, when it is quite cool during sowing and becomes very hot at the end of the cycle, and the July–August to November–December winter rainy season, when it is relatively hot during sowing and cooler at the end of the cycle. Climate variability (radiation, temperature, air humidity) is substantial during these seasons. Air temperatures below 18 °C during the stem growth phase (rapid internode elongation) can lead to yield losses of around 100 % because of abnormal pollen grain development during the microsporogenesis stage (male meiosis leading to the transformation of diploid cells into haploid gametes), or because of poor panicle exertion (incomplete panicle deployment outside the stem sheaths). Air temperatures over 35 °C at flowering (May–June) reduce pollen fertility by affecting anther opening (male pollen-bearing flower organs located at the stamen tips), pollination (anther to pistil pollen transport) and pollen germination. The RIDEV model was developed to map sterility risks for different rice growing areas in the Sahel, while taking the local climatic conditions, variety and cropping calendar into account. Optimal sowing windows that minimize climate risks were identified with this model.

The relevance of these recommendations was recently questioned when decent rice yields were obtained with later sowing (September). Surveys conducted in 2012 on changes in cropping practices (Baldé et al. 2014) revealed that the main constraint to farmers is the delay in preliminary cultivation in plots (difficulties in equipment, credit and input access). Farmers also mentioned a climate change trend in the Senegal River valley over the last 15 years—72 % of farmers interviewed underlined a general increase in temperatures and wide temperature variations, while 36 % of them noted a shift in the cool period to later in the year. Delayed sowing in September, rather than July or August, is thus perfectly in line with the shift in the cool period from November–February to December–March, which explains why some farmers readily delay rice sowing.

An analysis of the records confirmed the farmers' views and showed that both day and night temperatures have been increasing since 1980. Maximum and minimum temperatures were found to be currently higher than they were during the reference period (1950–1980) by a minimum of 1–2 °C, be it at Podor (16.35° N/15.02° W), Saint-Louis (16.05° N/16.45° W) or Matam (15.37° N/13.19° W), with even a significant 2–3 °C increase at Podor from September to December and March to April (Baldé et al. 2014). Current climatic conditions (2001–2012) thus differed from those during the reference period when the sowing window recommendations were drawn up (Dingkuhn 1995; Dingkuhn and Miezan 1995; Dingkuhn et al. 1995).

Sowing recommendations should be updated in the light of the changes in climatic conditions that have occurred over the last decades and the characteristics of new varieties. Moreover, climate forecasts for tropical areas strongly indicate that the focus should be placed on risks associated with high rather than low temperatures. These risks mainly concern the anthesis period when pollen in open flowers fertilizes pistils of the same flowers, as rice is a self-pollinating crop. A quite detailed crop model is thus required to simulate the spikelet sterility rate while taking the phenology (number of days from sowing to flowering) of new cropped varieties, time of day of anthesis, panicle temperature at anthesis, and varietal diversity regarding temperature sensitivity into account.

3.3 Adaptation Through Escape—Anthesis Early in the Day

Anthesis is recognized as being the development stage the most sensitive to environmental variations, especially high temperatures. The time of day of anthesis during two crop seasons in Senegal was closely monitored in four different varieties (Julia and Dingkuhn 2012): anthesis on a given spikelet occurred only in the morning, generally between 7 am and 1 pm and lasted no longer than 2 h, while panicle flowering lasted 4–6 days during the hot season and 7–10 days during the cold season. This short duration highlighted the extent to which the anthesis time is an important adaptation trait with respect to temperature variations recorded during the morning. Little is known, however, about the variability in this trait under the effects of cropping conditions. To quantify the impact of climatic variables on the time of day of anthesis, and better predict its occurrence, the weight of each of these variables on the determinism of this trait should be identified separately. The only way to decorrelate these often linked variables (increased radiation, day and night temperatures and decreased humidity) in field conditions is to conduct a set of experimental trials to test different combinations of radiation, minimum and maximum temperatures and air humidity. This was done by Julia and Dingkuhn (2012) during two cropping seasons in Senegal, one in the Philippines (hot and humid) and one in the French Camargue region (Mediterranean climate). The climatic effects on the time of day of anthesis were analysed in a range of plant material, including three improved semi-dwarf *indica* varieties derived from the Green Revolution, selected in the tropics and having a high yield potential (i.e. Sahel 108, a standard Senegalese erect variety, IR64, a standard Asian variety that is smaller than Sahel 108, and IR72, an Asian variety with a longer growing cycle than IR64), in addition to Chomrong, a conventional short-cycle *japonica* variety that is cold tolerant and slightly taller.

The period of anthesis sensitivity to climatic variables was defined on the basis of the 7 day period before flowering—the explanatory power of average climatic conditions over this period was higher than that of climatic conditions during individual days (Julia and Dingkuhn 2012). The period was individualized according to genotype, season and site in order to account for the diverse range of studied situations. The mean minimum temperature (Tmin) during this period ranged from 15.4 °C in France to 23.9 °C in the hot season in Senegal, and the maximum temperature (Tmax) from 28.5 °C in Camargue to 35.6 °C during the hot season in Senegal. The air dryness, represented by the saturation vapour pressure deficit (VPD), calculated using temperatures and relative minimum and maximum relative humidity (air dryness rises as the VPD value increases), ranged from 0.5 kPa in the Philippines to 1.4 kPa in Camargue, and up to 2 kPa in Senegal. The mean daily global radiation was similar for all seasons, ranging from 20.1 to 22.1 MJ/d.

Anthesis onset—expressed in number of hours after sunrise (hasr) to exclude between-site variations due to the day length and time of solar noon—ranged from 3.4 hasr in the Philippines to 6.75 hasr in the cold season in Senegal (Fig. 3.1) (Julia and Dingkuhn 2012). Variations in the time of onset and end of anthesis were similar in all situations, with a 2 h lag between onset and end—so predicting the hour of onset was sufficient to temporally position anthesis. Research on potential correlations between the time of day of anthesis and climatic variables is warranted considering the broad range of variation in the time of the anthesis process.

Variability in the time of day of anthesis was correlated with mean climatic variables, except radiation, calculated for the 7 day period before flowering, with the four seasons and four varieties combined. The best predictive variables were first Tmin (Fig. 3.1) and then VPD (negative correlations), with low values of both

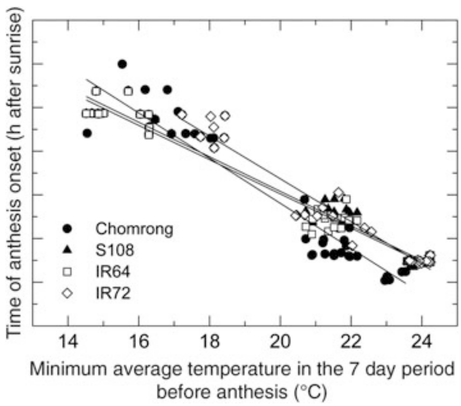

Fig. 3.1 Relationship between the time of anthesis onset and the minimum air temperature (T min) for each genotype and in three tropical environments (cold and hot dry seasons in Senegal and dry season in the Philippines)

being associated with late times of day. These were both also the main variables explaining the time of day of anthesis of Sahel 108, IR64 and Chomrong varieties when considered individually. However, VPD and the sunshine duration, instead of Tmin, were the two main variables explaining the time of day of anthesis of IR72. No impacts of climatic conditions on the time of day of anthesis were noted per individual site because of the low site variability in climatic conditions.

The high temperature and air humidity during the 7 day period before flowering caused a shift in anthesis to the early morning hours. Conversely, anthesis onset was later when the conditions were relatively cool and dry during previous days. This behaviour reflects an adaptation mechanism of escape from high late morning temperatures which, combined with humid conditions, reduce the ability of the plant to cool down its microenvironment via transpiration—the atmospheric evaporative demand and consequently the plant's transpiration activity are low under low VPD (humid conditions). The ability of the plant to cool down its microclimate (i.e. the air/panicle temperature differential) seems to be another mechanism of adaptation to high day temperatures.

3.4 Adaptation Through Avoidance—Panicle Cooling Through Transpiration

For rice sterility prediction, it is essential to gain insight into interactions that occur between the panicle temperature, the climate, the presence of a layer of water and the plant cover architecture. The panicle has no functional stomata (leaf epidermal cells whose opening is controlled by the plant to regulate water loss) but transpires through epidermal pores that are permanently open and thus directly subject to evaporative demand. High transpiration leads to panicle cooling through high energy consumption. Conversely, panicle heating is induced by solar radiation uptake. The panicle temperature can thus be several degrees lower or higher than the air temperature, depending on the prevailing climatic conditions.

An analysis of thermal variations between the panicle and air temperatures at 2 m height was conducted under the experimental design described above, which was perfectly tailored for this study because of the contrasting varietal architecture and climate sequences (Julia and Dingkuhn 2013). Panicles of the Chomrong variety, which are tall with an aerial morphology and borne by a long stalk, clearly dominate the leaf canopy, making them especially sensitive to air temperature variations. In contrast, compact panicles of the Sahel 108 variety, borne by a short stalk associated with erect leaves, benefit directly from the transpiration activity of the upper leaves that encircle them. Daily VPD values reached as high as 4 kPa during the two seasons monitored in Senegal, associated with a Tmax of 40 °C in the dry season and 35 °C in the cool season. Conversely, in the Philippines, the VPD values were systematically below 1 kPa, with Tmax values not above 32 °C. Intermediate VPD values (1–2 kPa) were recorded in Camargue, where the Tmax values were also not above 32 °C. Practically, panicle and leaf temperatures were measured on infrared images systematically combined with a digital photo (Fig. 3.2). Temperature gradients measured between the water surface, cover surface and air at 2 m aboveground varied markedly between seasons and during the day (Julia and Dingkuhn 2013). In Senegal, the cover temperature at panicle height varied between that of the water layer (close to the minimum air temperature) and

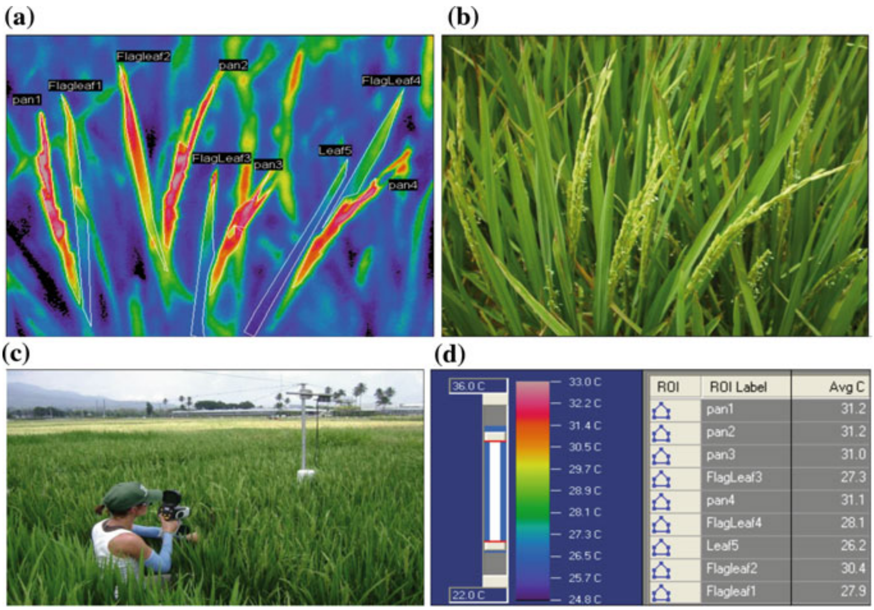

Fig. 3.2 Infrared image (**a**), digital photo (**b**), photo from the device's digital camera (**c**) and a screen shot of temperatures associated with rice cover at the flowering stage (**d**). Panicles and leaves were identified retrospectively using Microspec Pro 4.0.10 infrared image analysis software (**d**), and temperatures were extracted. This scene corresponds to the flowering stage of the IR64 variety in Senegal during the hot season on 27 May 2010 at 12:29 pm local time

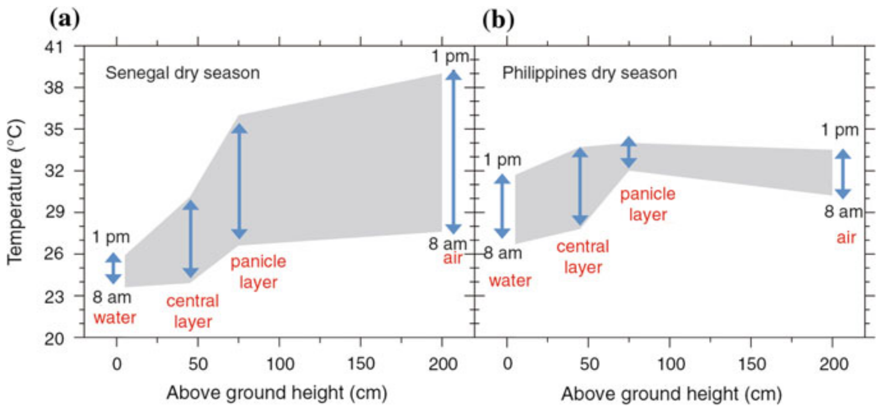

Fig. 3.3 Temperature gradient (T) between the water layer and the air 2 m above the ground, recorded at 8 am and 1 pm. Hourly mean temperatures between 8 am and 1 pm for the IR64 variety grown in Senegal during the hot dry season (**a**) and in the Philippines during the dry season (**b**). The gradients presented were measured during hot days and temperature sensors were placed at four measurement levels: in the air (2 m above the ground), on the cover surface at panicle height, in the middle of the cover (between the cover surface and the water surface) and in the water

that of the air—so it was always lower than the air temperature. The water temperature was well buffered, ranging from 24 to 26 °C (Fig. 3.3a). In the Philippines, the cover temperature was systematically hotter than the air temperature, while the water temperature fluctuated over a broader range, from 27 to 33 °C (Fig. 3.3b). The relationship between the panicle and air temperatures differed markedly depending on the season studied.

A multiple linear regression model was built to identify variables that would best explain the panicle/air temperature difference. The regression factors considered were VPD, air temperature, solar radiation, panicle height and sunlight angle. Where the model explained 80 % of the air/panicle temperature variation, VPD alone explained 65 % while relative humidity of the air (64 %) indicated that these closely interrelated variables are by far the most important explanatory variables (Fig. 3.4). The correlation between temperature differences and VPD was not as robust in the Philippines where the VPD was too small to reveal any correlations. A high VPD (dry conditions) had a marked effect on the temperature difference, thus modifying the panicle temperature relative to the air temperature from 9 °C lower to 2 °C higher (Fig. 3.4) (Julia and Dingkuhn 2013). Moreover, the mathematical model, which integrates the climatic determinism of the time of day of anthesis and the air/panicle temperature gradient, predicted panicle temperatures, relative to the air temperature, slightly higher in the Philippines, 4 °C lower in Senegal, and 1.2 °C lower in Camargue. This confirms the importance of taking the relative humidity of the air into account in assessing the plant's capacity to cool its panicles by transpiration (Julia and Dingkuhn 2013).

A significant positive correlation was obtained between the spikelet sterility rate and the maximum panicle temperature at flowering for the four environments and

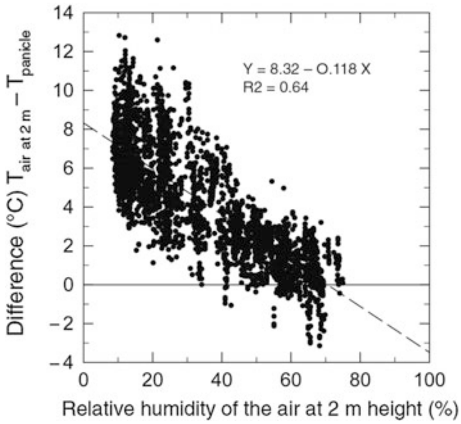

Fig. 3.4 Correlation between the air/panicle temperature difference at 2 m height and the relative humidity of the air measured at the same time. These measurements were obtained in Senegal during the cold dry season

the four combined varieties, whereas no correlation was obtained when the maximum reference temperature was the air temperature (Fig. 3.5). By extrapolation, this correlation predicted minimal sterility from a panicle temperature of 30 °C, and 50 % sterility with a panicle temperature of 33–34 °C. This ability of the plant to reduce its panicle temperature to support its production is typical of an adaptation behaviour through avoidance. It is also an adaptive trait under water deficit conditions where partial stomatal closure causes leaf warming. The range of thermal conditions under which the *indica* subspecies is cropped also suggests that the anthesis process is tolerant to high temperatures.

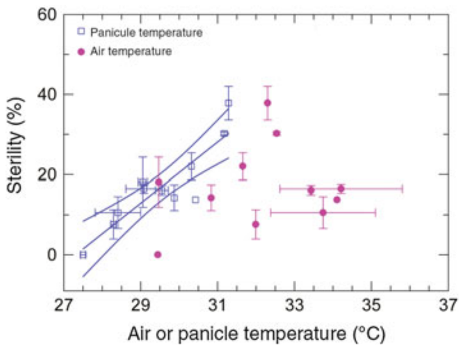

Fig. 3.5 Correlations between grain sterility at maturity, and firstly the mean maximum air temperature ($T_{air\ max}$) during flowering (*black circle*), and secondly the mean maximum panicle temperature ($T_{p\ max}$) during flowering (*square*). Correlation between $T_{p\ max}$ and sterility for the four combined environments: $y = 7.61x - 207.74$, $R^2 = 0.79$

3.5 Adaptation Through Tolerance—Genes that Maintain Fertility Despite Heat

A genome-wide association study was conducted to search for genes involved in heat tolerance at flowering (Lafarge et al. 2013). This involved detecting statistical correlations for the target trait between genotype and phenotype variations in a set of unrelated varieties (association panel) representative of the genetic diversity of the species or of a subset of the species. The study involved a group of 167 traditional varieties (from different geographical origins) and modern varieties (derived from the main world rice improvement programmes) representative of part of the *indica* subspecies most cultivated in irrigated rice growing systems in the tropics as well as *aus*, a minor group from the Indian subcontinent. Genotypic variations in these varieties were characterized by genomic fingerprinting (430 million bases), every 30,000 bases on average (Lafarge et al. 2013). These markers are point mutation sites on the genome [single nucleotide polymorphisms (SNPs)] identified by DNA sequencing.

Varieties were differentiated in terms of variations in the target phenotypic trait, spikelet or flower sterility rate in response to heat during the time of day of anthesis. Plants grown in pots under a 29/21 °C day/night thermal regime were subjected for six consecutive days to a constant temperature of 37 °C between 8 am and 2 pm (to cover the entire range of times of day of anthesis) (Lafarge et al. 2013). This constraint was limited in time to reduce unwanted side effects. The sterility rate was quantified at maturity by counting the number of empty grains on the top half (to avoid counting fertile grains that were empty due to a lack of carbon substrates) of panicles that had been subjected to heat at flowering (unlike panicles on the same plants that had flowered after 6 days of treatment).

An analysis of correlations (or associations) between the sterility rate of the 167 varieties subjected to 37 °C at anthesis and genotypic variation in these varieties monitored at 18,000 different points (loci) on the genome detected 91 significant associations. These loci were grouped in 12 independent regions located on eight chromosomes on the basis of their genome positions (Fig. 3.6) (Lafarge et al. 2013). A comparison of these results with those reported by the international community (rice genome annotation database) revealed that these 12 segments, significantly associated with heat tolerance, contained gene families involved in thermal stress perception and sensitivity, in the maintenance of proteins providing protection against these stresses and in the synthesis of transcription factors regulating the growth and response of plants to abiotic stress, as well as pollen development. The highest heat tolerance was detected for N22, an *aus* variety from India, and Peh Kuh, a traditional variety of the *indica* subspecies from Taiwan. The detection of these rice genome segments paves the way, firstly for cloning the genes involved and characterizing associated molecular mechanisms, and secondly for setting up a molecular marker assisted selection programme.

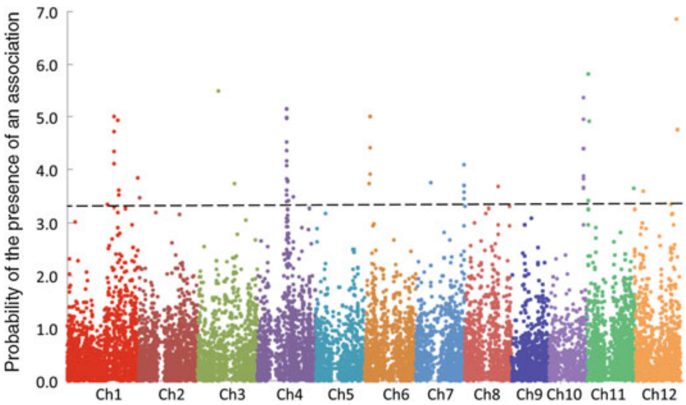

Fig. 3.6 Level of significance (probability value) of the association between heat tolerance during flowering and 16,232 genome loci distributed on 12 rice chromosomes. This study was focused on 167 genotypes of the *indica* subspecies

3.6 A Yield Prediction Tool

The relevance of yield forecasts in rice fields in response to climate change could thus be enhanced by including the heat sensitivity of anthesis by considering the time of day of anthesis, panicle temperature and presence of genes involved in tolerance. The time of day of anthesis can vary by 3 h during the morning depending on the climatic conditions. The panicle temperature can be up to 9 °C less than that of the air under the effect of plant cover transpiration in dry conditions. The genes of interest are grouped in 12 genetic segments distributed on 8 chromosomes within the species. Crop models designed to assess the best combinations of phenotypic traits for heat adaptation should thus take the three identified modes of adaptation into account (escape, avoidance and tolerance).

The RIDEV model includes a module that predicts the cover temperature in three layers from the bottom to the top of the canopy as a function of climatic variables, cover structure and presence of a layer of water on the ground. The plant temperature is simulated according to the height of the meristem or panicle in the cover, either close to the ground (vegetative phase), or at mid-cover height (reproductive phase), or at the canopy surface (flowering and grain filling phase), in a thermal range bounded by the soil and air temperatures (Dingkuhn et al. 1995). A new version of the model (RIDEV_V2) was developed to simulate the time of day of anthesis estimated according to climatic conditions during the previous days and the panicle temperature weighted by the transpiration activity of the cover. This model, which was calibrated for the Sahel 108 variety in the Senegal River valley, correctly predicted the cycle duration of stands subjected to different ranges of conditions (Fig. 3.7a). At flowering, the heat sensitivity of anthesis of this variety was estimated at 29.7 °C by the model. The model then accurately simulated variations in the sterility rate of the cover according to sowing dates (Fig. 3.7b). Hypotheses to

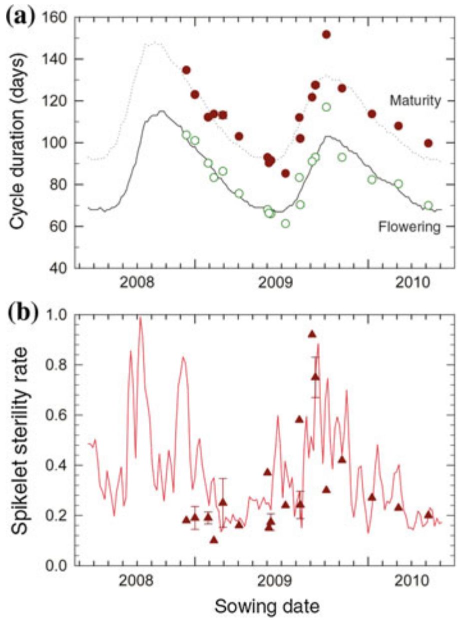

Fig. 3.7 Comparison of simulated (RIDEV_V2 model) and observed (from 19 sowing dates from late 2008 to mid-2010 at the Ndiaye site, Senegal) with the number of days to flowering and maturity (**a**) and the sterility rate at maturity (**b**) in the Sahel 108 variety

explain differences between the simulated and observed values include confusion, among empty grains, between sterility and lack of carbon resources, the propagation of errors on the phenology and sterility, and the presence of biotic constraints.

The RIDEV_V2 model was thus developed to take the different modes of heat adaptation into account, integrate reference algorithms and enhance the relevance of predictions of the sterility rate under climate change conditions. It was found to effectively account for the phenology of the Sahel 108 variety (for which it was calibrated and validated on an independent dataset) and for temporal variations in its sterility rate. Although datasets from different sites are essential to be able to validate the model's capacity to properly simulate the sterility rate in a broader geographical area, the development of this improved version will help boost the relevance of identifying new sowing windows to communicate to farmers and improve the prediction of climatic risks associated with high temperatures.

3.7 Conclusion

In-depth knowledge on the heat adaptation mechanisms of rice described in this chapter, including escape (time of day of anthesis), avoidance (panicle cooling by transpiration) and tolerance (involvement of key genes), illustrates the diversity of adaptive capacities of this crop and the rice variety improvement potential. The information from farmers obtained through surveys was in line with the corresponding climate datasets. Observations of shorter cycles and the success of sowing outside of the recommended windows, obtained in recent years in the Senegal River valley, confirmed the need to revise current integration and modelling tools. Integration of this knowledge in fertility prediction tools could have a direct impact on the adjustment of cropping practices. This makes it possible to conduct simulations for designing better phenotypes that maintain a high yield potential while also being tolerant to high temperature conditions. These advances should on the one hand help validate new sowing windows to avoid the most risky climatic periods, and on the other enhance rice improvement schemes to breed better adapted varieties of this major food crop.

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Chapter 4
Adaptation to Salinity

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Abstract The increase in salinity of aquatic and terrestrial ecosystems is a major consequence of current climate changes. It is therefore essential to be able to propose more adapted genotypes to farmers whether it concerns farmed fish or annual and perennial crops. To address these challenges, research is focused on acquiring better knowledge on mechanisms of adaptation to salt stress in order to effectively guide genetic improvement programmes and optimise breeding. We present various cases of adaptation to salinity in fish, rice and citrus. The selection of a tilapia strain adapted to salinity, especially via successive hybridizations and backcrosses, broadens the prospects for these farmed fish. Breeding rice to enhance salt tolerance has long been based on 'conventional' selection methods and is now oriented towards molecular marker assisted selection, while citrus adaptation to salt stress is based on rootstock choices and exploitation of polyploidy.

4.1 Background

The growing presence of salt in soils and changes in salinity in aquatic environments are major ecological disturbances related to climate change. In tropical agriculture, the severity of the phenomenon is especially high in irrigated areas. In this chapter

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we discuss the effects of increased salt water content on Nile tilapia, a major species for tropical fish farming. In agriculture, soil salinization can have a similar impact on annual crops such as rice, or tree crops like orange. Although tolerance mechanisms may be similar at the cellular level, research strategies to develop genotypes better adapted to these increasingly restrictive conditions often differ.

4.2 Tilapia Adaptation to Salinity

Rising sea levels and higher typhoon frequencies and intensities (e.g. in the Philippines) are causing saltwater intrusion in estuaries, salinization of rivers, groundwater, aquaculture ponds and saltwater flooding of mangroves (SEAFDEC-AQD 2013–2014). In West Africa, hypersalinity has been observed in Sahelian estuaries with a low flow rate, because the high water evaporation associated with successive droughts is no longer compensated by rainfall. The Sine-Saloum Estuary (Senegal, Gambia) has thus not only become hypersaline, but its salinity gradient has been reversed (with higher salinity upstream than downstream) (Savenije and Pagès 1992). In these estuaries, the lagoon tilapia *Sarotherodon melanotheron heudelotii* is tolerant to hypersalinity, but the energetic cost and the chronic stress of adapting to these waters have negative impacts on some of its life traits, such as growth and fertility, to the extent that the future of wild populations is threatened (Panfili et al. 2006).

Tilapia is the second major farmed fish group after carp (mainly produced and consumed in China), and all forecasts indicate that it will most likely exceed carp by 2025. Tilapia, of African origin, are farmed in over 100 countries. Within this species group, the Nile tilapia (*Oreochromis niloticus*) grows extremely well in freshwater environments and represents 90 % of the total tilapia production. However, it does not tolerate salinity variations.

Three main approaches can promote better tilapia adaptation to salinity. These include using the strong euryhalinity of *O. mossambicus* or *S. melanotheron* and improving their low growth through a selection programme in a saline environment; benefiting from the high growth-rate of Nile tilapia and selecting its salinity tolerance; and hybridizing a species with high salinity tolerance, such as *O. mossambicus* or *S. melanotheron heudelotii* with a fast growing species such as *O. niloticus*.

4.2.1 Osmoregulation of Fish in Saltwater Environments

Adaptation to a saline environment involves strict control of an organism's salt and water balances—this is osmoregulation which has an energetic cost that represents 25–50 % of the metabolic expenditure. Since the 1960s, *O. mossambicus* and *S. melanotheron heudelotii* have become models for studying osmoregulation for tilapia adaptation to salinity.

Fish are hyperosmotic in freshwater environments. They balance their water input by producing highly diluted urine, while limiting Na^+ (sodium) and Cl^- (chloride) ion loss, thus enabling them to maintain stable plasma levels. In saltwater environments, however, they are hypoosmotic and tend to drink. Ions are then filtered in the gut and the excess salt subsequently eliminated via their gills.

An osmoregulation study performed in four *S. melanotheron heudelotii* populations showed that the strategies of adaptation to hypersaline waters were partly based on high branchial activity of the Na^+/K^+-ATPase enzyme, which helps maintain plasma osmolality at around 400 mOsm/kg (Fig. 4.1a, b). Morphological and functional modifications were noted in gill chloride cells. The number of these cells—which have a high mitochondria content and are specialized in ion transport—increased with the salinity, and in hypersaline conditions were observed along multiple layers with an increase in cell volume (Fig. 4.1c) (Ouattara et al. 2009).

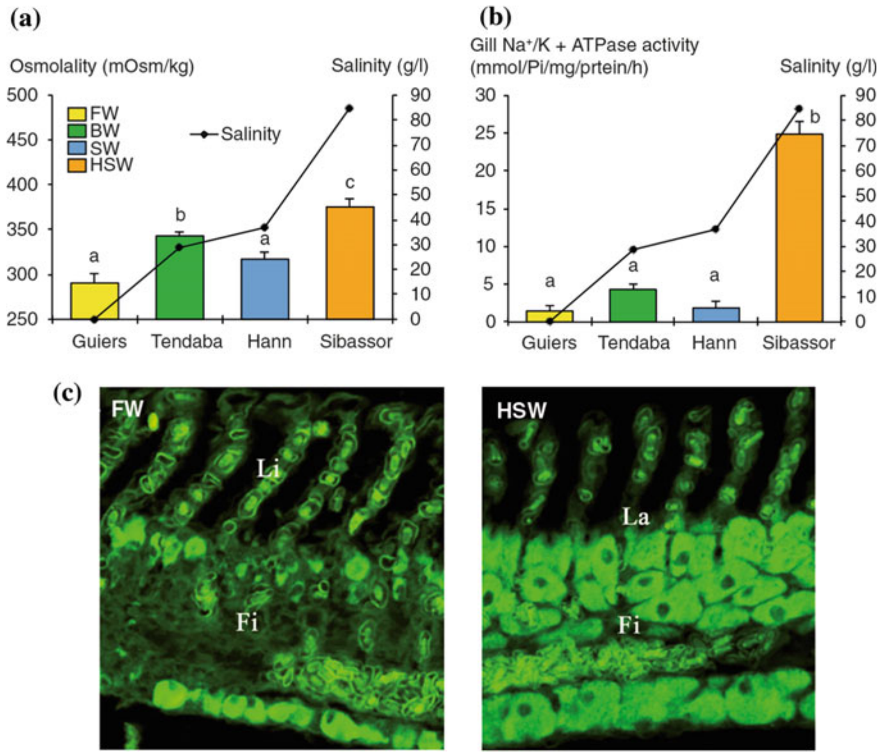

Fig. 4.1 **a** Plasma osmolality of natural *S. melanotheron heudelotii* tilapia populations living in very different saline environments: freshwater (FW), brackish water (BW), seawater (SW) and hypersaline water (HSW). **b** Gill Na^+/K^+-ATPase enzyme activity. **c** Na^+/K^+-ATPase pump immunolocalization, 72 h after transfer from FW to HSW at 70 g/l; *Fi* filament; *La* lamellae (from Ouattara et al. 2009)

The expression of candidate genes such as growth hormone and growth factors is stimulated in gills during transfer from freshwater to seawater, whereas it is inhibited in kidneys (Link et al. 2010). In fish adapted to hypersalinity, the genes identified were found to be mainly involved in transport activities, biological regulation and metabolic processes, thus confirming a higher metabolic activity in these fish (Tine et al. 2008).

4.2.2 Selection of a Saltwater-Adapted Tilapia Strain

The Molobicus project (CIRAD and the Bureau of Fisheries and Aquaculture Research, Philippines) focuses on the production of a fast-growing tilapia strain that is resistant to brackish water and seawater. The first phase carried out in freshwater, was based on hybridization and successive backcrosses between *O. niloticus* (high growth/low salt tolerance) and *O. mossambicus* (low growth/high salt tolerance). A rotational crossing design ensured high genetic variability in the hybrid population. As of the 2nd generation (H2), the strain bearing 25 % *O. niloticus* genes had high salt tolerance, thus enabling its rearing in brackish water. Growth of the hybrid population was then selected according to an intrafamilial design on the basis of 50 unrelated hybrid H2 families. This step was conducted in a saltwater environment and combined passive selection of salt-tolerant individuals and active selection for growth. An 'extensive' line (low-density, fertilized ponds, no feed provided) and an 'intensive' line (high-density ponds, protein-rich feed supply) were selected in parallel. After four generations, 7.3 % (12.5 g) genetic gain per generation was obtained (from Verdal et al. 2014; Fig. 4.2).

4.2.3 Future Research Opportunities

Selection programmes aimed at obtaining tilapia strains that are salinity-tolerant should, despite the cost, be based on selection approaches assisted by molecular markers. The sequencing of the Nile tilapia genome (Brawand et al. 2014) will allow to increase the number of genes and markers that can be used in association studies with the salinity-adaptation trait. However, this genomic selection is not yet possible due to the low tilapia prices. The presence of females that reproduce on a monthly basis while having a much lower growth-rate than males is an obstacle to tilapia production. This growth dimorphism is also found in salinity-tolerant tilapia strains. The high estrogen level in females also seems to reduce salinity tolerance. Temperature-dependent sex determination (as a substitute for current hormone treatments) should be an effective way to produce only males (more resistant to salinity with a higher growth-rate). A further option involves the production of sterile individuals (no energy expended in reproduction) via triploidization.

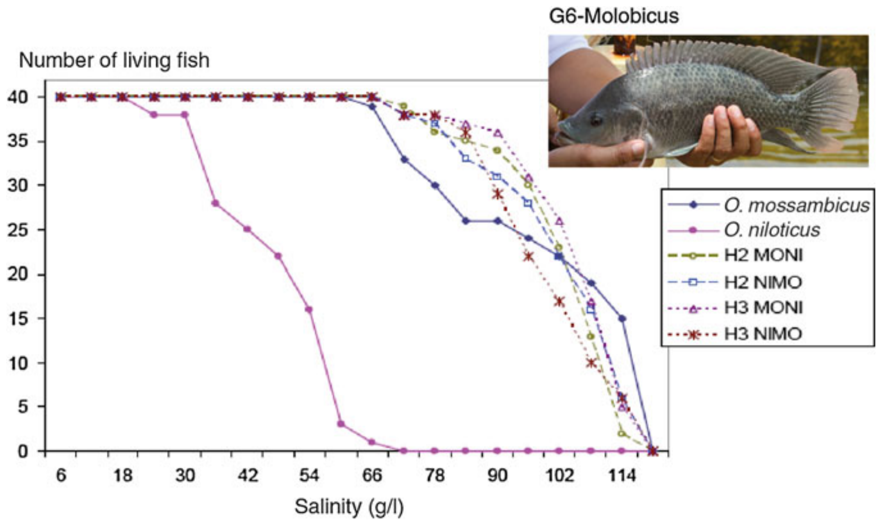

Fig. 4.2 Testing the salinity tolerance of Molobicus hybrids (H2-2nd and H3-3rd generations) and of the parental species *O. niloticus* and *O. mossambicus* during a gradual increase in salinity of 3 g/l a day

4.3 Salinity and Rice Growing

Around 10 % of the 160 million ha of rice fields worldwide are affected to various extents by permanent or temporary salinity due to the presence of sodium chloride (NaCl), especially in coastal and delta regions. Climate change will increase the incidence and severity of this problem by causing a rise in sea level and temperature, leading to greater evapotranspiration. Rice (*Oryza sativa* L.) is moderately susceptible to salinity. The growth and development of this species are affected when the soil electrical conductivity associated with the presence of Na^+ ions exceeds the threshold of 3 decisiemens per metre (dS/m). Sensitivity is especially high at the seedling stage and during the reproductive phase. The yield components most affected are the number of grains per panicle, spikelet fertility and grain weight (Fig. 4.3).

Control of the salinity impact could be based on three non-exclusive approaches: overcoming the problem by changing the cropping environment, avoiding rice cropping during periods of the year when there is a high salt stress risk, and mitigating the effects of salinity on the crop. The first approach requires expensive irrigation schemes and is often unaffordable for rice smallholders. The second approach, which requires rice varieties with an adapted crop cycle, remains uncertain because the onset of water salinization episodes is not always predictable. The third approach involves the use of tolerant varieties and is thus the main way to cope with salinity in rice cropping.

Fig. 4.3 A rice field affected by salinity. In the absence of sufficient rainfall or irrigation, intense evaporation is accompanied by a rise in the groundwater salt content, northern India (© IRRI)

4.3.1 Rice × Salinity Interaction—Adaptation Mechanisms

In saline environments, Na^+ ions are taken up by rice roots and enter the transpiration stream via the apoplastic pathway or move toward aerial parts via symplastic pathways involving the activity of specific transmembrane transporters. This results in two types of tissue stress: osmotic, associated with the higher concentration of solutes in the soil, and ionic, due to alteration of the K^+/Na^+ ion ratio. The almost immediate short-term response is the reduction in transpiration and photosynthesis to avoid dehydration, and the activation of perception and signalling mechanisms. The medium-term response, i.e. after a few hours, includes the activation of osmotic adjustment mechanisms, the restoration of K^+/Na^+ homeostasis and oxygen-free radical (OFR) control. Adjustment of the osmotic potential between the cytoplasmic matrix (cytosol) and the apoplastic solution to prevent cell dehydration and the resulting protein denaturation is achieved by the accumulation of nontoxic metabolites, or so-called 'compatible solutes', particularly the proline amino acid. The restoration of K^+/Na^+ homeostasis throughout the plant requires selective exclusion of Na^+ ions by epidermal root cells, preferential K^+ uptake in the xylem, Na^+ retention in the upper root parts and stem base, K^+ to Na^+ exchange and intracellular sequestration of Na^+ ions in vacuoles. K^+/Na^+ homeostasis avoids inhibition of the activity of cellular enzymes, allowing them to function normally despite the high Na^+ concentration. The plant increases antioxidant synthesis to control OFRs, which will otherwise destabilize the cell structure. In the longer term, i.e. a few days, the change in cellular osmotic and ionic balances affects the entire plant in its growth, development and grain production.

Finally, if salinity intensity is too high or if the expression of salt-tolerance mechanisms is not sufficient to exclude salt from the transpiration system, the accumulation of salt to toxic levels in the oldest leaves, that have transpired the longest, will lead to their death. As the growth of new leaves depends on carbohydrates from older leaves, the plant's fate depends on the balance between the rates of old leaf death and new leaf emergence. Salt stress also delays panicle initiation and flowering and reduces spikelet fertility because of the lower pollen viability. The plant will die before flowering or maturity if the salinity intensity is very high and if salt exposure exceeds 2–3 weeks.

4.3.2 Genetic Basis of Salinity Tolerance in Rice

There is substantial genetic variability in salinity tolerance in rice. The Indian landrace variety Nona Bokra, belonging to the *indica* group, is a reference in this respect. Genetic variability has also been noted for most tissue and cellular mechanisms of rice responses to salinity. Correlations are loose between individual tolerance mechanisms and between those mechanisms and whole plant survival or grain production under salinity stress. Regardless of the mechanisms involved, the plant's ability to maintain a high tissue K^+/Na^+ ratio is a key tolerance factor. The leaf K^+/Na^+ ratio is a good predictor of production loss under salt stress (Fig. 4.4).

An analysis of phenotypic diversity regarding the impact of salinity on whole plant growth and development and on the leaf K^+/Na^+ ratio led to the identification of tolerant varieties in *O. sativa indica* and temperate *japonica* groups (Fig. 4.4). Tolerance seems infrequent and low in *O. glaberrima*, the African cultivated rice species. However, high tolerance exists in *O. coarctata*, a distant wild relative of cultivated rice. A viable plant was recently obtained from an *O. sativa* x *O. coarctata* cross, thus enhancing the prospects for developing a 'supertolerant' rice variety.

Insight has been gained on the genetic and molecular bases of a high number of biological processes described above through techniques involving genetic mapping, functional genomics, as well as analysis of the differential expression of genes in different organs at various rice development stages under salt stress.

Genetic mapping in the offspring of crosses between a susceptible variety and a tolerant variety, which were assessed under hydroponic or field cropping conditions, led to the identification of a high number of quantitative trait loci (QTLs), especially on chromosomes 1, 4, 6 and 7.[1] One of these QTLs located on the short arm of chromosome 1 and having a marked effect on plant survival and grain

[1]These have been compiled in the following database: <http://tropgenedb.cirad.fr>.

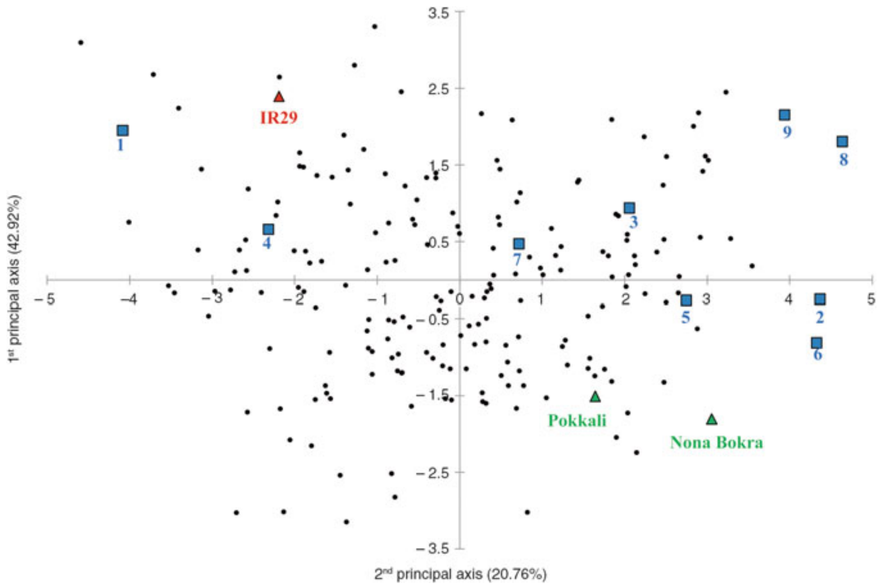

Fig. 4.4 Scatterplot of 200 rice varieties projected on the two first axes of a principal component analysis using seven developmental response variables and an ionic response variable (leaf K^+/Na^+ ratio) under moderate salt stress in the vegetative phase. The leaf K^+/Na^+ ratio, which highly contributed to defining axis 1, clearly differentiated tolerant varieties such as Nona Bokra from sensitive varieties such as IR29 (from Ahmadi et al. 2011)

production was the focus of positional cloning. The identified gene, i.e. *SKC1* (*OsHKT8*), codes for a Na^+ transporter and promotes Na^+/K^+ homeostasis. The same zone on chromosome 1 seems to host a group of genes involved in the rice salt stress response.

Differential expression and functional and comparative genomics approaches have revealed a very high number of candidate genes involved in the rice salt stress response (Negrão et al. 2011). All of these approaches are based on genetic engineering techniques, which are well established in rice.

An association study focused on a temperate *japonica* group led to the detection of 19 loci significantly associated with one or several phenotypic salinity response variables (Ahmadi et al. 2011). The analysis of the function of these loci showed that all major salinity adaptation mechanisms were present in the temperate *japonica* group, but that no varieties in the panel had a sufficient level of expression for all of the mechanisms. Under moderate salt stress, some varieties achieved the same level of tolerance as the tolerant Nona Bokra reference variety, but without having the same allele at several tolerance-related loci. This suggests that there are differences between *indica* and *japonica* varieties regarding QTLs and genes involved in salinity tolerance and that it would therefore be possible to enhance rice salinity tolerance beyond that of the reference variety.

4.3.3 Breeding Salt-Tolerant Rice

Rice breeding programmes geared towards obtaining salt-tolerant varieties were for a long time based on selection for yield under salt stress in progeny of crosses between a salinity susceptible yet popular variety and a tolerant variety. The efficiency of this ‘conventional’ selection method was hampered by the lack of control of the period of salt stress and its intensity and by the difficulty of distinguishing and cumulating the effects of different tolerance mechanisms.

The advent of molecular marker-assisted selection (MAS) has overcome some of these difficulties. For instance, the favourable allele of the *SKC1* tolerance gene in the Nona Bokra variety was transferred to many modern varieties. Salinity tolerance is, however, a complex trait involving a high number of genes, each explaining a small share of the observed phenotypic diversity. The *SKC1* gene has the greatest known effect but it only explains 40 % of the observed variation in its segregating progeny. We thus recommend recurrent MAS schemes in biparental or (even better) multi-parental crosses, to achieve pyramiding of favourable alleles from the many loci involved in tolerance.

Future progress towards gaining insight into the functioning of one or several gene networks involved in the rice response to salinity should enable better targeting of genes to be included in conventional MAS approaches based on associations between molecular markers and the targeted phenotypic trait. But as tolerance to salinity is a complex trait, the new so-called genome-wide MAS is probably the most suitable breeding approach. This approach does not require any prior knowledge of associations between the genotype (marker) and phenotype, but it does require an ability to accurately assess the tolerance of a large number of plants in order to formulate prediction equations.

Another way of improving rice salinity tolerance involves modification of the expression of genes involved in plants’ response to salinity using genetic engineering techniques. Over the last 15 years, these techniques have been applied to a large number of mechanisms and genes of rice salinity tolerance. The results are hard to assess in the current societal and regulatory setting with regard to field testing of genetically modified plants. Future progress on the accuracy of genetic engineering and of spatiotemporal control of expression of target genes should enhance the efficiency of these techniques within the limits imposed by global balances that govern plant growth and development. Genetic engineering techniques can also be used to insert genes from wild relatives or other salt-tolerant species into rice.

There is hence considerable room for progress in improving rice tolerance to salinity.

4.4 Citrus Adaptation to Salinity

Citrus represents the top tree fruit crop on the world market. Citrus fruits—native to tropical and subtropical Asian regions—are grown in all hot regions, usually under irrigation, as is the case throughout the Mediterranean Basin. Water resources are increasingly limited on the southern shores of the Mediterranean Sea, for instance, where the water demand is so substantial that the groundwater is lowering, with a concomitant increase in salt content. This is already having an impact on agriculture. Citrus trees are amongst the most susceptible of all trees to salt stress. The critical electrical conductivity level of water is 3 dS/m. For grapefruit and orange trees, the minimum tolerable electrical conductivity in soil is around 1.8 dS/m. The sensitivity can, however, vary depending on different parameters, such as tree age, rootstock, grafted variety, irrigation system, soil type and climatic conditions.

To ensure better citrus adaptation to salinity, it is essential to effectively manage irrigation practices in order to hamper salt seepage in the soil, while having access to rootstocks capable of limiting Na^+ and Cl^- uptake in the root system and to varieties that foster physiological and molecular mechanisms that will reduce the impact of toxic ions.

4.4.1 Citrus Propagation Strategies

Citrus are classified in three main sexually compatible genera: *Citrus*, *Poncirus* and *Fortunella*. Most currently used rootstocks belong to *Citrus* and *Poncirus*, or are hybrids obtained by crosses between these two genera. Rootstocks are seed propagated. Rootstock seeds that are generally used are polyembryonic. Supernumerary embryos are from nucellar cells (somatic tissue) and are genetically identical to the parent tree. The most commonly cultivated fruit varieties (orange, mandarin, lemon, grapefruit and lime) all belong to the *Citrus* genus. Varieties are clonally propagated by grafting.

Most citrus varieties are diploid (2x). Other polyploidy levels have also been identified such as tetraploidy (4x) resulting from incomplete meiosis, which produces nucellar cells with a double set of chromosomes. Around twenty 4x rootstocks have been selected in the San Giuliano collection in Corsica, jointly managed by INRA and CIRAD. These trees produce polyembryonic seeds that give rise to 4x seedlings after they are sown.

4.4.2 Citrus × Salinity Interactions—Adaptation Mechanisms

Unlike most plants, the susceptibility of citrus to salt stress is due to the presence of Cl^- ions but the molecular mechanisms involved have yet to be specifically identified. The negative impacts of salinity on citrus trees result in symptoms such as leaf burn, stunting and reduced fruit production. The impact of salinity on plant growth and development is associated with serious physiological disorders, leading to a reduction in the cellular osmotic potential, the accumulation of Cl^- and Na^+ ions to toxic levels, and finally to nutritional imbalances that can ultimately induce a reduction in growth and fruit yield. Several adaptation processes are induced, such as cellular K^+ uptake, the compartmentalization of Na^+ and Cl^- ions out of the cytoplasm and solute synthesis, thus enhancing osmotic adjustment. Finally, oxidative stress triggering is a side effect of the presence of toxic ions in the cytoplasm, which can cause major damage to the photosynthesis machinery. As noted in rice, the presence of cellular OFRs triggers detoxification systems to limit the induced oxidative stress.

4.4.3 Rootstock, Diversity and Salt Tolerance

Oppenheimer (1937) was the first to demonstrate the impact of rootstock on the behaviour of citrus trees exposed to salt stress. Three main groups were identified: a tolerant group, including 'Sour' orange and 'Cleopatra' mandarin which are considered to be well adapted to abiotic constraints, a susceptible group with 'Rough' lemon and 'Carrizo' citrange, and finally a highly susceptible group represented by *Poncirus* accessions (*Poncirus trifoliata*). Despite the good behaviour of some rootstocks in response to salt stress, their use is very limited due to their susceptibility to certain diseases, such as *Phytophthora* spp. and tristeza. *Poncirus* accessions are tristeza tolerant but do not limit root Cl^- uptake. Once in the roots, these ions transit through the xylem via the transpiration stream to the upper part of the tree, often causing leaf necrosis. The leaf Cl^- content can thus be considered a good criterion for assessing the salt tolerance/susceptibility properties of rootstock seedlings (Hussain et al. 2012a). 'Cleopatra' mandarin x *Poncirus* hybrids are now widely used in rootstock selection programmes to transmit biotic and abiotic stress traits to progeny.

An analysis of physiological salt stress tolerance behaviour as a function of citrus species was recently conducted (Fig. 4.5; Hussain et al. 2012a). Citron were the most susceptible whereas mandarin and pummelo were much more tolerant. Susceptible genotypes exhibited chlorosis symptoms combined with high leaf Cl^- and Na^+ ion uptake. Photosynthesis and growth were maintained in the tolerant genotypes and had low Cl^- and Na^+ ion uptake. Rapid leaf loss was observed in some species such as grapefruit. This phenomenon was followed by growth of new

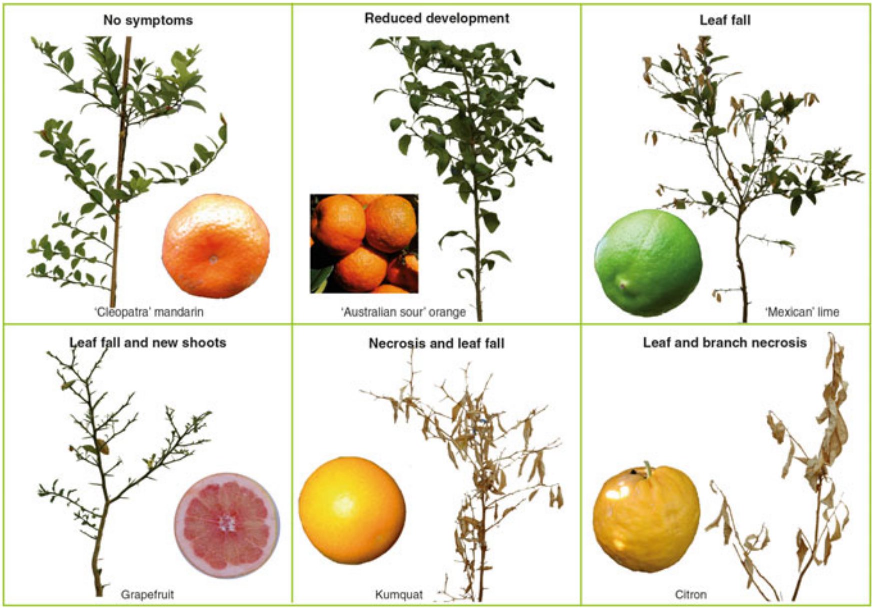

Fig. 4.5 Illustration of the impact of salt stress on major citrus fruit varieties (Hussain et al. 2012a)

leafy shoots, which could be interpreted as an adaptation response. New sources of tolerance could thus likely be tapped within citrus diversity in order to enhance salt tolerance in citrus trees.

4.4.4 Polyploidy and Adaptation to Salt Stress

The morphology and anatomy of 4x citrus genotypes differ markedly from those of their 2x counterparts. The growth of 4x plants is usually lower than that of 2x plants. Stems and roots of 4x plants are generally thicker and more succulent than those of 2x plants (Allario et al. 2011; Hussain et al. 2012b) since 4x cells are larger than 2x cells.

In salt stress conditions, 4x rootstocks were found to be more tolerant than 2x rootstocks (Saleh et al. 2008; Mouhaya et al. 2010), although leaf Cl^- and Na^+ ion accumulation was not significantly different. These latter results suggest that 4x genotypes have better compartmentalization and detoxification capacities than 2x, as documented in other 4x plants (Zhang et al. 2010). However, the impact of salt stress on grafted 4x rootstocks in orchard conditions is not yet known.

4.4.5 Breeding Salt-Tolerant Varieties

Germplasm and polyploidization (tetraploidization) will be exploited in the coming years to select new rootstocks in order to hamper toxic ion uptake in roots and thereby enhance salt stress tolerance. Several rootstocks developed by CIRAD are currently being evaluated, which should broaden the range of rootstocks available for citrus industry. Another way to deal with this issue is to assess the salt tolerance properties of newly created fruit varieties (scions) rather than those of rootstocks. Several thousands of 2x and 3x citrus varieties are being assessed in collaboration with private partners as part of the CIRAD citrus breeding programme. An assessment was recently conducted regarding the salt tolerance properties (including compartmentalization of toxic ions and improved OFR detoxification capacity) of varieties preselected for their taste qualities. It should thus be possible to strengthen the tolerance properties of orchard trees through the association of more salt-tolerant varieties with rootstocks adapted to saline soil.

4.5 Conclusion

There have been major efforts to develop more salt-tolerant genotypes. However, it is essential that not only the biological aspects but also the economic and social factors be taken into account to ensure that human activities will mitigate the impact of this stress on ecosystems as much as possible. Research innovations can prompt rethinking on livestock and crop farming practices, but users must also participate closely in the assessment of these new genotypes adapted to growing in salt stress conditions.

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Chapter 5
Enhanced Drought Adaptation in African Savanna Crops

Jean-Marc Lacape, Romain Loison and Daniel Foncéka

Abstract Producing varieties tailored for sustainable agriculture, especially with high resilience in response to environmental constraints, is a challenge for geneticists. In the framework of climate risk characterization regarding drought, a multidisciplinary approach combining ecophysiology and genetics could be effective for developing varietal ideotypes that combine adaptive traits that could be useful for breeding. Selection initiatives geared towards obtaining varieties with high drought resistance are focused on natural or hybridization-based diversity and on adaptive trait screening tests. Examples of research programmes developed in partnership by CIRAD are presented with regard to two tropical crops—cotton and groundnut. The beneficial features of African sorghum associated with its photoperiodic nature are discussed. Broad-ranging investigations to tap the gene pool of wild species related to cultivated species are required to make effective use of the genetic diversity.

5.1 Climate Change and Plant Drought Adaptation

5.1.1 Drought Diversity

Drought is a major agricultural production constraint in developing countries. The global decline in rainfall volume may be associated with a reduction in the length of the rainy season or an increase in the frequency of periods without rain during the

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cycle. It is widely recognized that climate change is accompanied by increased risks in terms of interannual variability and the onset of extreme climatic events. The impact of drought periods on crop yields varies depending on the crops concerned, especially on the nature of their development and reproduction. There are also, for instance, critical sensitive phases that differ between continuously growing crops on the one hand and cereals on the other.

5.1.2 Plant Adaptation Mechanisms and Genetic Improvement

In this setting, varietal selection and the dissemination to farmers of the best adapted improved varieties could be an effective way to reduce the impact of drought. This seed-based response should usually be combined with adjustments to crop management practices.

In crop plants, adaptive responses to water constraints are generally associated with three main strategies (Blum 1988):

- escape, via adjustment of the development cycle (see sorghum example in Box 5.1);
- avoidance, which corresponds to the plant's ability to avoid drying, typically by controlling water loss and/or maintaining water uptake;
- tolerance, or the plant's ability to overcome degradation of its water status, e.g. by osmotic adjustment.

Box 5.1. Sorghum adaptation to climate change—the potential of African sorghum.

Gilles Trouche, Michel Vaksmann

Sorghum [Sorghum bicolor (L.) Moench] is a key crop for farmers in semiarid regions because yields remain steady even under low or irregular rainfall conditions. Sorghum is the fifth-ranking cereal crop in the world and a staple food for over 500 million people in over 30 countries, mainly in Africa and Asia.

African farmers have long experience in coping with irregular rainfall conditions. They have developed effective techniques to deal with this irregularity. The most spectacular of these takes advantage of photoperiodism as a result of ancestral selection of local varieties under these harsh environmental conditions. The photoperiodic feature enables synchronization of flowering with the end of the rainy season—which is relatively stable between years—independently of the sowing date. With the potential rise in average temperatures, an increase in rainfall variability and in the frequency of extreme events such as drought and flooding could be expected. Thanks to suitable phenological features, photoperiodism could mitigate the effects of climatic variability by improving the production stability and grain quality, while avoiding the development of mould, which otherwise occurs when flowering is too early.

African sorghum local varieties can thus be utilized for the development of varieties specifically adapted to a range of variable environmental conditions. CIRAD sorghum improvement programmes now incorporate this broad genetic base, thus reconciling the production potential of modern varieties and the specific qualities of local varieties.

5.1.3 Towards the Identification of Adaptation Traits and Selection

Yield—an integrative trait on the plant, plot and temporal scale—generally involves low heritability and high genotype × environment interactions. For breeding, it is thus necessary to break down yield into simpler individual and more heritable components that could be used in screening tests, i.e. easier to measure than field yield, but in correlation with the latter, and that could be assessed over large populations. Depending on the species, mechanisms involved or monitoring level (organ, whole plant, plot), various physiological indicators are recommended for use in selection characterization, including global indices (stress index, leaf roll, etc.), indicators associated with photosynthesis and gas exchange, consumption and water use efficiency, water status variables and osmotic adjustment.

Multidisciplinary approaches (genetics, physiology, genomics, modelling, agronomy) are needed for the development of more efficient varieties under water stress conditions. This development is based on effective use of genetic variability for yield under stress conditions or for the physiological traits involved. In marker-assisted selection (MAS) approaches, plant material (segregating populations and diversified germplasm) is the focus of simultaneous characterizations of the genotype using DNA markers and of the phenotypic traits (under stress *versus* no-stress conditions). Such cross characterizations can help identify the genome regions involved, or quantitative trait loci (QTLs), allowing indirect progeny selection. Recent developments in molecular biology and genomics have led to a major change of scale in the genetic dissection of traits, thus facilitating the analysis of variations in the expression of thousands of genes in many individuals under various stress conditions (Blum 2011; Mir et al. 2012). When candidate genes are identified, genetic engineering can be used to check the effects of genes, or even develop marketable transgenic varieties (Varshney et al. 2011). Approaches such as MAS or genetic engineering have been widely developed to enhance plant resistance to biotic and abiotic stress, mainly by private seed companies, but there are still very few applications.

5.2 The Example of Cotton

5.2.1 Context

Cotton crops (Fig. 5.1) have relatively high water requirements of at least 500–600 mm over the 120–150 day crop cycle.

Cotton cropping is an important component on farms in West and Central Africa because of the financial revenue it generates. It is primarily conducted on smallholdings under rainfed conditions in rotation with food crops. These small farms are highly vulnerable to production constraints, especially erratic rainfall and the international market setting when export crops like cotton are grown (variations in world raw material prices).

5.2.2 Questions and Avenues of Research at CIRAD and Worldwide

5.2.2.1 Wide Genetic Resource Diversity in the *Gossypium* Genus—The Wild *G. Hirsutum* Pool

The current variability in species belonging to the *Gossypium* genus is remarkable since wild types still exist in their natural state, as is the case for *G. hirsutum*, the main cotton crop species. Perennial *G. hirsutum* cotton populations in the Mesoamerican and Caribbean regions were recently the focus of a combined

Fig. 5.1 Cotton bolls (© J.-M. Lacape/CIRAD)

ecological niche modelling and genetic study (Coppens d'Eeckenbrugge and Lacape 2014). A total of 950 georeferenced data points, representing the same number of described populations, were pooled. Around 100 of these were truly wild cotton populations encountered at some 15 locations from Venezuela to Yucatan (Mexico), and through the Greater and Lesser Antilles to Florida (Fig. 5.2a). The other points mainly formed the so-called 'feral' group (domesticated form returned to its natural state). These wild cottons, which could be assigned to the *yucatanense* race of *G. hirsutum*, are confined to coastal environments generally under the constraint of limited water supplies or saline stress. A principal components analysis on the 19 climatic variables of the ecological niche modelling and genetic analysis component based on marker dissimilarities positioned them a posteriori as a distinct homogeneous entity (Fig. 5.2b). This pool of wild cotton diversity represents a gene reservoir that could potentially be used to improve cultivated *G. hirsutum*, particularly regarding traits of environmental stress resistance—the advantage is that these cottons are easy to hybridize since they belong to the same species as cultivated cotton.

5.2.2.2 Exploitation and Effective Use of Genetic Diversity in Global Cultivated Cotton Germplasm

A genome-wide association study (GWAS) project on responses to water deficits within the cultivated *G. hirsutum* pool is under way as part of a collaboration between the Brazilian agricultural research agency EMBRAPA and CIRAD. Both institutes have cotton germplasm collections that encompass a substantial share of the variability (Campbell et al. 2010) studied in this project. A panel of 200 varieties of various origins will be the focus of morphological characterizations under controlled conditions in rhizotrons for root system analysis (Fig. 5.3), and also using a high-throughput measurement facility at INRA, Montpellier (PHENOARCH platform for automated measurement of aboveground plant parts under various moisture conditions). High-throughput genotyping will be performed [50,000 single-nucleotide polymorphism (SNP) markers] to correlate variations noted on the genome scale with measured traits. The initial results of the rhizotron studies in Brazil highlighted marked variability in root growth parameters.

5.2.2.3 Understanding the Response Mechanisms

The findings of cotton physiology studies and a physiological analysis of the response of cotton plants to water deficit conditions (Blum 2011) highlighted the importance of taking the effective stress status of compared treatments into account, e.g. compared genotypes. This was achieved by characterizing the fraction of transpirable soil water (Lacape et al. 1998; Lacape and Wery 1998) (Fig. 5.4). In a second step (Lacape and Wery 1998), different conceptual models of final yield breakdown (per-ha production) enhanced the understanding and interpretation of

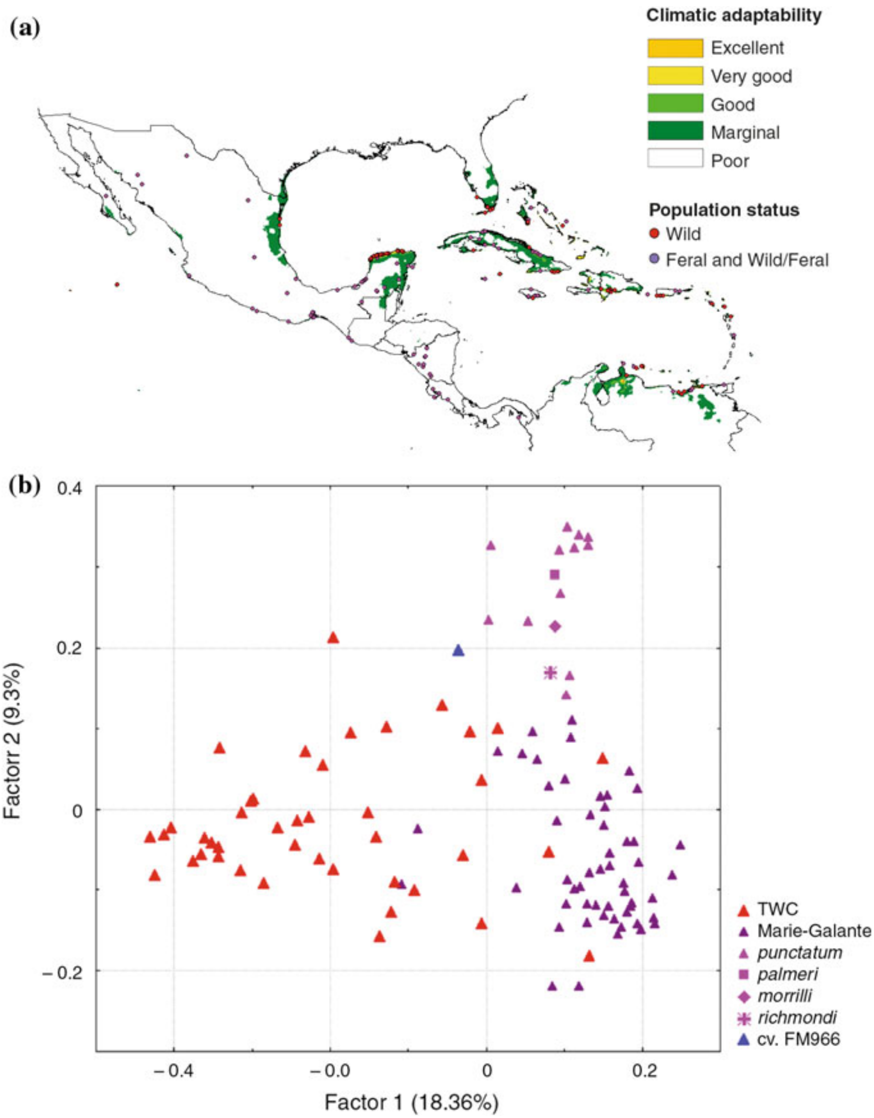

Fig. 5.2 **a** Distribution of populations of perennial cotton (*G. hirsutum*) in Mesoamerica and the Caribbean and climate model associated with wild types. **b** Principal components analysis of genetic dissimilarities (26 microsatellite markers) between 110 chosen genotypes and distributed between wild types, or truly wild cotton (*TWC*) and feral types (other categories) (from Coppens d'Eeckenbrugge and Lacape 2014)

observed differences. Two types of model were tested, i.e. a yield component framework model (a 'development' model), which considers the dynamics of flower and fruit production and losses combined with their weight, and a biomass

Fig. 5.3 Partial view of the rhizotron study set up. Each cotton plant grows in a space filled with soil between two glass plates. At the end of the experiment (21 days after sowing), the root system is photographed and processed by image analysis (M. Giband/CIRAD)

production framework model (a 'biomass and efficiency' model), in which daily total biomass production was related to the water or radiation use efficiency, and also to the harvest index.

5.2.2.4 Genotype × Environment Interactions

A recent historical analysis by R. Loison (CIRAD) of the main cotton cultivars widely grown in Cameroon revealed a significant genetic gain in fiber yield, quality but not in seed cotton yield. It should be possible to increase seed cotton yield by gaining insight into the effects of the interaction between the genotype (G), environment (E) and cropping system (CS), on the morpho-physiological traits involved in water stress adaptation (Pettigrew 2004). An analysis of experiments carried out under controlled conditions in France and in the field in Cameroon revealed a transition in favour of a new water stress adaptation strategy in the last cultivar disseminated in the region of Cameroon with the least rainfall (Table 5.1). A good representation of the different behaviours adopted in response to water constraints

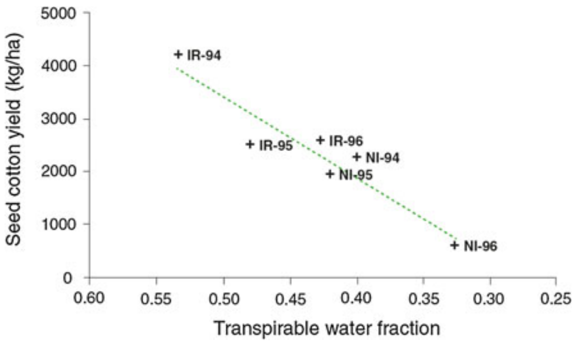

Fig. 5.4 Relationship between seed cotton yield and the mean fraction of transpirable soil water during the effective flowering period over three study years (1994, 1995, 1996). Means of five varieties under two water regimes; *IR* irrigated, *NI* not irrigated (from Lacape and Wery 1998)

in current mechanistic models could enable accurate simulation of cotton growth and development under various moisture conditions. This would also facilitate the determination of ideal genetic parameter values of cultivars for given agroclimatic and socioeconomic contexts, i.e. define a varietal ideotype.

Table 5.1 Main discriminating traits when comparing a recent cotton variety (IRMA L484) from the far northern region of Cameroon with older varieties, measured under limiting water conditions and two ecophysiological analysis frameworks

Analysis framework	Traits of the recent cultivar (IRMA L484) compared to older cultivars
RUE	Same leaf area per plant, but with smaller and more numerous leaves
	Thicker leaves with higher chlorophyll levels
	Overall lower radiation interception with identical total biomass produced
	Greater assimilation per cm^2 of leaves
	→ RUE higher, also for instantaneous values
WUE	Same total leaf area
	Greater transpiration/cm^2 per leaf
	Same total transpiration
	Same total biomass produced
	→ WUE identical
Production	Same total biomass
	Same harvest index
	Same final yield (kg/ha of seed cotton)

RUE radiation use efficiency; *WUE* water use efficiency

5.2.2.5 What Genomics and Biotechnology Contributions?

QTL-based genetic mapping approaches in cotton have mainly been developed for fiber quality traits. The few published studies concerning the detection of QTLs associated with drought tolerance (Levi et al. 2009; Saeed et al. 2011) were focused, for instance, on osmotic adjustment while MAS approaches are not yet feasible. Massive sequencing of genes expressed under water stress conditions (Park et al. 2010), or the recent publication of the cotton genome (Paterson et al. 2012), broaden the prospects for identifying candidate genes and for fine assessments (QTL cloning).

Finally, transgenesis is among the available cotton genetic improvement tools being implemented worldwide with the dissemination of insect- or herbicide-resistant transgenic cotton varieties. The transgenesis approach was recently applied to achieve water stress tolerance in cotton as part of a CIRAD collaboration with an Israeli partner, with a view to the potential transfer of a tomato drought tolerance gene into cotton. The application of these results depends of course on the social acceptability of the genetic changes involved. Other transgenic studies targeting drought tolerance genes in cotton are being carried out by private seed companies that are highly active in this area, but they do not publish their findings.

5.3 The Example of Groundnut

5.3.1 Context

Groundnut (Fig. 5.5) is a major crop in most tropical and subtropical regions. Cultivated groundnut is an annual self-pollinating and underground fruiting plant. In Africa, groundnuts are cropped during the rainy season and are subject to rainfall hazards and irregularity. Cultivated groundnut (*Arachis hypogaea* L.) is one of the 80 species in the *Arachis* genus. This allotetraploid species is the result of one

Fig. 5.5 Unearthed groundnut pods at the Bambey research station, Senegal (© D. Foncéka)

single hybridization event between two diploid species with A and B genome. The history of groundnut speciation and domestication mostly explains the low diversity observed in cultivated species. However, there is high diversity amongst wild diploid species since they have been evolving for millennia and have colonized various ecological niches, ranging from semiarid regions of northeastern Brazil to the Andes. These wild species are a source of new alleles and may be used in breeding programmes to improve simple traits such as disease resistance, in addition to more complex traits such as adaptation to water deficit conditions and productivity.

5.3.2 Questions and Avenues of Research at CIRAD and Worldwide

5.3.2.1 Towards an Integrated Selection Strategy for Groundnut Drought Adaptation

Improvement of groundnut drought tolerance is a major goal of breeding programmes. In Senegal, studies carried out by the *Institut sénégalais de recherches agricoles* (ISRA) and CIRAD have led to the dissemination of new varieties through a broad range of selection approaches: recurrent selection in populations with a broad genetic base, and backcrossing to reduce the cropping cycle length of local varieties based on multidisciplinary approaches (genetics, physiology, genomics). This has given rise to key recommendations for an integrated groundnut selection strategy (Clavel et al. 2007), focused especially on the early selection principle under moisture constraint conditions in the field, on the use of plant material combining different favourable traits, such as membrane stability under water stress conditions, and earliness, and when possible (identification of a physiological trait) on the use of molecular markers and MAS.

5.3.2.2 Contribution of Interspecific Hybridization and Highly Self-Limiting Populations

After identifying the wild diploid ancestral species of cultivated tetraploid groundnut (Seijo et al. 2004; Favero et al. 2006), research teams from different parts of the world [USA, Brazil and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), in India] produced wild synthetic tetraploid hybrids crossable with cultivated groundnut (Favero et al. 2006). This material has the same ploidy level as cultivated groundnut and is used in selection programmes to improve interesting traits such as disease resistance. CIRAD, CERAAS,[1] the

[1]Centre d'études régional pour l'amélioration de l'adaptation à la sécheresse.

Senegalese *Centre national de recherches agronomiques* at Bambey and EMBRAPA in Brazil recently developed a programme for broadening the genetic base of cultivated groundnut through a molecular marker-assisted introgression process. A first synthetic tetraploid hybrid, combining the A and B genomes of two wild diploid species (*A. duranensis* and *A. ipaensis*) was used in crosses with the Fleur11 variety to produce—for the first time in groundnut—highly resolutive populations, thus facilitating detailed genetic analysis, including an AB-QTL (advanced backcross-QTL) population and a CSSL (chromosome segment substitution line) population. An analysis of the AB-QTL population enabled mapping of many QTLs involved in groundnut plant and pod morphology, as well as in yield and yield components under normal or water stress conditions (Foncéka et al. 2012a). The CSSL population is of special interest for genetic analysis and improvement applications. It consists of a set of genetically fixed lines, with a genetic make-up that is very close to that of the cultivated groundnut genome, with each including a small chromosome segment of wild origin such that the set of introgressed segments are representative of the entire wild parent genome (Fig. 5.6) (Foncéka et al. 2012b). The CSSL population was exchanged and is currently being

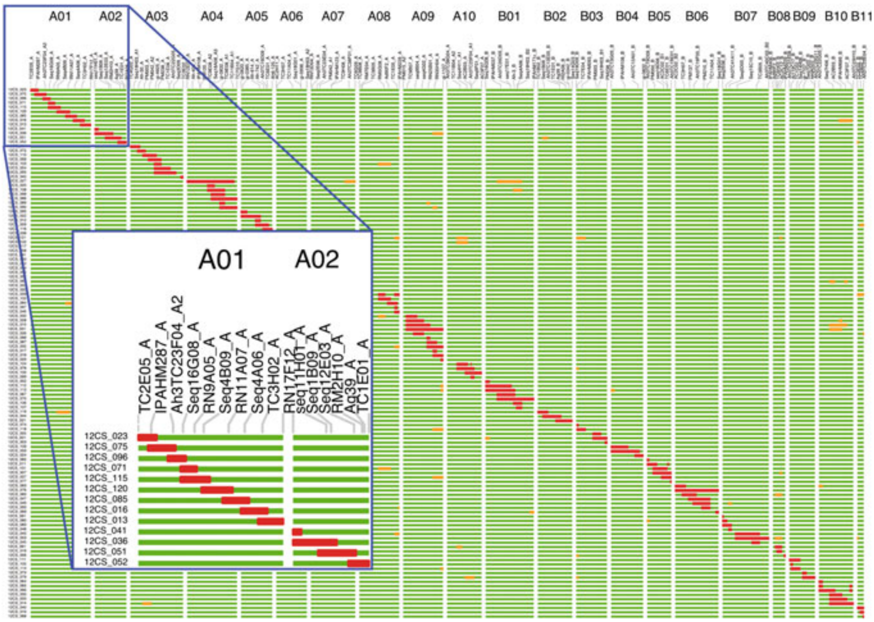

Fig. 5.6 Schematic representation of 122 lines (*rows*) of the CSSL population along the 20 chromosomes (*columns*). Chromosome regions derived from the wild parent are shown in red, with the rest of the genome (*green*) being from the cultivated variety. The enlarged inset represents the first 13 CSSLs bearing introgressed segments from the first two chromosomes A01 and A02 (Foncéka et al. 2012b). *CSSL* chromosome segment substitution line

characterized in several groundnut genetic improvement programmes (Senegal, Mali, Niger, Malawi, India and Brazil) for use as starting breeding materials. These interspecific populations are presently the focus of several PhD research studies.

5.4 Conclusion and Outlook

To address major global challenges associated with climate change, plant breeders are using different approaches to improve the response of crops to water deficit conditions through the development of better adapted varieties. A joint approach, illustrated here with regard to both cotton and groundnut, is focused on more effective use of the features of related wild species. In all cases, insight into the adaptation mechanisms and identification of traits to be targeted for selection are essential. These research issues concerning the enhancement of drought adaptation are pivotal to international initiatives aimed at pooling initiatives and resources—CERAAS in Senegal is emblematic in this respect (Box 5.2).

Box 5.2. CERAAS in Senegal.

The *Centre d'études régional pour l'amélioration de l'adaptation à la sécheresse* (CERAAS) was founded in 1989 in Senegal to pool—on a regional scale—research initiatives of research institution members of the West and Central African Council for Agricultural Research and Development (WECARD), with strong ongoing involvement of CIRAD scientists. CERAAS, based at Thiès, has infrastructures, laboratories and field facilities devoted to research studies on plant drought adaptation.

CERAAS targeted research projects are aimed at developing a multidisciplinary approach involving agronomy, physiology, selection, modelling and molecular genetics to be included in breeding programmes. Research is focused on gaining insight into the physiological and molecular basis of plant responses to drought, on the analysis of germplasm diversity and use in breeding programmes, and on the improvement of agricultural production forecasting and modelling methods.

The degree training component in partnership with local or international universities (CIRAD, IRD, universities in developed countries), or research-based training through the hosting of researchers from the subregion, or modular training via theoretical and practical courses, represent a substantial part of its activities.

Different recent developments have placed CERAAS at the centre of several international initiatives, including projects with the World Bank or a new platform in partnership with CIRAD.

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Chapter 6
Tropical Crop Pests and Diseases in a Climate Change Setting—A Few Examples

Christian Cilas, François-Régis Goebel, Régis Babin and Jacques Avelino

Abstract Climate change alters the behaviour of pests and their distribution. There is a genuine risk that pest and disease pressure will increase as a result of environmental and agrosystem disturbances. This is a concern for all agricultural stakeholders, especially in temperate countries where introductions of new pests, diseases and weeds abound. The list of introductions in Europe is getting ever longer, with the onset of disturbing phenomena that are a real threat to food security. The impact of climate change on pest populations and their natural enemies in the tropics is even harder and more complicated to grasp—changes in pest status, introductions, dramatic development of diseases or insect populations and extension of their ranges are being observed. Based on examples of insects and diseases affecting a few tropical agrosystems, we discuss the impact of climate change on these pests and propose new agroecological protection strategies while promoting the conservation of natural regulation services to sustainably reduce pest and disease risks.

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6.1 Background

Since the advent of agriculture, diseases and pests have affected agricultural production worldwide, sometimes causing substantial yield losses. Changes in climatic conditions increase these losses, while threatening food security and farmers' livelihoods. Developing countries are highly dependent on agriculture and hence especially vulnerable to changes in pest status. Hundreds of millions of smallholders depend solely on agriculture for their livelihoods. In recent decades, pest control has been heavily reliant on pesticide treatments, which can have adverse effects on humans and the environment, especially rural communities that do not always have access to proper treatment and protection equipment. Climate change can also have an impact on food safety by, for instance, creating favourable conditions for the contamination of stored produce by fungi that produce mycotoxins which are harmful to human health—this concerns foods such as groundnuts, wheat, maize, rice and coffee.

There is evidence that climate change alters the distribution of plant pests and pathogens, but it is hard to predict all of its effects. Changes in temperature, humidity and atmospheric gas concentrations can modify plant, fungus and insect growth and renewal rates, therefore disturbing biological and chemical interactions between pests, their natural enemies and hosts. This is particularly true in tropical environments where geophysical features (no climatic breaks in pest cycles) and biological features (high biodiversity, very complex community networks and substantial biotic constraints) are conducive to pest outbreaks or quick changes in their status. Climate change is, however, only one of a number of components of what is now called global change, which also includes the large-scale increase in material and commercial trade as well as human modification of natural environments. Climate change is a complex phenomenon, so it is hard to separate and identify the role of the different components that have a bioecological impact and modify pest pressure on agrosystems. Based on a few examples of tropical crop pests of economic importance, we describe the phenomena observed in association with climate change and potential solutions to mitigate the impact and reduce the pest pressure.

6.2 Impact on the Epidemiology of Coffee and Cocoa Diseases

6.2.1 Coffee Rust

Rust is one of the most serious fungal diseases affecting *Coffea arabica* and a major epidemic has been developing in recent years in Latin America. The impact of coffee rust varies depending on the fruit load on coffee trees (Avelino et al. 1991), temperature, rainfall, humidity, cultivar, treatments and landscape configuration

(Avelino et al. 1991, 2012). The factors determining recent rust epidemics in Central America are economic, but climatic factors are also strongly suspected in light of the unusual severity of the epidemics. Several meteorological anomalies (temperature, rainfall, sunshine duration) were noted over the 2008–2013 period, which was crippled by major epidemics. The mean annual temperature in 2012 in the region was close to the average for the 1981–2010 period, but very little variability was observed. Low temperatures which hamper rust development are less frequent. Epidemics are now occurring in highland regions where high quality coffee is grown and where rust outbreaks seldom occurred in the past.

Several options are being investigated. The dissemination of resistant plant material seems to be one of the most promising solutions, but coffee is a tree crop and it takes many years to replace an orchard. Moreover, several resistance traits developed in genetic improvement programmes have turned out to be relatively unsustainable, with resistance breakdown appearing after a few years. It would therefore be preferable to promote quantitative resistance (horizontal), which is generally more sustainable than monogenic resistance. Genetic strategies cannot solely overcome the spread of rust epidemics—agroecological management strategies against the parasite complex (including the coffee berry borer which we will discuss hereafter) should also be developed. Gaining insight into dispersion and development phenomena according to the landscape setting and cropping conditions is thus essential (Avelino et al. 2012). Efficient management of shading, appropriate pruning, fertilization tailored to fruit load and soil conditions, and timely fungicide applications could reduce the rust pressure and incidence in coffee orchards, while also delaying resistance breakdown after the resistant material has been planted. Coffee genetic improvement studies (Chap. 7) aimed at obtaining healthy, more resistant and resilient plants are complementary to the agronomic approaches presented here.

6.2.2 Cacao Swollen Shoot Virus—Climate Change, Deforestation or Both?

The cacao swollen shoot virus disease (CSSVD) is causing heavy production losses in West African cocoa plantations (Fig. 6.1). The virus alters the physiological functioning of cocoa trees, ultimately killing them within a relatively short period (6 months–3 years). As cocoa trees are native to the Amazon Basin and the virus was initially only present in Africa, a switch in host from an African plant to cocoa occurred. Is the progress of this epidemic due to climate change? Several hypotheses have been put forward, but deforestation of cocoa growing areas in Côte d'Ivoire is the most common explanation. This vector-borne disease is transmitted by several mealybug species and differs markedly from coffee leaf rust. Deforestation could have led to a rise in their populations on cocoa trees. Moreover, the virus strains detected in Côte d'Ivoire are new strains that have not been found in former outbreak

Fig. 6.1 Cacao swollen shoot virus disease, Soubré, Côte d'Ivoire (© C. Cilas/CIRAD)

areas in Côte d'Ivoire, Ghana or Togo (Kouakou et al. 2012). The dramatic increase in CSSVD therefore seems to be due to the transmission of new strains derived from other plants in Côte d'Ivoire as a result of global changes induced by deforestation, which is also disrupting climatic conditions in the vicinity.

6.3 Lepidopteran Stem-Borers and Other Insect Pests of Sugarcane—Biological Control Disturbances, Expansion of Infested Areas

Chilo sacchariphagus (Fig. 6.2) and *Eldana saccharina* are two lepidopteran stem-borer pests that have a major economic impact by causing significant sugar and biomass losses in sugarcane crops (Goebel and Way 2009). Biological control is one of the most common strategies used to manage these pests. Tiny *Trichogramma* parasitoid wasps attack lepidopteran eggs and are among their natural enemies, thus

Fig. 6.2 A *Chilo saccharìphagus* stem borer larval caterpillar on a sugarcane stalk (© R. Goebel/CIRAD)

playing a key role in regulating natural stem borer populations. A decline in natural *Trichogramma* parasitism has been noted in some countries and several factors have been advanced to explain this situation, e.g. chemical treatments, cane field burning (still carried out in many African countries), or the occurrence of acute recurrent droughts. This has led to a scarcity of resources and shelters for *Trichogramma* that are naturally present or released via biological control operations, thus hindering their maintenance and survival in the agrosystem. *Trichogramma* wasps live on external plant parts and are hence very sensitive to temperature variations, whereas stem borers are endophytic, living inside sugarcane stalks, therefore benefiting from more buffered living conditions (Goebel et al. 2010).

A change in the status of these pests and an extension in their distribution have been observed. A study carried out in South Africa showed that there is a good chance that the sugarcane stem-borer, *Chilo sacchariphagus*, which is already present in other southern African countries (Malawi, Mozambique, Zimbabwe), will infect ‘cooler’ sugarcane growing areas in South Africa due to the overall increase in temperatures in this country (Bezuidenhout et al. 2008). Agricultural areas in the highlands of Réunion, where the cool temperatures still hamper colonization by lepidopteran stem-borers, could also be increasingly affected by infestations. Such changes in status may be further illustrated by the infestation and rapid adaptation of the sugarcane thrips, *Fulmekiola serrata*, in South Africa (Way et al. 2010), and very recently by *Sipha flava* aphids. These aphids can transmit yellow leaf syndrome, a serious sugarcane disease that could have a major impact on the South African sugar industry.

6.4 Changes in the Helicoverpa Armigera Population Dynamics in Cotton Fields

Helicoverpa armigera is a lepidopteran cotton pest in West Africa. The life cycle of this species is closely linked with the climatic conditions and it may undergo up to 10 generations a year under tropical climates. The length of each stage during the life cycle depends on the environmental conditions (resource availability, rainfall and temperature). The caterpillar enters diapause when the conditions are unfavourable (resource availability, rainfall and temperature), which lengthens the cycle and reduces the number of generations.

In northern Benin, during infestation peaks in cotton plots, it was reported that the pest abundance was dependent on the extent of heterogeneity of host plants (cotton, maize, tomato, sorghum) in the landscape around the plots (Tsafack 2014). This heterogeneity is dependent on the cropping calendar, which in turn is closely related to variations in temperature and rainfall. The prevailing hypothesis is that the agricultural landscape around cotton plots could include more or fewer host plants for these pests depending on the temperature and rainfall variation patterns (drought, flooding).

6.5 Coffee Berry Borer—A Spreading Pest

The coffee berry borer, *Hypothenemus hampei*, is a tiny beetle (1 mm) and the main coffee insect pest throughout the world. This pest of African origin has an impact on the production output of most of the 20 million coffee growers worldwide, resulting in global losses that are estimated at $500 million a year (Vega et al. 2003).

Pesticides are not very effective in controlling this beetle since it spends most of its life cycle within coffee berries. Good cropping practices such as limiting shade, pruning coffee trees and harvesting all berries, can reduce infestations to an economically acceptable level (Damon 2000). An attractant-baited coffee berry borer trap developed by CIRAD and marketed under the trade name BROCAP® has proven effective when combined with these practices (Dufour and Frérot 2008). Biological control operations using African hymenopteran parasitoids have been under way in Latin America since the 1980s. Three species, i.e. *Prorops nasuta*, *Cephalonomia stephanoderis* (Bethylidae) and *Phymastichus coffea* (Eulophidae), have been introduced on a large scale, but with limited results so far.

Coffea arabica cropping conditions (above 1300 m elevation) do not seem to suit coffee berry borers, which are scarce in areas above 1500 m, likely because the temperatures are too low. Global warming could foster the spread of this pest into more highland areas, therefore jeopardizing highland *Coffea arabica* production, which is generally renowned for its quality. One study revealed that complete coffee berry borer development is only possible between 20 and 30 °C (Jaramillo et al. 2009) and that this pest could develop in areas where it was previously absent, such as the Jimma region in Ethiopia where coffee is mainly cropped in the highlands. The coffee berry borer was detected for the first time in 1928 in Kenya (Waller et al. 2007), a country that shares its northern border with Ethiopia. It is now found at several locations in southern Ethiopia (Mendesil et al. 2004). Models predict an increase in the coffee berry borer range in most East African coffee producing countries over the next 50 years (Jaramillo et al. 2011).

Rainfall has an indirect influence on the coffee berry borer population dynamics because coffee flowering and fruit set are dependent on the rainfall regime. Rainfall partially determines the number of berries available for coffee berry borer infestation during the year. During extreme dry seasons, coffee berries ripen simultaneously and a shortage period that is detrimental to this pest occurs after the coffee harvest. In the reverse situation, coffee berries are available year round, which is favourable for the beetle. A change in the rainfall regime, as already observed in some regions worldwide, could therefore cause differences in infestation levels of coffee berry borers and change their seasonal patterns.

The failure of successive parasitoid-based biological control campaigns in Latin America has yet to be explained. The climatic conditions in regions where these parasitoids have been introduced could be partly responsible for this situation. One reason put forward to explain the effects of temperature increases on pest abundance is the disruption of trophic systems involving crop plants, pest insects and their natural enemies. Hymenopteran parasitoids at the top of the trophic system are particularly affected by climate change (Hance et al. 2007). Global warming could thus be upsetting pest/natural enemy trophic balances by reducing the ability of natural enemies to curb pest outbreaks (Harrington et al. 2001). Regarding the coffee berry borer, a rise in temperature could affect the regulation of this pest by these parasitoids and challenge biological strategies to control it. Many signals indicate that the global impact of coffee berry borers on coffee production—highland *Coffea arabica* production in East Africa or coffee produced by smallholders worldwide—could increase as a result of global warming.

6.6 How to Cope with Climate Change and Provide New Pest Control Solutions

Climate change leads to ecosystem disturbances at all trophic levels and modifies interactions between different biological and ecological communities, including crop plants, natural habitats, aboveground biodiversity and soil (Fig. 6.3).

Cropping systems must now be tailored to these disturbances by modifying farming practices, including landscape features. Some local farming practices worsen climate change on a global scale, but incentive measures are available to foster changes in these practices and they should be applied. Because of the risk of the spread of pests beyond the current limits of their distribution due to the combined effect of trade globalization and climate change, it is essential to strengthen export crop management measures and the implementation of preventive measures in areas that have so far been unaffected. An effective biosecurity plan should be set up, including increased border surveillance, regular warnings, trapping networks and information exchange between different neighbouring countries. Australia is a leader in this area given its high drought susceptibility and constant exposure to insects and diseases from neighbouring tropical countries, such as Indonesia and Papua New Guinea (Goebel and Sallam 2011).

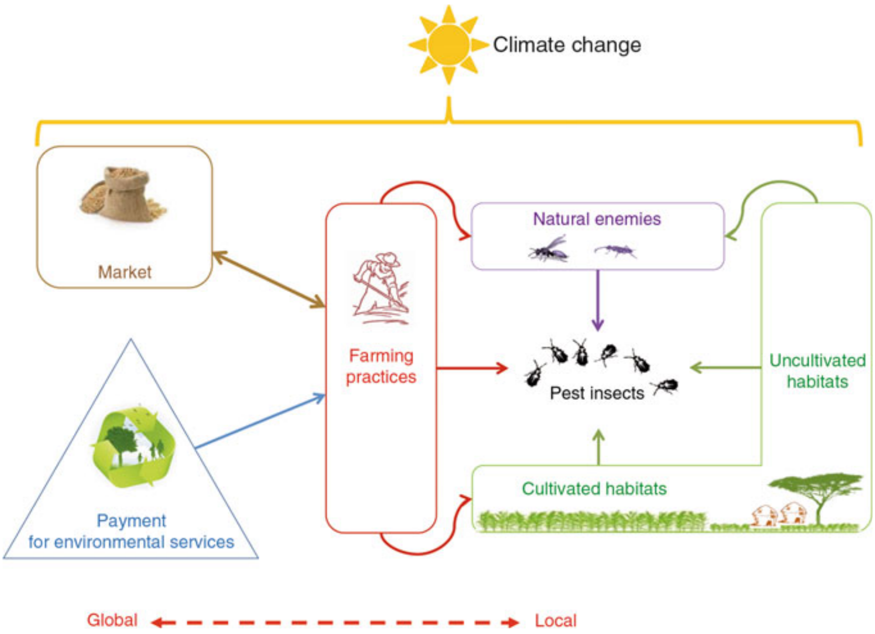

Fig. 6.3 All relationships to consider in an agrosystem under the pressure of climate change: pests and their natural enemies, link with noncultivated areas, cropping practices as well as economic and political settings on different scales (markets, especially export markets, public environmental policies), which can impact agricultural practices

The research priorities should focus on:

- local management of pest and disease risks aggravated by climate change in order to adapt cropping systems to their effects;
- adaptation of crop protection strategies to not increase the risk of climate change on a global scale;
- forecasting and prevention of the introduction of tropical pests and their establishment in more temperate areas once they become potentially invasive or emerging as a result of climate change.

This type of research is currently underway and some promising results have prompted us to continue on this path. In a study carried out in Madagascar, an improvement in the water balance and a reduction in evapotranspiration via conservation agriculture contributed to reducing the impact of blast disease in upland rice crops (Sester et al. 2013). Maintaining plant cover in rice crop fields also enables a reduction in crop losses due to pests by enhancing the local biodiversity (above- and below-ground) while reducing the use of inputs with a high carbon footprint. Coffee pest management could be facilitated via associations of coffee with other trees (Tscharntke et al. 2011). Such agroforestry practices for coffee have been adopted by most coffee smallholders in the world because these associated trees provide shade necessary to achieve a good balance between productivity and sustainability on plantations without systematic use of irrigation or fertilizers (Chap. 16). These practices should nevertheless be carefully designed because intense shade conditions could be conducive to coffee berry borer development (see above and Vega et al. 2009). But the introduction of shade trees could also be effective for maintaining the air temperature in plantations below that favourable for pest development, especially in highland regions. Moreover, shading could hamper sudden temperature changes, which are detrimental to the biological balance of agrosystems, thus contributing to the agroecological regulation of pests (Verchot et al. 2007). Ecological services can therefore be preserved while mitigating the impact of the climate on biodiversity. Moreover, it is essential to find novel ways to design cropping systems that will provide efficient pest protection through ecological processes.

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Chapter 7
Healthy Tropical Plants to Mitigate the Impact of Climate Change—As Exemplified in Coffee

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Abstract The impacts of climate change on coffee trees are hard to foresee and dependent on the cropping system (ranging from high input monocultures to almost natural agroforestry associations), soil and water resources. Pests and diseases are also affected. Research on adaptation to climate change is mainly focused on cereals but there are few studies on perennial tropical crops where stress can alter the behaviour of the plant for several seasons. Some parasites can adapt more quickly to climate change than the perennial host plants and spread into new habitats. The aim of CIRAD's coffee genetic improvement research is to obtain 'healthy' crops, i.e. more resilient and resistant. Here we present integrative approaches focused on the functioning of the genome (transcriptomic, metabolomic, genomic, epigenetic) and the whole plant, as well as adaptive responses to combined stresses. The goal is to propose targets for coffee breeding in order to improve resistance to coffee rust, nematode control and adaptation to drought.

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7.1 Coffee—A Model for Studying Climate Constraints

Coffee is a perennial tropical crop that is grown on around 11 million ha in the intertropical zone under cool highland climatic conditions (arabica coffee from *Coffea arabica*) or hotter equatorial climatic conditions (robusta coffee from *C. canephora*), from sea level to 2000 m elevation. It is hence a choice model for studying the impact of climate change on a tropical tree.

The impacts of climate change on coffee trees are hard to foresee and dependent on the cropping system (ranging from high input monocultures to almost natural agroforestry associations), soil and water resources. Pests, diseases and beneficial organisms are likely also affected.

From 2011 to 2013, a coffee rust epidemic hit the region from Colombia to Mexico, including highland areas which had never been infested before, causing production losses of over 15 %. These repeated epidemiological events were probably associated with the high humidity—but not necessarily high rainfall—and an increase in temperature.

In Brazil, the 2014 drought caused a 16 % decline in arabica coffee production and triggered considerable tension on international markets, leading to a twofold increase in coffee prices. According to a recent study, a 2–2.5 °C temperature increase would considerably reduce the available coffee growing area (Assad et al. 2004).

Most research on adaptation to climate change is focused on cereals (rice, maize, wheat), but there have been few studies on perennial tropical crops, which react differently to stress. An abiotic stress can affect the behaviour of a plant for several seasons. Some parasites can adapt to climate change more quickly than the perennial host plants and subsequently spread into new habitats.

At the same time, modern agriculture must forgo the massive use of pesticides, which have been used too long without reserve, with negative impacts on ecosystems and health, while also being costly for smallholders. The aim should be to have access to 'healthy' crops that are more resilient and resistant. Here we present CIRAD's coffee genetic improvement research in this direction.

7.2 Enhancing Plant Health—A Revisited Concept

In the recent past, plant health was too often restricted to plant protection strategies using a range of phytosanitary products or to breeding strategies whereby one or several resistance genes were selected to protect plants against major diseases.

Global warming prompted a paradigm shift in favour of the 'good health' status of plants. What, however, is a plant in good health? It is obviously one that is not sick but also one which is resilient when attacked by a parasite or an abiotic stress.

How is it possible to establish a balance in plants without using pesticides, while ensuring that productivity will be sufficiently high to fulfil farmers' economic needs? Intuitively, this good health seems to be the result of a combination of heritable and non-heritable traits. Geneticists and agronomists must be able to differentiate the genetic and non-genetic aspects. Here we address some priority targets for geneticists, such as drought tolerance, and the effects of abiotic stress on tolerance to rust and nematodes. First of all, readers should be aware of the importance of implementing long-term research that encompass all of the most likely global warming scenarios in order to be able to accurately model the adaptation capacities of trees like coffee to biotic and abiotic stresses. We then briefly discuss regulation by small RNAs to illustrate the complexity of the molecular mechanisms involved and highlight potential avenues of research.

7.3 The Specificity of Perennial Crops—Specific Field Research and Integrative Approaches

Unlike annual species, trees are subjected to and cumulate the impacts of biotic and abiotic stresses over long periods. Global warming has begun modifying known interactions between plants and different stresses. The impacts are numerous and hard to understand in the long term. In this setting, how can experiments be designed and set up to predict the adaptation capacities of coffee trees to biotic and abiotic stresses under all probable scenarios (Box 7.1)?

Box 7.1. Studying adaptation capacities through experiments tailored to perennial crops in various environments.

Plants are constantly coping with a range of different stresses, so studies cannot be focused solely on one stress. It would be hard to conduct phytotron studies on perennial plants due to their large size. The impacts of climate change vary depending on the environment considered. The effects may be buffered or, conversely, exacerbated by the elevation, latitude, shading or sunlight conditions in which the crop is grown. Studies must take all of these elements into account. One factor—the rise in carbon dioxide level associated with climate change—cannot, however, be simulated in field experiments.

CIRAD and partners have set up several unique field experiments in Brazil, Colombia, Central America and Mexico to analyse the adaptation capacities of new improved varieties (hybrids). The hypothesis is that hybrids have higher stress tolerance and are better adapted to growing in shady agroforestry systems, which are effective in buffering the effects of climate change. To gain insight into the molecular basis of heterosis (increased vigour of hybrids compared to inbred lines), an experiment was set up in Colombia, in partnership with the *Federación de cafeteros*, to compare hybrids and their parents in full sun or shaded conditions under high coffee rust pressure (Fig. 7.1).

Fig. 7.1 Experimental set up to compare the behaviour of arabica hybrids and their parents under shaded or full sun conditions in a coffee rust infected area at Manizales, Colombia (Cenicafé/CIRAD collaboration)

A multisite experiment set up in Veracruz State, Mexico, is designed to mimic the effects of global warming and analyse the behaviour of grafted or non-grafted hybrids in comparison to conventional varieties. A temperature and coffee rust parasite pressure gradient was obtained on the basis of the elevation gradient (Fig. 7.2) to study coffee adaptation mechanisms in response to a combination of thermal stresses and fungal attacks over several

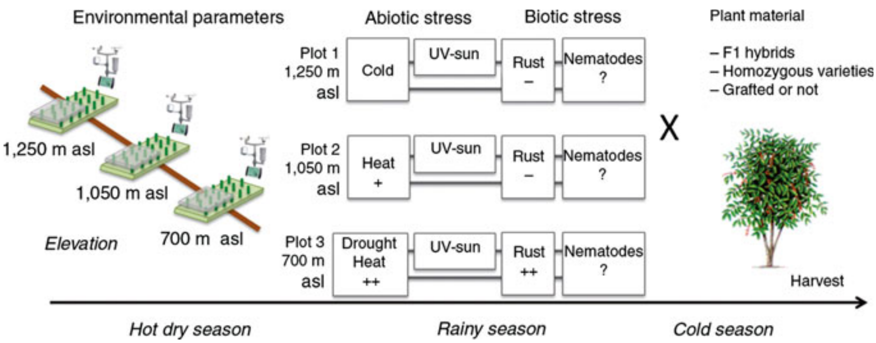

Fig. 7.2 Diagram of a multisite, multielevation experimental set up in 2013 to study the adaptation of coffee trees to rust according to temperature increases, Veracruz State, Mexico. A single varietal range (hybrids vs. line, grafted or not) was set up at three elevations under shaded or full sun to mimic the effects of temperature and agroforestry conditions (INECOL/COLPOS/CIRAD collaboration)

years. In Costa Rica, the mechanisms of coffee adaptation to multiple stresses, combining high production conditions and rust attacks, are being studied in collaboration with World Coffee Research (Texas A&M University) through experiments on trees with different fruit load in a coffee rust infested region. In Brazil, CIRAD and EMBRAPA (Brazilian Corporation of Agricultural Research) have been collaborating for several years on coffee tree drought adaptation. Experiments set up in the semi-desert Cerrado region are geared towards controlling the duration of the drought period using central-pivot irrigation. When a finely detailed mechanistic approach is to be implemented for a short period, the use of a phytotron is nevertheless essential to obtain uniform controlled environmental conditions. The study is then carried out on young plants. CIRAD, in partnership with Nestlé, are trying to gain insight into the molecular basis of heterosis leading to rust tolerance. Hybrids and their parents are thus placed in phytrons under conditions that are conducive or not to rust development.

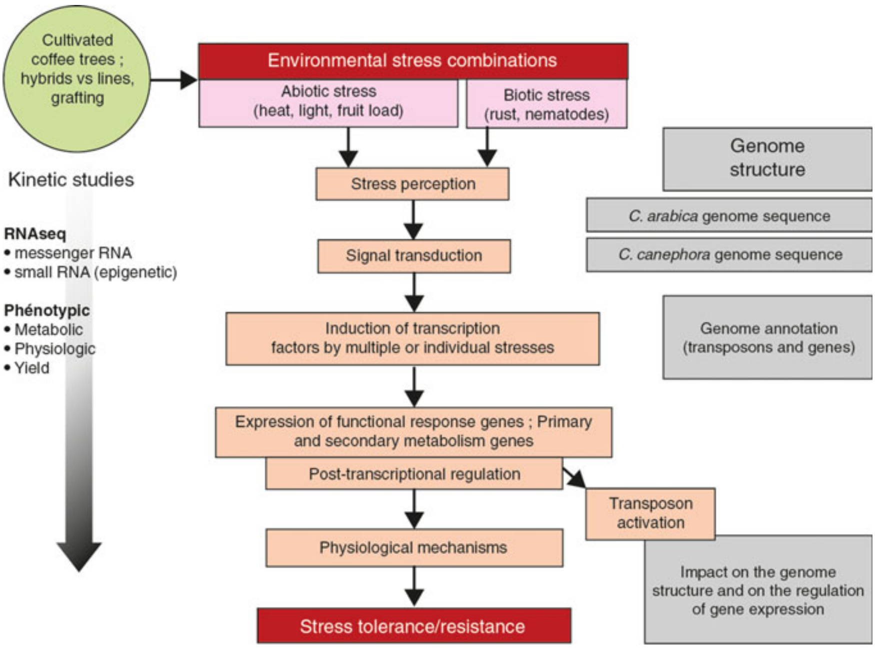

Fig. 7.3 Diagram of environmental stress transduction pathways leading to tolerant phenotypes. CIRAD is interested in coffee adaptation—specifically on improved hybrids or grafted varieties—to combined biotic and abiotic stresses. This research is conducted at the molecular level. The analysis of transcriptomic, epigenomic (miRNA, transposable elements, DNA methylation) and metabolomic modifications at different steps of the signal transduction pathway shed light on the stress adaptation mechanisms

All partnership research conducted by CIRAD provides a framework for understanding how metabolic pathways, cell signalling pathways and developmental processes are linked with both genome and phenotype expression, and hence for characterizing plant-environment relationships (Fig. 7.3). We study, for instance, interactions between the thermal or water regime, production level and intensity of infestations of leaf rust (induced by the *Hemileia vastatrix* fungus) and soilborne *Meloidogyne* nematodes (microscopic worms) on susceptible and resistant varieties. The aim is to use integrative approaches, focused on genome functioning (transcriptomics, metabolomics, genomics, epigenetics) and whole plants, to study adaptive responses to combined stresses in order to propose targets for breeding.

7.4 Rust, Nematodes and Drought—Three Major Targets

7.4.1 Coffee Rust Tolerance

Coffee rust (Fig. 7.4) can cause major defoliation and subsequent yield losses. Variations in temperature and moisture conditions have induced an upsurge in epidemics in recent years. Varieties with major resistance genes have been selected to control rust. The problem with this type of complete resistance is the risk that the pathogen will circumvent it.

Susceptible coffee trees are spontaneously highly tolerant if production is experimentally halted (elimination of young fruits). How can this phenomenon be explained? What are the underlying molecular mechanisms? Can plants having both high tolerance and a good production level be bred? Over the last 20 years, American *Arabica* varieties crossed with Ethiopian coffee landraces have shown a strong heterosis effect (40 % on average) (Bertrand et al. 2012). Some of these F1 hybrids seem to have high rust tolerance. Recent advances in genomics have given rise to new tools that can help to understand the molecular mechanisms responsible for this phenomenon. Recent studies using thale cress (*Arabidopsis thaliana*)—a plant model

Fig. 7.4 A young rust-infested coffee plant (*inset* spores on leaves). Climate change will alter interactions between host plants and pests (© CIRAD)

that is widely used in molecular biology studies—have revealed that this hybrid vigour is at least partially the result of epigenetic and transcriptional regulation of key genes, especially major plant circadian clock genes that regulate, in cascade, a huge network of genes (Ni et al. 2009). Moreover, miRNA and trans-acting siRNA reprogramming in the hybrid genome (Box 7.2) could give rise to new phenotypes, thus explaining the hybrid vigour and good health of the plants (Chen 2010).

Box 7.2. Epigenetics, stress and adaptation.

Plants cope with biotic and abiotic stress by constantly reprogramming the expression of their genes so as to adapt their functioning to these constraints. Genomic analyses carried out on stressed plants have revealed substantial changes in the expression of several hundreds or even thousands of genes at transcriptional and post-transcriptional levels. The quantity of mRNA in a cell depends on the transcription of the parental gene, as well as its stabilization, degradation level and protein translation capacity (Nakaminami et al. 2012). Plant small RNAs are essential regulators of the expression of genes involved in plant growth, development and adaptation to environmental stresses. They mainly regulate the activity of transcription factors, which in turn regulate the activity of many genes (Sunkar et al. 2012). The identification of noncoding small RNAs and their role could help to gain insight into the mechanisms plants use to control their development in stress conditions.

There are two main classes of noncoding small RNAs, i.e. miRNA (or micro RNA) and siRNA (or small interfering RNA), which are mainly distinguished by their biosynthesis pathway, mode of action and role (Fig. 7.5) (Guleria et al. 2011).

miRNAs are major drivers in the adaptive response to stress. Their regulatory role in constraints associated with nutritional deficiencies (phosphate, sulphate, copper and nitrogen), oxidative and thermal stress (heat and cold), drought, salinity and pathogen attacks is now recognized (Sunkar et al. 2012). For instance, under thermal stress, miR398 is overexpressed, especially in reproductive organs, thus increasing the intensity of oxidative stress (reduction in mRNAs CDS1, CDS2 and CCS1). This alteration of the redox potential in cells leads to activation of the transcription of heat-shock factor (HSF) proteins and heat-shock proteins (HSPs) involved in thermotolerance mechanisms (Guan et al. 2013).

Concerning biotic stress, the involvement of miRNA in pathogen control has also been demonstrated. For instance, miR393 inhibits the action of auxin and stops cell growth, which enables mobilization of resources to control the pathogen and activation of the secretion pathway via the Golgi apparatus to promote the secretion of defence proteins.

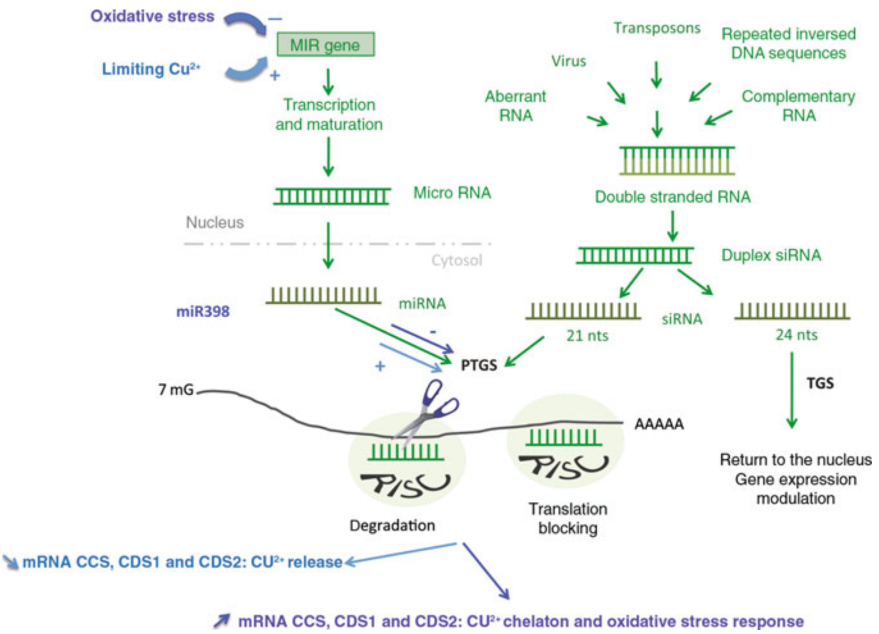

Fig. 7.5 Biosynthesis pathways and mechanisms of action of miRNA and siRNA. miRNAs are encoded by MIR genes. Their transcription leads to the formation of a 20–22 nucleotide miRNA/miRNA duplex. In the cytoplasm, a strand of the duplex is incorporated in a protein complex (RNA inducing silencing complex, RISC) where it serves as a guide for targeting mRNA degradation, and/or blocking of its translation. siRNAs are the result of the degradation of double-stranded RNAs of different origins into small 21 and 24 nucleotide RNAs. At this stage, they resemble miRNA and, in the same way, they incorporate a RISC protein complex to which they serve as guides for degrading target mRNAs (21 nucleotides) or for blocking gene transcription by methylation (24 nucleotides). The regulation example (shown in blue) highlights the key role of miR398 in the response to oxidative stress and copper deficiency

The essential role of plant small RNAs in plant adaptation mechanisms is now well documented for different types of stress. The next step involves studying them in multiple stress conditions, which are closer to actual conditions in the field. In this setting, they seem to be major regulators that closely coordinate the adaptive response of plants so as to effectively utilize available resources in order to maintain growth and enable the plant to fulfil its development programme (Atkinson and Urwin 2012). Identifying miRNAs involved in multiple stress conditions could be useful for designing new coffee breeding approaches.

7.4.2 Impact of Climate Change on Coffee/Nematode Interactions

Nematodes of the *Meloidogyne* and *Pratylenchus* genera are a major constraint in many coffee-producing countries, particularly Brazil and Vietnam (Campos and Villain 2005). The root system degradation caused by these parasites leads to a substantial reduction in the nutrient and water assimilation potential of coffee trees and makes them even more susceptible to water stress. This phenomenon gets worse when coffee trees begin producing and is exacerbated when they are grown in full sun.

The soil temperature increase in the range proposed by the different climate change forecasting models should be conducive to nematode development by shortening their life cycles. This has been demonstrated for *M. incognita* on coffee trees in Brazil (Ghini et al. 2008). It is now known that an increase in atmospheric CO_2 will modify carbon allocation in plants in favour of the roots (Compant et al. 2010). This could promote nematode development. Annual variations in *Pratylenchus* populations on coffee trees are indeed dependent on the plant phenological cycle, with the lowest population levels observed when carbon allocation occurs at the expense of the roots and to the benefit of the fruits during bean filling and ripening (Campos and Villain 2005).

The expression of resistance to *M. incognita* conferred by the *Mi* gene in tomato is inhibited at soil temperatures above 28 °C (Dropkin 1969). Conversely, resistance conferred by dominant *Ma* genes in *Prunus cerasifera* were found to be stable, even at high temperatures (Esmenjaud et al. 1996). What will the effects of climate change be on the expression of nematode resistance genes that have been discovered in coffee trees?

Climate change, especially during drought periods, will have a direct impact on rhizosphere microbiota. Through meta-analyses, Compant et al. (2010) and Pritchard (2011) showed that these impacts are complex and variable depending on the biological systems considered. These microbiota changes will have implications on the three main modes of suppressive action of beneficial soil microorganisms, i.e. antibiosis (relationship between two or several organisms at the expense of one of them), systemic resistance induced in host plants and specific antagonisms against pathogens (Haas and Defago 2005). The impact of climate change on ecosystems—whether natural or highly affected by human activities—will be inversely proportional to species diversity at the different trophic levels (Pritchard 2011). Agroforestry cultivation practices (Chap. 16) should help buffer the impacts of climate change and promote rhizosphere biodiversity. Comparative studies on different cropping practices should be carried out in various ecological conditions and on different varieties to assess how the microbial community associated with coffee trees reacts to concomitantly mitigate the many biotic stresses, such as nematode and rust attacks.

Fig. 7.6 Drought resistance tests conducted near Brasilia, Brazil (EMBRAPA/CIRAD)

7.4.3 Towards the Identification of Genes Responsible for Drought Tolerance in Coffee Trees

Prolonged drought periods represent an abiotic factor that has a major effect on the vegetative growth of coffee trees, as well as flowering, bean development (Fig. 7.6) and consequently coffee production. They are also known to increase bean defects, modify their biochemical composition and reduce the final beverage quality (Silva et al. 2005). These droughts, which have been observed during the rainy season, are often accompanied by high temperatures (>32 °C) and can be detrimental to the current and following years' production depending on the extent of their negative impact on vegetative shoot growth. Changes in cropping practices are necessary to ensure coffee adaptation to this constraint, while also taking advantage of genetic diversity to breed better adapted varieties. This may be illustrated by the drought tolerance programme conducted in Brazil by EMBRAPA and CIRAD.

7.4.3.1 Genetic Diversity of Coffee Trees and Mechanisms Involved in Drought Tolerance

Genetic variability regarding drought tolerance is high within the *Coffea* genus, especially in the *C. canephora* species. This provides an opportunity to study the physiological, molecular and genetic determinism involved in plant responses to this stress. *C. canephora* Conilon clones, which are drought tolerant or susceptible, have been the focus of several assessments (DaMatta and Ramalho 2006). It seems that drought tolerance could be the direct result of better stomatal control and of a more developed root system (Pinheiro et al. 2005).

Studies have shown that control of stomatal closure and transpiration is less efficient in susceptible Conilon clones than in tolerant ones (Marraccini et al. 2012). When the susceptible clone is grown under limited water conditions, its basic leaf water potential (Ψpd) decreases faster and its net carbon dioxide assimilation (*A*) is more sharply reduced in comparison to the tolerant clone. Concerning the metabolism of sugars, which can serve as osmoprotective compounds, sucrose phosphate synthase activity was found to be maintained when the basic leaf water potential declined in some tolerant clones (Praxedes et al. 2006). Several biological mechanisms are hence involved in drought tolerance.

7.4.3.2 Identification of Candidate Genes

In superior plants, there are two known drought signal transduction pathways involved in controlling the expression of genes involved in the stress response—one is dependent on abscisic acid (ABA) and the other not (Yamaguchi-Shinozaki and Shinozaki 2005). These pathways, or ‘cascades’, involve the expression of genes coding for transcription factors that activate the expression of a set of genes coding especially for ‘protection proteins’, such as heat-shock proteins (HSPs) and dehydrins. It should be mentioned that, in field cropping conditions, drought and high temperature stresses are actually associated and common biological mechanisms are probably involved in the intracellular signal perception and transduction.

Over 80 candidate genes have been found (Marraccini et al. 2012). These genes are characterized by differential expression patterns in leaves or meristems in susceptible/tolerant plants, or according to the water stress conditions. Several of them code for proteins involved in the synthesis of ABA, for compounds that are osmoprotective or involved in coping with oxidative stress, and for transcription factors of the intracellular transduction of abiotic and even biotic stress signals. Here it is interesting to note that the drought-tolerant *C. canephora* Conilon clone is also highly resistant to all *Meloidogyne* species and populations (Carneiro et al. 2009). This suggests that there are direct ‘crosstalks’ between biotic and abiotic stress response pathways in coffee trees.

Quantitative differences in the expression of some candidate genes when comparing drought tolerant and susceptible clones could be due to mutations in promotor regions that reduce the expression in susceptible clones.

7.5 Outlook

Coffee trees are cultivated in highly variable intertropical environments. Coffee growing is already being affected by climate change. Coffee is thus an ideal tropical perennial plant model for studying the impacts of climate constraints. CIRAD and partners have thus set up original experimental projects to address this issue. Plant material selected for its resilience and resistance to various biotic and abiotic stresses (drought, heat, rust, nematodes, etc.) is being tested in more or less stressful environments. The following questions can now be answered on the basis of the findings of these experiments and on recent advances in genomics. What are the key genes in the adaptation to stress? What are the characteristics of epigenetic regulation of the stress response? How do plants subjected to many stresses manage to balance growth and production with stress defence mechanisms? What heterosis and grafting mechanisms promote this balance and ensure the success of stress adaptation?

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Chapter 8
Climate Change and Vector-Borne Diseases

Véronique Chevalier, Fabrice Courtin, Hélène Guis, Annelise Tran and Laurence Vial

Abstract Diseases transmitted by insect vectors have a major impact on human and animal health, as well as on the economy of societies. Because of their modes of transmission, these vector-borne diseases—zoonotic or not—are particularly sensitive to climate change. The climate and its variations determine, sometimes substantially, the presence of vectors at a given place, as well as their density and capacity to transmit diseases. The climate also has an influence on the presence and density of animals and humans, in addition to the survival capacities of pathogens in a given environment. All of the components, conditions and processes necessary for the transmission of these diseases form a complex dynamic system whose behaviour, under the influence of the climate and other environmental variables, will determine whether or not transmission will occur. Experimental and epidemiological studies are carried out in laboratory and field conditions to gain greater insight into the underlying biological processes and measure the impact of climate parameters on these processes. Mathematical modelling is used to represent these systems and simulate their behaviour under different environmental conditions. This major tool sheds light on the biological phenomena involved in the

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transmission of given pathogens, while also simulating, over a more or less long time scale, spatiotemporal variations in the intensity of this transmission so as to be able to tailor control strategies against these diseases.

8.1 Background

Changes in climatic and environmental conditions are part of a set of ecosystem alterations that can lead to the emergence or increased incidence of animal and zoonotic diseases. According to a global study conducted by the World Organisation for Animal Health (OIE), the impact of climate change on the emergence and re-emergence of animal diseases has been confirmed by a majority of OIE member countries, 58 % of which have claimed that the recent onset of at least one emerging disease within their territory was directly associated with climate change (Black and Nunn 2009). Vector-borne diseases—zoonotic or not—are especially sensitive to these changes. The three most often mentioned emerging diseases, i.e. bluetongue virus (BTV), Rift Valley fever (RVF) and West Nile fever (WNF), are all vector-borne. Some authors claim that these diseases could even serve as early climate change indicators (Randolph 2009).

Vector-borne diseases can be described as a 'pathogen complex' involving three major elements of the epidemiological cycle—the pathogen, hosts and vectors—and by the relationships between these three elements (Sorre 1933). Each element of this complex has its own so-called 'intrinsic' characteristics that govern the relationships between the elements. These characteristics are, for instance, the vector's trophic preferences, which may influence its choice of host species for its blood meal, the host's behaviour which will more or less expose itself to the vector's bites, or the pathogen's virulence. These characteristics also determine the behaviours or reactions of the hosts, vectors and pathogens in response to external environmental constraints such as the temperature or landscape structure, or so-called extrinsic factors. This combination of pathogen complex plus extrinsic factors is a dynamic pathosystem (Fig. 8.1). To ensure the existence and functioning of this pathosystem, the external conditions must be suitable for a direct relationship between each of the elements of the pathogen complex. Environmental changes can upset the disease transmission pattern, but in other situations they can, conversely, increase disease transmission. Ecological disruptions, induced especially by climate change, but also by other factors such as human-induced environmental changes or socioeconomic disturbances, may trigger the emergence, dissemination or persistence of a disease. Understanding the mechanisms and conditions that underlie these processes is a major challenge facing the scientific community in the coming years (King et al. 2006).

Here we provide a few examples to illustrate the impact of the climate and climate change on some pathosystem elements and their consequences on the geographical distribution, intensity of transmission or emergence of vector-borne diseases.

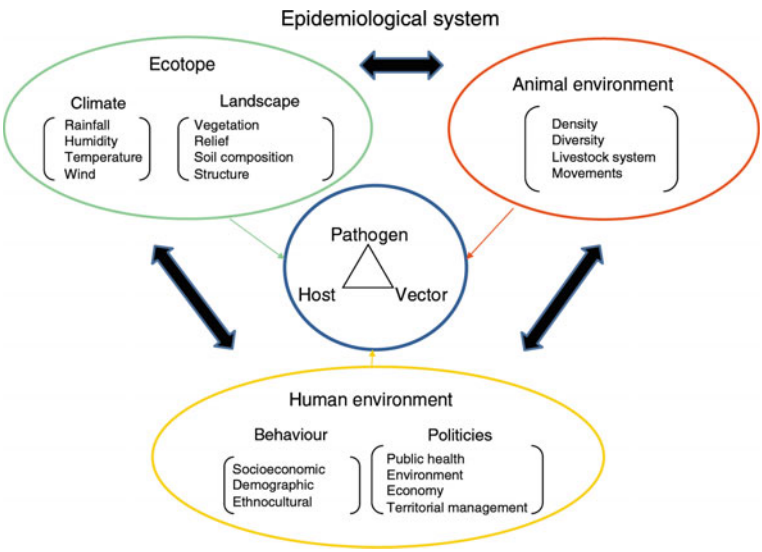

Fig. 8.1 A pathosystem (adapted from Rodhain 1985)

8.2 Climate Impact on the Distribution of Disease Cycle Components

The survival, reproduction, spread and abundance of arthropod vectors are particularly dependent on the climatic conditions. The arrival of the *Culicoides imicola* midge, a Bluetongue virus (BTV) vector, in Europe in the 2000s illustrates that the distribution range of vectors is never definitive. Bluetongue (BT), an arbovirus infection of ruminants that is widespread in the intertropical region, was considered an exotic disease in Europe until the late 1990s. In the last two decades, several serotypes[1] of BTV have spread to Mediterranean countries, and then Northern European countries, causing a major health and economic crisis (over 100,000 livestock farms infected). Little data was available on the distribution of *Culicoide*s midges before the end of the 1990s. *C. imicola* had only been identified in Spain and on some Greek islands (Mellor et al. 1983). Since the emergence of BT in the Mediterranean Basin, many entomological studies have revealed a more widespread presence of this vector, but the exact dates when it took a foothold in these regions have yet to be determined. The entomological monitoring system set up in France detected the arrival and settlement of this species for the first time in continental France, in the Var region, in 2004. Since then, the colonization process has been advancing at a rate of approximately 15 km a year (Venail et al 2012). The massive

[1]A serotype represents an antigenic property that enables identification of a cell (bacteria, red blood cell, etc.) or virus by serological methods.

outbreak of BTV serotype 8 from 2006 in Northern Europe, in an area where *C. imicola* was absent, prompted the scientific community to assess potential changes in the distribution and abundance of the Palearctic vectors involved. *Culicoides* abundance models were developed to address this issue. They support the hypothesis that the climatic conditions favoured the northward migration of the tropical species *C. imicola*, but they revealed that the climate in Northern Europe may not have been conducive to increasing densities of Palearctic *Culicoides* species of the *Obsoletus* complex (Guis et al. 2012), considered to be the main vectors in this area.

Vertebrate hosts—whether they are susceptible, healthy carriers of pathogens or serve as an arthropod food source—are also dependent on climatic and environmental conditions. Their abundance, movements or the synchronization of their development cycle with that of arthropods allow or not the host-vector interaction. A geographical approach and historical perspective of the spatial dynamics of tsetse flies and trypanosomosis sheds unique light on the impact of climate change on the trypanosomosis pathosystem (Box 8.1).

Box 8.1. Trypanosomosis.
Trypanosomoses are caused by trypanosoma parasites that are transmitted to humans and animals by bites from the tsetse fly vector. Trypanosomosis diseases hamper the development of crop and livestock farming due to the morbidity and deaths they cause to humans and livestock. They have an impact on the most isolated agricultural and pastoral farmers. Other insect mechanical vectors (stable flies, tabanids, etc.) are involved in the transmission of African animal trypanosomosis (AAT, or Nagana). Animal trypanosomosis diseases are transmitted within distribution areas of the different vectors worldwide, except at the northernmost and southernmost latitudes.

Tsetse flies are the sole vectors of human African trypanosomosis (HAT, or sleeping sickness). This disease exists only in sub-Saharan Africa, the only part of the world where tsetse flies occur.

One impact of climate variability in sub-Saharan Africa is increased human mobility (population migration and displacement), and thus livestock mobility—a well known adaptation strategy of herders in the Sahel region is: “Grass doesn’t grow, millet doesn’t grow, so we have to move on” (Fulani proverb) (Boutrais 1999). This mobility is, however, particularly conducive to the spread of diseases. It was shown that population migrations from Upper Volta to Côte d’Ivoire linked with the droughts of the 1970s were responsible for HAT propagation in the Ivorian-Burkinabe area (Courtin et al. 2010). Similarly, in 1998 in Uganda, the arrival of AAT-infected herds escaping the droughts in the North triggered a *Trypanosoma brucei rhodesiense* outbreak in the Soroti region (Fèvre et al. 2001).

This remodelling of human and livestock distributions in favour of more southern regions where rainfall conditions are better resulted in exposing human

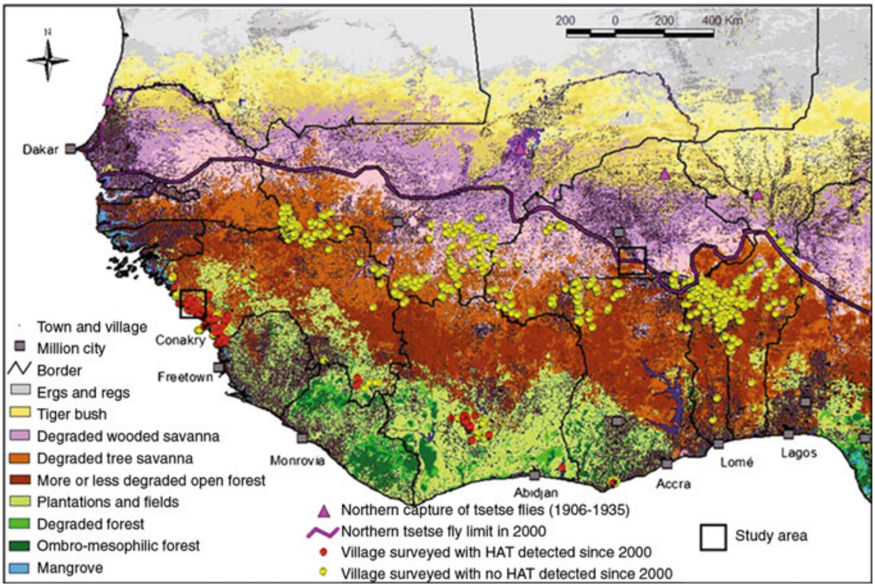

Fig. 8.2 Spatial dynamics of human African trypanosomosis and tsetse flies in West Africa (1906–2010) (Courtin et al. 2008)

and livestock populations to tsetse fly bites and therefore to trypanosomosis. Moreover, the population-resource imbalance and massive influx of climate refugees (farmers, herders) affected the tsetse fly spatial distribution, e.g. via destruction of their refuge areas (interstream areas and gallery forests). In the first half of the 20th century, almost all HAT hotspots in West Africa were thus located in savanna areas. Since the early 1990s, no HAT cases have been detected in savanna areas and all detected cases were located further south, in mangrove and forest areas, with the 1,200 mm isohyet as northern boundary (Fig. 8.2). The decreased rainfall and increased temperatures, associated with population growth, clearly contributed to this trend (Courtin et al. 2008).

8.3 Climate Impact on Disease Transmission Dynamics

Environmental conditions can also alter the transmission parameters—vector competence is one of these parameters (Box 8.2).

Box 8.2. Vector competence.
Vector competence is the ability of an arthropod vector to—after ingestion of an infected blood meal—acquire, maintain, multiply and transmit a pathogen to another vertebrate by an infecting bite. It is a measure of the extent of

pathogen-vector coadaptation and one component of the vectorial capacity. The latter is defined as the number of potentially infecting bites that a vertebrate host can generate, via the vector population, per unit time. This is an indicator of the disease transmission risk.

Given the major economic or health issues associated with certain diseases, it is essential to know if changes in climatic conditions can impact the vector bioecology and competence, or promote the emergence of new vectors via the adaptation of pathogens to certain arthropods for instance. These are essential questions with regard to African swine fever (ASF).

ASF is a haemorrhagic fever of pigs caused by a DNA virus of the *Asfivirus* genus. It can be responsible for up to 100 % mortality in domestic pigs and can also infect wild pigs, which may be susceptible or healthy carriers depending on the species. The ASF transmission mode is multifaceted—it is highly contagious between pigs, readily survives in the environment and in contaminated pork foods and is also transmitted by soft ticks of the *Ornithodoros* genus. Native to Africa, it was recently introduced in Caucasian countries and Russia and has been spreading through Eastern Europe since January 2014.

Three African and European tick species were collected in the field and reared in the CIRAD insectarium to test the impact of the environment on the vector competence of soft ticks for the ASF virus. An artificial blood feeding and experimental infection system was developed (Fig. 8.3). It has already been found that low temperatures of around 20 °C and high humidity of over 85 % slowed down the *O.*

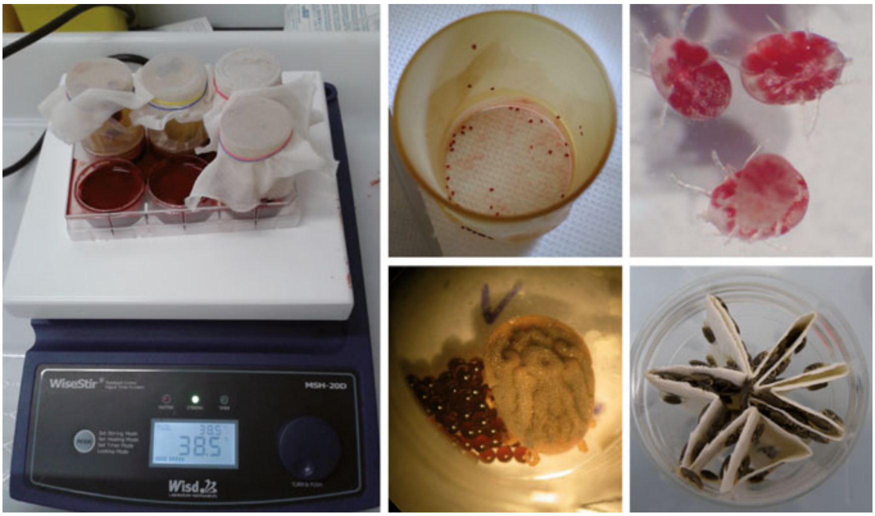

Fig. 8.3 Artificial blood feeding system for *Ornithodoros* soft ticks reared at CIRAD (*photo* L. Vial)

erraticus digestion process and reduced the blood feeding frequency and thus the biting rate. Moreover, in Spain, it was demonstrated that the same tick stopped blood feeding when temperatures were below 13 °C (Oleaga-Perez et al. 1990). *Ornithodoros* ticks colonize their host's habitat (inside houses, stables, etc.), thus protecting them from extreme climatic conditions, but their biology is still clearly subject to external temperature and humidity conditions (Vial 2009).

Human relapsing fever (borreliosis), which prevails in West Africa, is caused by a bacterium (*Borrelia crocidurae*) and is transmitted by a soft tick to humans and rodents. The climatic conditions may modify the dynamics of borreliosis reservoir rodent populations and thus modify the probability of tick-rodent contact. Rodents proliferate every year after the rainy season when feed resources are maximal and, in contrast, high mortality is noted in the late dry season. Being opportunistic regarding its vertebrate hosts, the tick usually feeds on humans when rodents are not present in its habitat, i.e. in the late dry season when a significant increase in the rate of borreliosis transmission to humans is actually observed (Vial et al. 2006).

8.4 Climate and Major Vector-Borne Disease Outbreaks

Rift Valley fever (RVF) is an important climate-sensitive disease that threatens the health of human and livestock populations in Africa, the Indian Ocean and the Middle East, but also the economy of pastoral societies (Peyre et al. 2014).

RVF is caused by a *Phlebovirus*. Domestic ruminants are hosts of this virus, which is transmitted mainly by *Aedes* and *Culex* mosquitoes. *Aedes* female mosquitoes lay their eggs in wet mud around watering points. When the water dries up, the eggs resist desiccation and can survive for several years in the dried mud. The eggs hatch when they are wetted again. This drying period, which occurs under the climatic conditions that prevail in the Sahelian region, is necessary for the emergence of a new generation of adult mosquitoes. In contrast, *Culex* females lay their eggs on the surface of water bodies and the eggs cannot withstand desiccation. A permanent water source is thus necessary for the development of a new generation of *Culex* mosquitoes (Mondet et al. 2005).

In the so-called 'Dambos' semi-arid areas of Kenya, RVF epidemics occur every 5–10 years and a correlation has been established between the onset of extreme rainfall events and the onset of RVF epidemics. Water from moderate rains seeps into the ground very quickly. Sustained flooding therefore only occurs in the Dambos when there are prolonged intense rainfall events. This flooding induces massive hatching of *Aedes* mosquito eggs that were laid in previous years, some of which are infectious. Indeed, in *A. mcintoshi*, a major RVF vector in this region, the virus can be transmitted from females to the eggs, leading to recirculation of the virus after massive hatching of eggs several years after the previous epidemic. *Culex* mosquitoes, which are confined to big ponds that do not dry out, then take over and amplify the RVF transmission process, leading to the emergence of cases in livestock and humans (Linthicum et al. 1999).

A system of temporary ponds is found in the Ferlo region in northern Senegal. No correlation has ever been established in this area between extreme rainfall events and the emergence of epizootic diseases, but Soti et al. (2012) showed that major RVF epidemics took place during years when *Cx. poicilipes* and *Ae. vexans* abundances peaked simultaneously. In addition, hundreds of transhumant herders converge in this area at the onset of the rainy season. Livestock management, herd replacement rates and transhumance movements impact the immune status and density of livestock present in this area. These parameters should be taken into account to gain greater insight into the emergence process and to try to forecast future epidemics in this region on spatiotemporal scales.

West Nile fever (WNF), caused by a *Flavivirus*, is also transmitted by mosquitoes of the *Culex* genus. Wild birds, mainly passerines, are the reservoir hosts. Humans and horses can be infected but are considered as dead-end hosts. The West Nile virus was newly introduced in North America in 1999, spread throughout the United States from east to west within a few years and has now become endemic. It has reached areas as far as southern Argentina. Between 1999 and 2010, around 1.8 million people were infected and over 12,000 cases of encephalitis or meningitis were reported, 1,308 of which were fatal (Kilpatrick 2011). In Europe, the virus has been present in the Mediterranean Basin since the 1960s, but without significant effects on human or animal health. However, the incidence of human and equine neurological cases increased sharply in the 2000s, especially from 2010. Two recent studies have shown that excessive temperatures, especially during months preceding epidemics, causing an increase in vector competence and a reduction in the gonotrophic cycle (time between blood meals and egg laying), was one of the factors triggering these epidemics (Tran et al. 2014).

8.5 Modelling to Understand, Predict and Control

It is now recognized that temperature and rainfall have an impact on the epidemiology of vector-borne diseases, but the extreme complexity of vectorial epidemiological systems makes it hard to understand the processes involved (Gould and Higgs 2009). Mathematical models—although imperfect and often simplistic—have proven valuable for understanding the functioning of these systems, and also sometimes for predicting periods and areas at risk. These models, when validated by field data and representing observed phenomena with a relatively high degree of accuracy, can be used to assess the impact of control measures such as insecticide treatments and vaccinations. The global risk of disease transmission depends on the respective abundances of cycle components and transmission parameters. The basic reproduction rate, represented by R_0, combines these elements and corresponds to the number of individuals newly infected after the introduction of an infectious individual in an immunologically naive population. When this rate is over 1, then there is an outbreak risk in the studied pathosystem. When the rate is under 1, an infected individual will infect less than one other individual, so the disease should

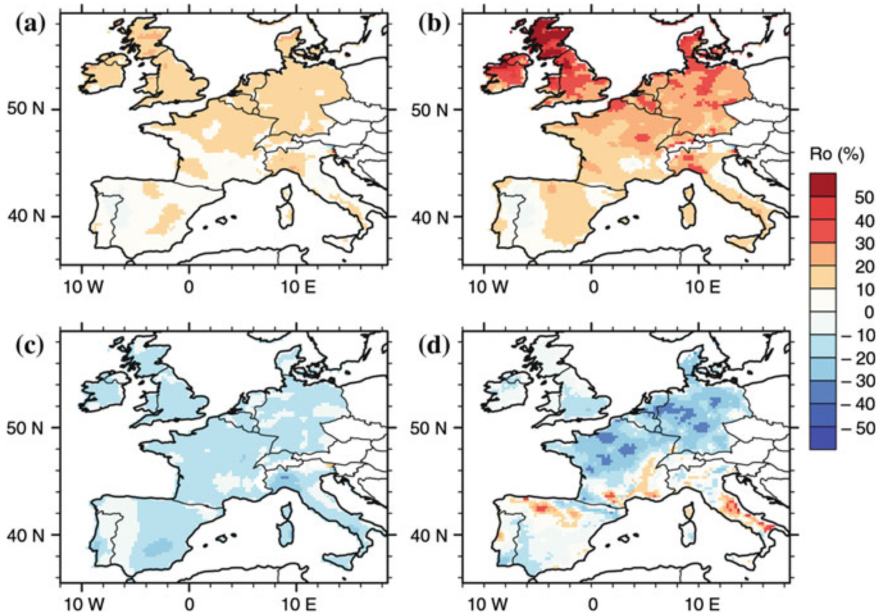

Fig. 8.4 Sensitivity of the baseline reproduction rate (R_0) to climate change. Relative anomalies (%) for the 2000–2008 period compared to the 1961–1999 climate data. All parameters are assumed to be constant except one in each window: (**a**) biting rate; (**b**) average duration of the extrinsic incubation period; (**c**) vector mortality rate; (**d**) vector/host ratio (Guis et al. 2012)

naturally disappear. Since R_0 combines in its mathematical formulation parameters such as the extrinsic incubation time or the vector survival rate (whose values largely depend on the climate setting), R_0 (and thus the capacity of the disease to be transmitted in a given environment) is also sensitive to temperature variations (Fig. 8.4). Estimation of this parameter regarding BTV in Europe has shed further light on the mechanisms involved in past outbreaks and enabled quantification of future risks—the risk seems greater in southern than in northern Europe, but its increase due to climatic conditions could be greater in the north (4.3 % increase per decade) than in the south (1.7 % increase per decade) (Guis et al. 2012).

Simplified mathematical formulation of R_0 (baseline reproduction rate).

$$R_0 = \left(\left(m \times a^2 \times p^n / -\ln(p)\right) \times b/r\right)$$

(**m**) Number of mosquitoes in relation to a host (vector/host ratio); (**a**) biting rate; (**p**) daily survival rate of the vector population; (**n**) average pathogen development time in the vector (extrinsic incubation period); (**r**) 1/average host infectious period; (**b**) vector competence.

Similarly, based on two climate scenarios of the IPCC Fourth Assessment Report, researchers modelled the impact of climate change on HAT (Moore et al. 2011). Their model simulations suggested that the temperature would become too high for the parasite to survive in some regions. However, disease outbreaks could occur in other previously unaffected areas due to the temperature increase. In the 14 outbreak areas reported in East and South Africa, three would thus disappear by 2090 in the first scenario, while 10 would be eliminated under the second one. In scenario 1, the model suggests that the area that would be favourable in 2090 would differ by 85 % from the current area because it would be too hot to host the disease. Moreover, 63 % of this distribution range predicted for 2090 concerns regions that are currently too cold to host the disease, including East African highland areas. Seventy-seven million inhabitants would thus be exposed to HAT by that time. It is quite likely that the tsetse fly distribution range will sharply decline in sub-Saharan Africa in the coming years as a result of climate change, population growth and current Pan African Tsetse and Trypanosomiasis Eradication Campaign (PATTEC) initiatives. However, some tsetse fly species, especially of the *Palpalis* group, are able to survive in areas of high human population density. These situations could constitute new epidemiological hotspots because of the promiscuity of tsetse flies, humans and domestic animals (periurban livestock farming).

8.6 Limits and Conclusion

Each model partly contributes to understanding the transmission cycles but, because of the complexity of the processes involved, the climatic conditions can seldom explain everything. One major risk associated with climate change is the predicted high variability and the multiplication of extreme climate events (drought, torrential rains, flooding, storms). Spatiotemporal modelling of these climatic phenomena using satellite imagery and climate indices such as sea surface temperatures or rainfall patterns enabled prediction—3 months in advance—of the Rift Valley fever epidemic that hit the Horn of Africa in 2006–2007 (Linthicum et al. 1999). However, an analysis of the performance of this model showed that it could predict 65 % of the risk areas in East Africa, 50 % in Sudan, but only 23 % in Madagascar and 20 % in South Africa. This highlighted the involvement of phenomena other than vector/climate relationships. This is true for many other diseases, especially WNF. Its transmission and intensity depend on the co-occurrence, on both temporal and spatial scales, of hosts (birds) and vectors. The distribution and density of potential reservoir birds, seasonality and geography of their migrations, landscape structure, trophic preferences of the vector present and the disease reservoir capacity of the hosts have to be taken into account (Chevalier et al. 2014).

To be robust, predictive models should thus combine the behaviour and biology of all components of the considered pathosystem with the impact of the environment. These models can only highlight the trends, with a level of uncertainty that depends mainly on knowledge of the underlying biological phenomena. They nevertheless help gain greater insight into pathosystems, setting up risk-based monitoring systems and enhanced forecasting of future risks.

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Chapter 9
Relationships Between Tropical Annual Cropping Systems and Climate Change

Edward Gérardeaux, François Affholder, Martial Bernoux and Bertrand Muller

Abstract Annual crops on family farms in tropical regions are highly sensitive to climate. The increase in temperature will accelerate the growth and development of crops, thus shortening their seasonal cycle, in turn resulting in a decrease in intercepted solar radiation. Climate warming will increase the atmospheric evaporative demand, thermal stress frequency and crop maintenance respiration, likely resulting in lower yields. Conversely, reduced cold stress and increased atmospheric carbon dioxide storage are factors that increase yields. Little is known about changes in rainfall patterns, wind velocities and solar radiation. Given the poorly predicted positive and negative effects of biotic stress and potential interactions, there are still too many uncertainties to be able to forecast how yield patterns will change for most crops. Crop models are promising prospective analysis tools because they incorporate some of this complexity, but there is still insufficient data and expertise to be able to calibrate and validate them. Tropical agriculture can contribute to enhancing carbon storage or to reducing greenhouse gas emissions, but adaptation to climate hazards is also necessary to ensure food security and income for farmers. Techniques such as conservation agriculture, agroforestry, sustainable rice intensification (intermittent drying of rice fields), planting holes or index insurance can help fulfil these two objectives.

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9.1 Background

Family farms that grow annual crops in tropical regions are usually smallholdings located in relatively unmodified natural environments, which means they are highly sensitive to climate hazards. Studies on the effects of climate change on the functioning of these crops are therefore crucial. Temperature is the climate variable whose long-term patterns can most readily be predicted and its impacts on crops are relatively well known. Other variables such as rainfall, atmospheric carbon dioxide (CO_2) enrichment, wind and solar radiation affect crops but there is not always consensus on their long-term variations and impacts on crop yields.

Farmers in these areas will have to adapt to new climatic conditions—generally hotter, sometimes drier, sometimes wetter and often harsher—particularly by changing their technical crop management strategies. Choices regarding species or cultivars, tillage and soil fertility management techniques will have to enhance the resilience of agriculture to climate hazards. Here we present the impacts of the main climate stresses on tropical annual crops and assess the stress adaptation prospects, as well as the possibilities of reducing greenhouse gas emissions by these crops.

9.2 Sensitivity of Annual Crops to Climate Variables

9.2.1 Effects of Increased Temperature

Temperature is a key plant growth and development variable. Rising temperatures have several impacts on crops.

- Shortened growth cycle. All plant development stages (phenological stages) are triggered when a certain quantity of heat ('temperature sum') has been accumulated since the previous stage. These temperature sums vary between species and varieties, which enables prediction of the duration of cycles according to temperature. For a given crop, an overall increase in temperature thus shortens its growth cycle (Fig. 9.1). With all other conditions being constant, this shorter cycle can have negative effects on yield since the crops intercept less solar radiation required for photosynthesis during each seasonal cycle. Very little breeding effort, using conventional plant improvement techniques, is required to lengthen the cycle when necessary.
- Increased maintenance respiration. Plant respiration, or so-called 'maintenance respiration', is proportional to the temperature and involves a loss of carbon (generally more than compensated by the photosynthetic production). A temperature increase, especially at night, tends to reduce yields in relation to the extent of received radiation (decline in photosynthetic yield). This is especially important for so-called 'C3' plants (wheat, rice, cotton, groundnut, soybean, etc.), whose photosynthesis is generally adapted to humid areas without excessive temperatures, contrary to C4 plants (maize, sugarcane, sorghum), which come from tropical areas with a marked dry season.

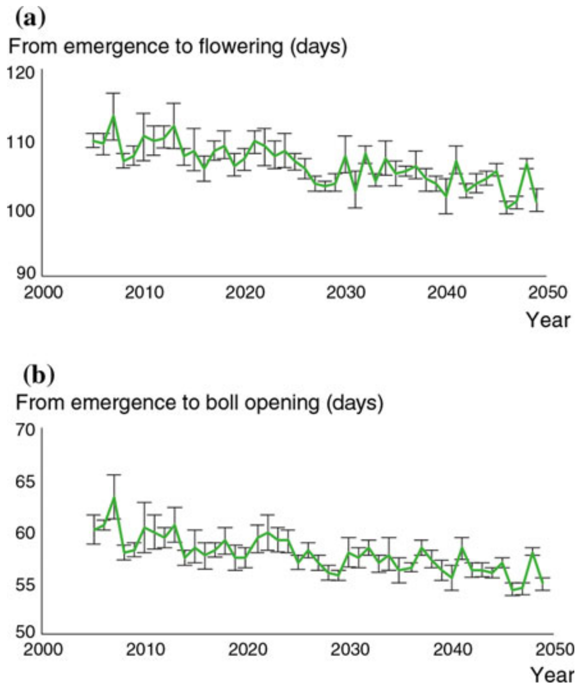


Fig. 9.1 Simulation of the effects of temperature increases according to six global models tailored for cotton phenology in northern Cameroon. Projections to 2050 (Gérardeaux et al. 2013)

- Modified thermal stress. The development of reproductive and storage organs of plants (that are generally harvested), can be affected by very high or low temperatures (sterility, abscission, abortion). Global increases in temperature should reduce stress associated with cold temperatures and increase that associated with high temperatures.
- Increased crop water demand. Temperature is involved (along with air humidity, radiation and wind velocity) in soil evaporation and plant transpiration phenomena, whose sum (called 'evapotranspiration') represents plant water consumption on a plot scale. Rising temperatures increase water consumption needs (called 'potential evapotranspiration') and, depending on the situation, the rainfall or irrigation conditions will not necessarily fulfil them. This should increase the risk of water stress (shortage of water) with a negative effect on yield.

9.2.2 Effects of Rainfall Variations

Sometimes a substantial portion of rainfall is lost for the crop via runoff or it infiltrates too deeply in the ground to be accessible for plant roots. Moreover, rainfall is one of the climate variables least accurately predicted by models. This especially concerns the rainfall distribution, which will likely be highly affected by climate change, with an expected increase in violent events such as storms and tornadoes, and an overall increase in interannual variability. Unfortunately the greatest uncertainties concern West Africa for which there are now as many models predicting increased rainfall as there are those predicting its decline, whereas rainfall is crucial for agricultural production in that region.

Cropping practices cannot change rainfall patterns but they can enable adaptation to them. Choices regarding varieties (cycle length) and sowing date help match crop development with the rainfall distribution. Some techniques (small contour bunds, mulch) can greatly reduce runoff, and others (multiple cropping or relay cropping) may optimize water resource consumption. Finally, a moderate intensification level can be adopted while keeping in mind that water needs increase when this intensification is increased (higher yielding variety, higher fertility via greater organic or chemical fertilization, higher seeding rate). Changes in rainfall patterns should therefore normally have less of an impact on family farming type extensive crops—which are less demanding and more resilient—than on intensive crops.

9.2.3 Effects of Increased Atmospheric Carbon Dioxide Concentrations

The increase in atmospheric concentrations of CO_2—the main greenhouse gas explaining climate change—should have a positive effect on photosynthesis. Some authors even speak of "CO_2 fertilization of the atmosphere." These positive impacts are expected to more specifically concern C3 crops than C4 crops.

9.2.4 Effects of Changes in Radiation

Solar radiation reaching the ground will be modified in association with the extent of cloudiness, but predictions regarding this variable are relatively uncertain. Radiation also affects the temperature and is involved in crop functioning (photosynthesis, evapotranspiration). In relatively dry climatic conditions, a decrease in radiation would a priori reduce plant development and yield as well as the risk of water stress, ultimately having little effect on yields. However, in more humid climatic conditions, a decrease in radiation would reduce yields.

9.2.5 Effects of Wind

Predictions indicate an overall increase in the average wind velocity and in the number of days with violent winds that could damage herbaceous stem crops, especially cereals. Moreover, the increase in wind velocity would increase potential evapotranspiration and thus the water stress risk.

9.2.6 Interactions Between Effects

Climate change will likely induce new heretofore unknown stress combinations. It would be simplistic, for instance, to think that a simple shift in latitude or elevation would offset the new environmental conditions. Climate variables could have effects following the same trend or, conversely, act antagonistically, sometimes for the same parameter according to the physiological functions. Moreover, the extent of these effects varies between species and varieties, but all expected effects of certain future conditions on all crops are unknown (even less so regarding the known range of genetic resources). This is the case, for example, concerning the impacts of extreme temperatures, increased atmospheric CO_2 and all of their possible interactions. It is essential to gain further insight into these issues and many studies are under way. In addition, if the different climate change scenarios are consistent, and even if advances are made on understanding the climate (except for rainfall in West Africa), it is sometimes hard to use the information because climate models produce data on spatiotemporal scales that do not match those that crop models use, especially with respect to rainfall.

However, many studies have been carried out to predict future trends and identify the best solutions. For instance, recent findings provide essential information on forecasted future sorghum yields in semiarid West Africa (Sultan et al. 2014). These studies are based on the use of simulation models that take interactions between the described effects of climate variables and those of cropping techniques on crop growth and development processes into account (Fig. 9.2). These models are necessarily imperfect simplifications of reality and there are many modelling approaches depending on the issues to be addressed and the biophysical and technical environments considered (Affholder et al. 2012). Prior to using a model, it is thus necessary to check its operational reliability for the studied context. It has already been determined that growth variations associated with fluctuations in temperature, radiation or atmospheric CO_2 concentration are generally much lower than variations related to water and nitrogen stress. The result is that in an environment in which rainfall is a constraint and farmers do not have access to nitrogen fertilizer, a modelling study that overlooks the impact of rainfall or fertilization (possibly with its substantial indirect impacts on weeds) would be mistaken on potential crop performance trends and recommended solutions. In family farming situations in developing countries, where many combined biotic and abiotic stresses affect farmers' plots, it would be unreasonable to rely simply on analyses focused on soil-climate variables to unravel the causes of current and potential future yield variations.

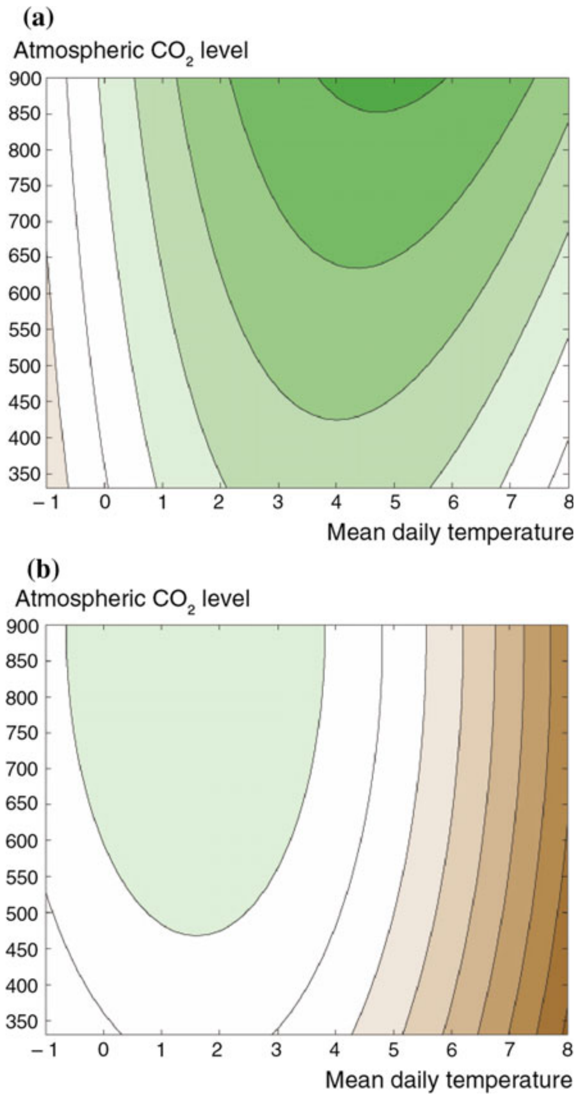


Fig. 9.2 Response surface for rice (**a**) and cotton (**b**) related to variations in average daily temperature and atmospheric CO_2 levels simulated using DSSAT-CERES-riz and DSSAT-CROPGRO-coton models. Upland rice at Antsirabé, Madagascar, and cotton at Garoua, Cameroon. Towards *green* 10 % increase in yield, towards *brown* 10 % decrease in yield. *DSSAT* decision support system for agrotechnology transfer; *CERES* crop estimation through resource and environmental synthesis; *CROPGRO* crop growth model

9.3 Mitigating the Causes of Climate Change

9.3.1 Limiting Input Consumption

High fossil energy consumption is required for input production. High fertilizer application has an impact on greenhouse gas emission and pollution. It is thus of interest to rationalize this energy consumption in Western agriculture. Fertilizer usage is however very low in tropical family farming situations, especially for food crops (less than 100 kg of fertilizer/ha). Reducing fertilizer applications in these situations therefore does not make much sense and research is focused mainly on improving the efficiency of fertilizers rather than on their substitution or reduction. Industrial nitrogen fertilizer production sectors could also progress in favour of lower fossil energy usage.

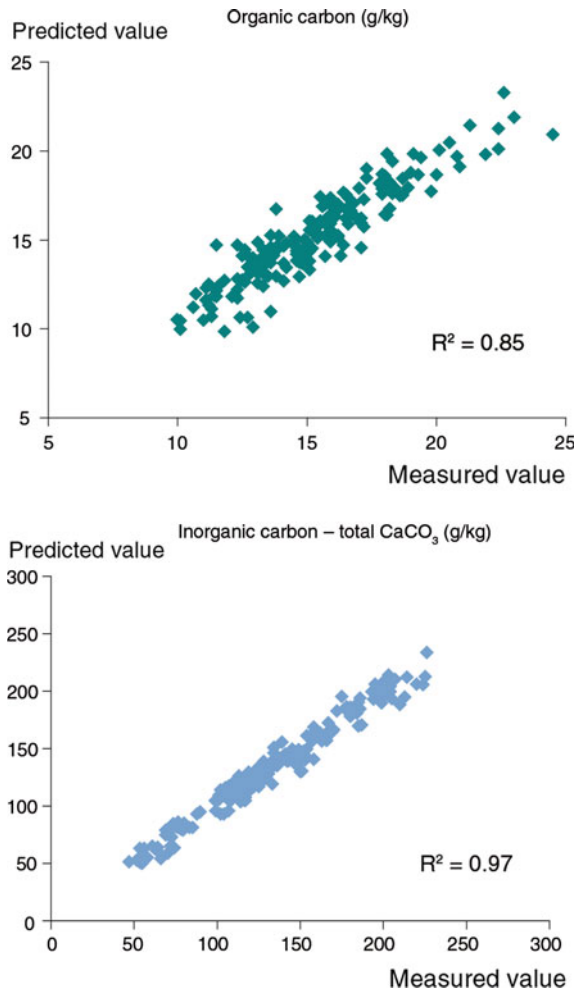
9.3.2 Increasing Carbon Sequestration

Different agricultural practices are recognized as being conducive to carbon sequestration. In early 2013, some 40 experts from around the world gathered to identify knowledge gaps, research requirements and policy innovations on the carbon sequestration issue. The workshop report (Banwart et al. 2014) provided a key update on the global societal challenge regarding soil carbon management. Although the practices (agroforestry, conservation agriculture, etc.) were not called into question, sequestration rates are still under debate because of the diverse range of systems and especially the lack of long-term studies. Soil carbon measures—which were once very expensive—are now feasible in situ and at low cost. A portable field spectrometer (visible and infrared) can be used to accurately assess the soil organic carbon content, total nitrogen and carbonate contents of in situ soils without preparation (sieving, grinding) or drying (Fig. 9.3). These measurement techniques will ultimately help gain insight into the high diversity of crop management techniques applied in a very broad range of soil and agroclimatic situations.

9.3.3 Limiting Methane Emissions

It is estimated that, due to the presence of methanogenic bacteria in the soil, irrigated rice fields generate over 50 % of all agriculture-derived methane (CH_4). Global rice production must nevertheless increase. Recent studies have fortunately indicated that some practices, such as sustainable rice intensification (intermittent drying of rice fields), could greatly reduce CH_4 emissions without reducing yields. The technique controls rice diseases and predators, as well as vectors of human diseases, but it comes with certain risks regarding weed control, which is normally achieved by constant immersion of rice fields.

Fig. 9.3 Prediction of organic and inorganic carbon levels by infrared spectrometry (from Bernoux and Chevallier 2013)



9.4 Adaptation to Climate Change

9.4.1 Forecasting the Effects

Forecasting is a tool used to lessen the effects of specific constraints. For instance, sugarcane crop yield modelling (Fig. 9.4) helps predict harvest losses when irrigation is interrupted because of a tornado.

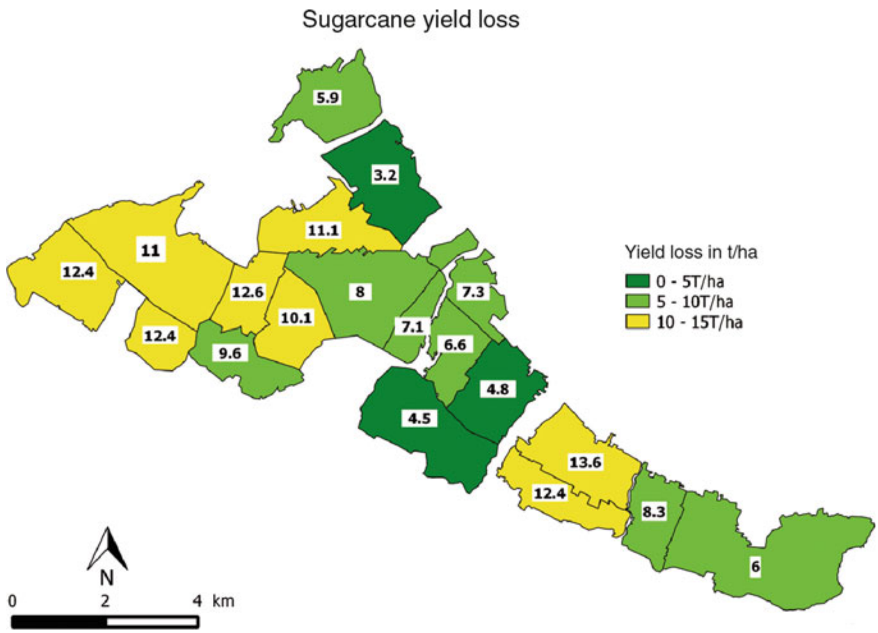


Fig. 9.4 Study on the impact of an irrigation interruption following a natural disaster on sugarcane production (in t/ha) in southwestern Réunion (J.-F. Martiné/CIRAD)

9.4.2 Adaptation of Cropping Systems

Many techniques and local variants are tailored for addressing climate change, especially regarding water hazards. A set of techniques have been recommended over several decades within the framework of water and soil conservation management programmes. They have been described in many books, sometimes well in advance of international negotiations focused on adaptation, e.g. in the *Introduction à la gestion conservatoire de l'eau, de la biomasse et de la fertilité des sols*, published by FAO (Roose 1994). These different techniques combine management of surface water, mixed localized organic and chemical fertilizer applications and various physical (stone barriers or rows, or even small walls) and biological (grass cover, hedges, mulch) erosion control measures.

Zai is a unique hole planting technique (Fig. 9.5) which serves to concentrate water and manure in microbasins in which seeds are sown. The planting holes are around 30 cm diameter and 10–15 cm deep, with a density of close to 10,000 holes/ha. Theoretically, *zai* is a simple technique, but it requires substantial labour and effective community organization (Bernoux and Chevallier 2013). In dryland areas, the primary aim of these practices is not to increase the carbon content but rather to preserve some organic matter, and thus carbon, in order to ensure the sustainability of farming practices. These techniques are emerging as attractive alternatives to cope with climate hazards.

Fig. 9.5 Millet sown using the *zai* method in northern Benin (© P. Silvie/IRD-CIRAD). *Zai* is a traditional soil cultivation technique whereby microbasins are dug to collect runoff water and concentrate manure and to sow millet or sorghum seeds

9.5 Conservation Agriculture

According to FAO, conservation agriculture is a technique that complies with the following three principles at the plot level: minimum tillage, crop associations or rotations and permanent soil cover—commonly referred to as 'direct seeding mulch-based cropping systems' in France. These techniques were originally developed and promoted for controlling erosion, especially in tropical and subtropical regions such as Brazil (Bernoux et al. 2006; Scopel et al. 2013). In the 1990s, they were adopted by a CIRAD research team, and by the French Cooperation in the 'Agroecological Action Plan' jointly coordinated by MAEDI, AFD and FFEM.[1] Conservation agriculture trials based on cover plants (*Stilosanthes*, *Brachiarria*, crop residue and external mulch, etc.) and no tillage were conducted in Africa south of the Sahara (Fig. 9.6). They effectively curbed erosion, improved water infiltration in the ground and extended the crop cycle when it had been stalled by a dry period. This increase in the cycle length boosted crop yields, thus offsetting losses caused by the delay in growth due to the absence of tillage at the beginning of the cycle.

[1]MAEDI: French Ministry of Foreign Affairs and International Development; AFD: French Development Agency; FFEM: French Facility for Global Environment.

Fig. 9.6 Direct seeded cotton with sorghum and weed mulch (conservation agriculture) in a farmer's field in the far north of Cameroon, 30 June 2004 (K. Naudin/CIRAD)

9.5.1 Conservation Agriculture—A Carbon Sequestration Solution?

Substantial research has been focused on quantifying soil carbon stock patterns under conservation agriculture. Plant cover (live or dead) is indeed able to increase annual organic matter inputs, and thus organic carbon levels. As inputs increase, it makes sense to expect an increase in carbon, which should be accurately quantified since it reflects a reduction in atmospheric CO_2 concentration and thus in climate change—this phenomenon is called carbon sequestration (Feller and Bernoux 2008). Studies on changes in the carbon stock were initially conducted in Brazil and Madagascar, and then Tunisia and Cameroon. Carbon sequestration was documented and the results were compiled to derive the average values cited by the Intergovernmental Panel on Climate Change (IPCC). It should be noted, however, that measurements are often carried out at optimized experimental sites or using potentially biased methodological approaches. The main lesson is that, although sequestration rates are only around a few hundred kilogrammes of carbon per hectare, there is considerable potential on the regional scale. The main factor determining the storage rate seems to be the quantity and quality of plant matter recycled in the soil. This is crucial, especially in regions where different uses are

Fig. 9.7 Upland rice growing in *Brachiaria* mulch, Laos (© F. Tivet/CIRAD)

competing for crop residue, which is a public good in many societal organizations. In Africa, for instance, crop residue is used as livestock fodder. Studies conducted in Brazil (Metay et al. 2007) and Madagascar (Razafimbelo et al. 2008) have also demonstrated that accumulation often occurs in the finest soil fractions, which are also the most stable. The supplementary carbon stored in these fractions should thus be quite temporally stable (Fig. 9.7).

One study focused on no-tillage cropping systems with cover crop mulching (Costa et al. 2013) showed that assessing carbon storage using synchronic (simultaneous sampling in plots with different cultivation histories) and diachronic (identical plots monitored over a time course) methods gave different results. In Brazil, for instance, studies using the synchronic method estimated carbon storage in the 0–20 cm horizon at about 1.3 t C/ha/year, while the findings of the diachronic assessment revealed a storage rate of 0.3–0.4 t C/ha/year. Sequestration rates have thus now been scaled down relative to the preliminary estimates made in the late 1990s and early 2000s. The potential of no-tillage cropping alone—not combined with plant cover—seems very limited in terms of climate change mitigation. Efficient crop residue/cover plant management is therefore essential for optimizing carbon sequestration.

9.6 Agroforestry

Agroforestry (Chap. 16) corresponds to associations of trees with crops involving, for instance, alley cropping (hedges or alignments of trees in annual crop plots), improved rotations and planted fallows, multilayer systems (trees scattered in the field, shade trees), edge or boundary demarcation plantations or windbreaks. These are often traditional systems. Agroforestry has, for example, been practiced for several centuries in sub-Saharan dryland regions. Selected tree species have a utilitarian value for households or a commercial value on domestic, regional or (but less frequently) international markets (Bernoux and Chevallier 2013). Some complex agroforestry systems, or so-called 'agrosilvopastoral systems' (combining annual crops, trees and shrubs of different sizes and livestock), such as the *Faidherbia albida* parklands in the southern Sahel, have a key role with respect to soil fertility management. They represent a solution for increasing soil carbon and biomass stocks. However, shade from trees also reduces the soil temperature and crop evapotranspiration, thus modifying the microclimate. Agroforestry is thus a mitigation and adaptation solution.

9.7 Risk Insurance

Agricultural insurance, as in other economic sectors, can help cushion, via compensation, the consequences of production losses arising from problematic events (drought, floods, frost, grasshopper outbreaks, etc.). Agricultural insurance systems have long existed in industrialized countries but are still not very developed elsewhere, despite the frequent occurrence of these problems, which endanger farmers and agricultural credit programmes, in turn hampering development. Since the early 2000s, innovative systems have been tested in different countries (India, China, Mexico, Kenya, Senegal, Mali, etc.) using indicators based on climate information rather than on direct damage observations (Muller 2013; Muller and Leblois 2013). These 'index insurances' are less expensive and easier to implement, especially if they are combined with credit. The most common are designed to protect crops against rainfall deficits (Fig. 9.8). They are seen as climate change adaptation instruments. However, experiments currently under way (involving several thousands of farmers in West Africa, several million in India) have highlighted two main shortcomings. First, it is hard to gain access to accurate rainfall information 'everywhere', especially in Sahelian and Sudanian regions of West Africa, where rainfall is highly spatially variable. Satellite techniques could provide a solution but their accuracy is so far not sufficient. Secondly, agricultural insurance plans—even index insurance—have a cost: worldwide and especially in developing countries, agricultural risks are much more common than in other activity sectors and they affect all farmers in a given area at the same time. In developed countries, different mechanisms (subsidies, etc.) support agricultural insurance. It remains to be seen

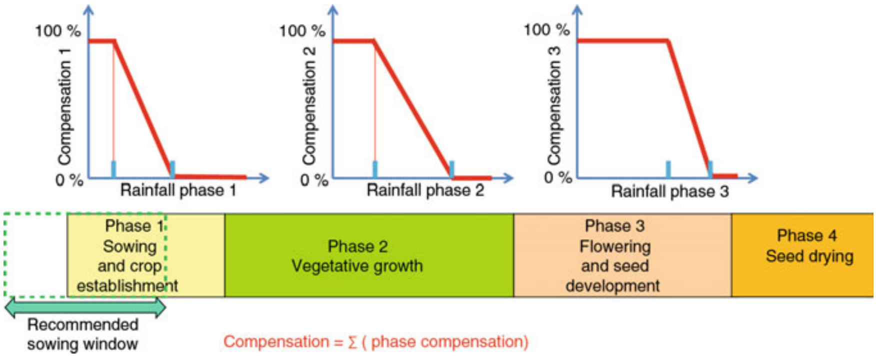


Fig. 9.8 Standard diagram of how a multiphase rainfall index functions

whether they will be economically feasible on a large scale in developing countries, while also being relevant compared to other agricultural aid.

9.8 Conclusion and Outlook

Many uncertainties remain about the impacts of climate change on crop yields of family farms in tropical regions. For a given crop variety, rising temperatures will shorten the crop cycle, while increasing water needs, stress associated with high temperatures and maintenance respiration of crops, in turn reducing yields. Conversely, a reduction in stress associated with low temperatures and atmospheric CO_2 enrichment would be favourable for crops. Other aspects of climate change are still poorly forecasted, such as changes in rainfall patterns, wind velocity, violent events and solar radiation at ground level. Simulation models are a promising way to take interactions between the effects of climate variables and cropping techniques into account. However, these models still have many shortcomings, especially with regard to assessing family farming in developing countries where a range of biotic and abiotic stresses are jointly present in farmers' fields. It would nevertheless not be reasonable to simply conduct analyses focused on a limited number of soil-climate variables with the aim of unravelling the causes of current and potential future yield variations.

The challenge will likely be substantial to cope with the forecasted changes—humanity's food needs can only be met at the expense of agricultural intensification in many regions. Ecological intensification, which is seen as intensification that will ensure the long-term sustainability of agriculture, must necessarily be 'climate smart'.

Despite the scale of the challenge and of all the uncertainties mentioned above, solutions are available to meet this objective, some of which are already being implemented by farmers. They generally include a set of agroecological practices aimed at improving regulation functions in cultivated ecosystems, and hence their resilience. Conservation agriculture is a typical example, which has the additional advantage of contributing to soil carbon storage—admittedly in a small way but enough to deserve the focus of public policies. The development of risk forecasting systems is also a promising avenue to help farmers in the 'tactical' management of cultivated ecosystems, enabling them to tailor their yield objectives according to climate constraints in real time. These technical options on a cultivated plot scale should necessarily be complemented by policies that give farmers sufficient flexibility to be able to constantly adapt their cropping systems, or that promote agricultural insurance to cushion the effects of hazards to which farmers are subjected.

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Part II
Seeking Novel Practices

Chapter 10
Livestock Farming Constraints in Developing Countries—From Adaptation to Mitigation in Ruminant Production Systems

Mathieu Vigne, Vincent Blanfort, Jonathan Vayssières, Philippe Lecomte and Philippe Steinmetz

Abstract The livestock sector's relationship with climate change is complex. The sector is a major contributor to agricultural greenhouse gas emissions, whereas it is subject to climate change and must adapt to ensure its survival. The diverse range of livestock farming systems worldwide provides a range of greenhouse gas emission mitigation options. Moreover, livestock production contributes to a significant and increasing extent to food systems and to agricultural systems in developing countries (manure, transportation, savings, income). In this sense, their integration in climate-smart agricultural systems is essential, especially since these regions are undergoing major changes in their demographic, environmental and consumption patterns. Livestock farming is thus a crucial adaptation mechanism for poor and vulnerable people living in changing environments who are subject to a range of risks.

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10.1 Background

Livestock farming systems are undergoing major changes in developing countries in response to many interdependent ecological, economic, social, political, security and health factors. Among these factors, the increased demand for animal products due to global population growth and changes in middle-class income and consumption patterns in emerging countries should play a major role. However, the productive features of livestock farming and agriculture overall are now being widely revamped. The multiple services provided by livestock farming activities, i.e. not simply ensuring peoples' food security, are now a key consideration. In developing countries, livestock farming systems are less productive—per head and per hectare with regard to products for human consumption—than in developed countries, but they offer many socioeconomic services that are just as important, such as building economic capital, social status, organic manure production and animal draught (Alary et al. 2011). Their positive impact on ecosystems should also be taken into account. Grasslands, for instance, have a very high greenhouse gas (GHG) mitigation potential (4 % of anthropogenic emissions) by sequestering and storing carbon dioxide (CO_2) in soil (Lal 2004; *in* Blanfort et al. 2011). The contribution of pastoralism to the ecosystem balance and sustainability in drylands is another prime example. It opens landscapes, hampers scrub encroachment, stimulates plant growth, fertilizes soil, increases nutrient cycling, participates in seed dissemination and enhances rainwater infiltration over large territories where it is the main economic activity.

The sector's global emissions amount to 7.1 Gt CO_2 equivalent (CO_2-eq), or 14.5 % of anthropogenic emissions (Gerber et al. 2013), mainly in the form of methane (CH_4), nitrous oxide (N_2O) and CO_2 (Fig. 10.1).

These emissions are gradually being taken into account in agricultural development policies in developed countries, while in developing countries they are often seen as being of lower priority than the fight against hunger, malnutrition, poverty and economic development. Yet the focus nowadays is on producing more,

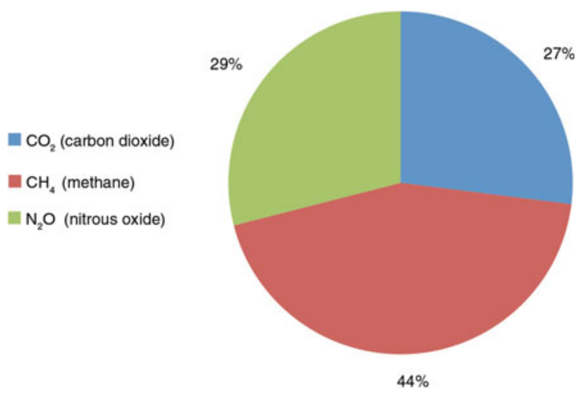

Fig. 10.1 Global emissions per type of greenhouse gas in the livestock farming sector

while improving the productivity of the production systems, but more sustainably and by taking climate change into account—in both developing and developed countries—in terms of adaptation and mitigation. Livestock farming is vital in the design of climate-smart agricultural systems because of the complex interactions between climate change and livestock farming systems in developing countries, associated with their obvious contribution to household food security and addressing the future demand for animal products.

10.2 Producing References on Livestock Farming Systems in Developing Countries

Few references are available on the specific contribution of livestock farming systems to GHG emissions in developing countries. An analysis on trends in major world regions (Gerber et al. 2013) showed that sub-Saharan Africa, given its low productivity, and Latin America and the Caribbean, due to the conversion of primary forests into grassland and cropland devoted to producing livestock feed, are regions with the highest emissions per produced kg carcass weight (around 70 kg CO_2-eq/kg carcass). However, these figures overlook some diversity that was highlighted in assessments of different livestock farming systems (Table 10.1).

Table 10.1 Greenhouse gas emissions measured in different livestock farming systems

Study site	Type of system	Greenhouse gas emissions
Democratic Republic of the Congo Lecomte et al. (2014)	Large ranches (50,000 ha)	
	Cattle on natural savannas	80 kg CO_2-eq/kg carcass
	Cattle on intensified *Brachiaria* grasslands	18 kg CO_2-eq/kg carcass
Senegal Assouma et al. (2014)	Silvopastoral systems in Ferlo	
	Fattening cattle	69 kg CO_2-eq/kg carcass
	Dairy cattle	9 kg CO_2-eq/kg milk
	Fattening cattle	28 kg CO_2-eq/kg carcass
	Dairy sheep	11 kg CO_2-eq/kg milk
Brazil Clerc et al. (2012)	*Fazenda*-type suckler cow rearing systems	20–80 kg CO_2-eq/kg carcass

10.3 Potential Greenhouse Gas Emission Mitigation Pathways

10.3.1 Improving Resource Use Efficiency and Livestock Productivity

Enteric CH_4 emissions from ruminant livestock represent around 40 % of emissions of the entire livestock farming sector (Fig. 10.2).

Reducing these emissions is therefore a priority. Pastoral and agropastoral herd feeding is largely based on the intake of resources of low digestibility, leading to high CH_4 emissions. In southern Mali, for instance, natural rangelands represent up to 70 % of the gross energy consumption per head in extensive dairy farming systems (Vigne et al. 2013). One option for reducing CH_4 emissions thus promotes the consumption of more digestible resources with a low methanogenic potential, such as concentrates and crop by-products. This option is especially interesting as it also enhances herd productivity. However, intensification of all of these livestock farming systems through massive inputs of commercial concentrates is not possible in most systems in developing countries. Most of them have already used external inputs to a limited extent, but for further intensification, substantial economic support policies would be necessary, which hardly seems possible (Corniaux et al.

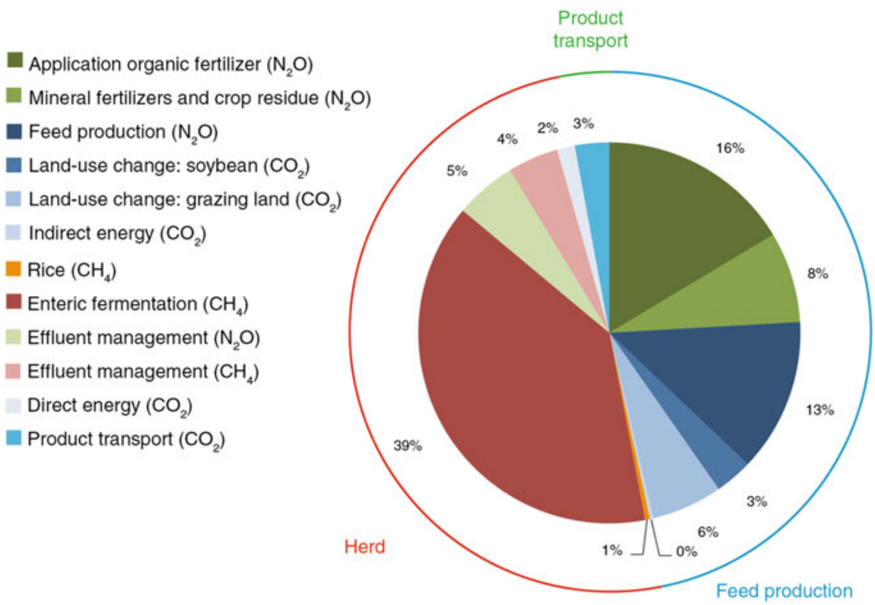

Fig. 10.2 Global emissions of the livestock farming sector per production sector. *CO_2* carbon dioxide; *CH_4* methane; *N_2O* nitrous oxide

Fig. 10.3 Hand milking on a farm in Sikasso, Mali (© M. Vigne/CIRAD)

2012). Other ways of increasing productivity involve improving herd health and access to good quality grassland, especially during the rainy season.

CO_2 and N_2O emissions for the production, processing and transportation of livestock feed represents around 45 % of the total emissions of the sector, a third of which are linked with fossil fuel combustion directly for herd management or indirectly for feed production (Gerber et al. 2013). The promotion of livestock farming systems that make effective use of this resource is a further way of reducing GHG emissions. Vigne et al. (2014) in Mali and Benagabou (2013) in Burkina Faso showed that, in the absence of mechanization, family dairy farming systems (Fig. 10.3) consume less fossil energy per litre of milk produced than more intensive periurban dairy farming systems. In the Democratic Republic of the Congo, Lecomte et al. (2014) demonstrated that the fossil energy efficiency of meat production was higher on intensified *Brachiaria* grasslands than on natural savannas (Fig. 10.4). Nitrogen loss through volatilization during storage and slurry spreading accounted for over 20 % of GHG emissions of the sector. Nitrogen conservation and recycling on the farm are thus important ways to reduce GHG emissions. In southern Mali, an analysis of local management practices regarding produced organic matter revealed that night paddocking of animals along with supplementation with crop residue litter, and the use of manure pits (Fig. 10.5),

Fig. 10.4 Conversion of part of a natural savanna into *Brachiaria* grassland on Kolo ranch, Democratic Republic of the Congo (© A. Duclos/CIRAD)

Fig. 10.5 Manure pit on a family farm at Koumbia, Burkina Faso (© M. Blanchard/CIRAD)

could double the farm nitrogen retention efficiency (Blanchard et al. 2013). Moreover, this crop-livestock integration helps decrease the dependency on industrial chemical fertilizers, which are high non-renewable energy resources consumers and indirect GHG emitters.

10.3.2 Carbon Storage in Rangelands

After oceans and fossil energy reserves, soil is the third largest global carbon stock, far ahead of aboveground plant biomass. Grasslands, which account for 30 % of the land surface, could store 0.3 billion t/year of organic carbon, or nearly 4 % of anthropogenic GHG emissions. However, the carbon sequestration potential would range from 0 to 4 t C/ha/year depending on the ecological zone, soil characteristics, climatic conditions and agricultural practices (Soussana et al. 2010). Agricultural soil management is therefore essential for controlling carbon flows in the fight against climate change (90 % of the emission reduction potential of the agricultural sector, according to Gerber et al. 2013).

The livestock farming development trend in the Amazon region clearly illustrates these new challenges. This development must be planned with a view to forest conservation and GHG mitigation, while maintaining the conventional production functions of livestock farming. Deforestation for the purpose of creating grasslands has significant environmental impacts, while leading to substantial CO_2 local emissions (biomass combustion) and biodiversity loss. Combating deforestation is thus a priority but needs to be accompanied by more sustainable management of cleared areas. In French Guiana, a regional research platform that contributes to the Guianese regional carbon and GHG observatory[1] studies carbon and GHG balances in forests and deforested areas. This CARPAGG (carbon and GHG in grasslands in French Guiana) research project is focused especially on *Brachiaria humidicola* grassland cattle grazing systems resulting from deforestation (Fig. 10.6).

Recent results have shown that the carbon storage function observed in native forests can be re-established in grasslands resulting from deforestation two decades after they have been created. Carbon flow measurements over a 2 year period and a chronosequence study respectively indicated carbon storage levels of 1.8 ± 0.5 and 5.3 ± 2.1 t C/ha/year (Blanfort et al. 2014). The net GHG balance for the 2011–2012 period in a 33 year old grassland with an annual stocking rate of 1.3 animals/ha showed that the grassland was a net carbon sink of -1.2 ± 0.5 t C/ha/year. Grassland ecosystems resulting from deforestation in French Guiana therefore function as carbon storage sinks provided they are preserved for several decades. Prospects for achieving production systems with lower GHG emissions are therefore possible for grassland systems in the humid tropics.

[1]http://www.oredd-guyane.fr.

Fig. 10.6 Cattle grazing on a *Brachiaria humidicola* grassland in the Amazon region, French Guiana (© V. Blanfort/CIRAD)

10.4 Impact of Climate Change on Livestock Farming in Developing Countries

Rising temperatures, changing rainfall regimes and the increased frequency of extreme weather events affect livestock farming systems and their productivity worldwide. These factors influence the different components of the system from the animal to the grazing resources. There are also marked impacts on animal health (Chaps. 9 and 18).

10.4.1 Thermal and Water Stress

Thermal stress following an increase in temperature and humidity variations induces major behavioural and physiological changes in animals, such as reductions in feed intake and movements. Energy and water intake required for body temperature regulation increase at the expense of other functions such as production and reproduction. Vulnerability to thermal stress varies depending on the species, genetic potential, age and nutritional status of the animal, as well as the setting. Local breeds in tropical and subtropical areas seem better adapted to these stresses, but few data are available to confirm this.

Droughts and the simultaneous increase in water needs resulting from the high prevailing temperatures can lead to substantial livestock mortality. Animals adapted to drylands seem less vulnerable, but the heavy losses that occurred over the last 10 years in the Horn of Africa is evidence that all animals are susceptible to these stresses. 38 % of the world's human population currently lives in water-stressed environments and this figure should rise to 64 % by 2025 (Rosegrant et al. 2002), which gives an indication of the potential frequency of such events and their impact on livestock worldwide.

10.4.2 Quantity and Quality of Forage Resources

Climate change has direct effects on fodder resources. CO_2 stimulates photosynthesis. According to Long et al. (2006), an atmospheric CO_2 concentration of 550 ppm as compared to the current 400 ppm rate could lead to a 30 % increase in yield for the most sensitive forage species. This increase in plant biomass will nevertheless only be possible if other climatic factors and soil fertility are not limiting. These factors are well documented for crop species, but not for species found in pastoral areas. An increase in temperature and CO_2 levels also results in higher soluble carbohydrate levels and lower nitrogen levels, in addition to higher lignification, which have an impact on livestock productivity and CH_4 emissions. Climate change will alter the composition of rangelands, especially regarding the proportion of grasses and legumes. More severe climatic conditions will tend to favour plants that are best adapted to extreme conditions.

The current balance regarding animal-plant-environment relationships will thus be upset. The extent of changes in plants available for grazing will determine the type of animal best adapted to the feed supply and could jeopardize the livestock species involved. It might then be necessary to modify livestock farming systems by changing the species (e.g. from cattle to small ruminants and camels), breeds (specialized or rustic), and herd feed management strategy (transhumance, crop and forage stocks, feed supplements).

10.4.3 Land Availability

The migration of herders prompted by the environmental degradation of rangelands upon which their herds previously grazed, concomitantly to population growth under way in many rural areas, has led to land saturation in some regions. This is particularly noticeable in sub-Saharan Africa where Sahelian herds have been moving to sub-humid areas since the 1970s. Historically nomadic herders have been gradually settling in these areas while organizing strategic transhumance movements of their herds to favourable sites. Competition between agricultural and pastoral activities has given rise to conflicts. Extensive livestock farming, which by definition requires considerable land, is thus faced with the reduction, fragmentation or even closure of grazing areas and transhumance corridors due to the planting of food crops, thus blocking access to quality grasslands and water points. While herd mobility is an adaptation to climate change, the structuring of areas concerned by new agreements between users is of equally vital interest.

10.5 Livestock Farming Adaptation Capacities

Livestock farming is a crucial adaptation mechanism for poor and vulnerable people in variable environments where there are many risks. Adaptation is based on the resistance mechanisms of some animals to climatic conditions, diseases and food shortages, on the ability of these animals to make effective use of the diversity of plant species, on the rapidly deployable standing capital function and on mobility (Mandonnet et al. 2011). This mobility is a response to the quest for new rangelands and more favourable climatic areas, marketing chains and feed management between good and harsh years. The diversity of livestock farming systems also enhances the range of adaptation capacities.

Because of the reduction in rangelands in some areas and the increased demand for animal products, there is growing interest in zero grazing systems as an adaptation alternative. Livestock productivity may be improved through these systems by controlling the livestock rearing conditions. For instance, Vigne et al. (2014) in Mali and Benagabou (2013) in Burkina Faso demonstrated that periurban dairy farming systems produced at least tenfold more milk than extensive family farming systems.

In mixed systems, forage production could have a larger share in the cropping plan as an adaptation to future climatic conditions. In food cropping systems, although crop farmers are generally hesitant to convert areas devoted to food crops into feed crops, this would reduce the dependence on grasslands. Research on grass-legume crop associations have been conducted in several countries to cope with the cyclical drought risk in southern Europe. Initial results show that certain crop combinations lead to a 12 % increase in total nitrogen levels in comparison to monospecific crop plots. Improved crop-livestock integration is also a key feature to study with regard to these systems. Silvopastoralism is an interesting option for systems with forage crop areas. The presence of trees in grasslands can indeed enhance grassland productivity, especially by delaying the impact of the dry season, and improving the comfort of animals by providing shade.

Finally, the grazing calendar of pastoral and agropastoral systems using natural areas will have to be adapted to cope with changes in productivity and in the composition of pastoral areas, and also with the decrease in available area. In Burkina Faso, an analysis of herd grazing practices revealed that adaptation strategies are already being applied to deal with these new constraints, especially conflicts (Vall and Diallo 2009). In North Africa, adjustments in herd management, enclosed grazing areas and replanting of natural forage cover are under way especially to enhance the long-term persistence of the vegetation and soil regeneration (Huguenin 2011). In the Mediterranean region, adaptation of sheep farming during drought periods has helped overcome veterinary problems (Box 10.1).

There are also some common adaptations to different types of system. The status of rustic breeds, which are less productive but better adapted to harsh conditions, must be reconsidered, especially to achieve a trade-off between livestock productivity aimed at fulfilling household food security needs and adaptation to climate change. Moreover, by diversifying species on individual farms, it is possible to take advantage of the specific adaptation capacities of each species and to improve the resilience of the system (Nozières et al. 2011).

Box 10.1. Adaptation of livestock farming in the Mediterranean region.
Pascal Bonnet, *Véronique Alary*, *Ibrahim Daoud*

In arid northwestern Egypt, the coastal strip gets around 150 mm/year of rainfall. This is the cradle of *wadi* agriculture (olives and figs) and renowned sheep farming (Barki breed). A drought affected the area from 1995 to 2010, which precisely confirmed the model simulations and predictions carried out with regard to the susceptibility of the area to become a hotspot of climate change (Lacetera et al. 2013). The ELVULMED project coordinated by CIRAD investigated how Bedouin livestock farming coped during this period of profound territorial economic transformation via different forms of adaptation of production systems and commodity chains (Bonnet et al. 2014). Livestock feed resources were diversified, livestock farming practices changed and the livestock farming territory increased in size, with the emergence of new forms of livestock feed management, increased animal mobility and forage diversification.

Before the drought, transhumance started from the northern coastal rainfed agriculture zone and proceeded toward the natural grasslands in the south, to the edge of the desert. It became more complex with complementary west-to-east movements starting in February-March from the agricultural *wadis* towards the edge of the Nile Delta, where irrigation was making new land available for agriculture. These lands provided new forage reserves for some livestock farmers, enabling them to graze their herds more or less temporarily before returning to the original breeding lands. This new form of to-and-from mobility had direct impacts on herd health, with veterinary services and livestock farmers having to adapt. Animals temporarily residing in these irrigated areas were exposed to new diseases and feed resources, and some animals returning from the Delta showed symptoms for which farmers and veterinary services in the original areas were unfamiliar.

Livestock farmers and veterinary services were surveyed on how these changes were perceived and on adaptations. Changes in practices leading to intensification of the livestock farming system (use of richer fodder) and exposure to new pathogens or parasites resulted in the emergence of 'enterotoxemia' type syndromes (caused by *Clostridium chauvei*, often due to contamination of forage and rumen acidosis) and various forms of blood (theileriosis and babesiosis) and digestive (nematodes, trematodes such as liver flukes) parasitism. Fifty percent of livestock farmers surveyed noted a moderate increase in internal and external digestive parasitism. This new livestock mobility also led government services to fear the spread of some major communicable infectious diseases such as foot-and-mouth disease, outbreaks of which have increased in the region, particularly in the Nile Delta and Libya.

Veterinary services and livestock farmers have analysed the change of situation and incorporated new intervention strategies, in turn modifying the health system (Chap. 18). Livestock farmers have often resorted to the private sector via veterinary pharmacies and self-medication to treat parasitic blood diseases (increased use of albendazole and multivalent covaccines for enterotoxemia). With these changes, State veterinary services increased vaccinations against foot-and-mouth disease and sheep pox. Team training was increased on managing diseases that were previously overlooked in the area, particularly hitherto unknown parasitism in wet grasslands. The province also began developing preventive strategies targeting specific areas in order to create a sanitary cordon between the west and the Delta to block the spread of certain infectious diseases, including pox. This involved a dual adaptation of the health system—via the market with livestock farmers resorting to private health care and via the State with amendments in the public vaccination application regulations.

10.6 Conclusion

There are many complex interactions between livestock farming systems and climate change over and above the issue of GHG emissions. Livestock farming is directly and indirectly impacted by this change, which threatens the sustainability of the systems and increases the vulnerability of millions of people on all continents. Livestock farming systems and homestead practices are highly diversified. Just with regard to the cattle farming sector, between industrialized systems in developed countries (animals fed crops), and extensive agropastoral and family systems in developing countries (animals fed almost exclusively by grazing natural seasonal rangelands), there is a highly diversified range of livestock systems that differ markedly in terms of GHG emissions, susceptibility to climate change and contributions to food security and income.

The knowledge gained so far is sometimes not sufficient to understand the changes induced or necessitated by climate change in terms of adaptation, mitigation or food security. Livestock herd demographic models such as Dynmod (Lesnoff 2010) can be used to simulate the impact of successive droughts on herd productivity dynamics, etc. Innovations should, however, also be proposed.

With regard to reducing GHG emissions, innovations involve carbon sequestration in soil and grasslands, the reduction in input and feed consumption, improved productivity of the most extensive systems, treatment of slurry and its subsequent integration in agricultural activities. With regard to adaptation to climate change, it is necessary to consider a range of different aspects, such as forage crops, animal genetics, animal health, animal housing. Social and political sciences should also be mobilized since new regulations for the management and sharing of pastoral areas are required to ensure the mobility and integration of livestock farming activities and farmers in changing societies.

For climate-smart livestock farming, it is essential to combine these approaches so as to be able to formulate proactive long-term public policies. This requires structured discussions between producers, livestock and crop farmers, private companies in the various commodity chains, policy makers and civil society. Research and development institutions are essential in this dynamic process. They must explain the issues and propose technical and institutional solutions that apply to the entire production chain and territory. This should be done from a short-term perspective, by providing support for decision making on the most frequent and intense crises, and from a long-term perspective, by forecasting trends and proposing measures that may be applied without social cost. For instance, the development of an information and early warning system to characterize and monitor pastoral dynamics in the Sahel (SIPSA) is particularly relevant for understanding the current dynamics and supporting decision making to cope with the different crises affecting the region (Touré et al. 2012).

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Chapter 11
Climate-Smart Farms? Case Studies in Burkina Faso and Colombia

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Abstract The climate-smart agriculture concept aims to encourage reflection on the transition to sustainable agricultural systems adapted to climate change. This chapter is based on participatory research studies carried out in Colombia and Burkina Faso to investigate, with farmers, the relevance of new (agroclimatic information) or long promoted (compost) solutions that could be considered climate-smart. These studies were based on an analysis of farmers' strategies to cope with climate change and variability, while also relying on modelling in the case of Burkina Faso. We highlight that these solutions should be dovetailed with existing strategies. The range of adaptation mechanisms used by farmers in Colombia influenced their agroclimatic information needs. In Burkina Faso, these adaptation mechanisms led to specific effects of compost on climate-smart

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agriculture assessment criteria. We discuss methodological lessons learned for the co-design of farms adapted to climate change.

11.1 Background

Farmers have developed a range of adaptation strategies to cope with changes in their climatic or economic environment (Thomas et al. 2007; Twomlow et al. 2008). These, however, are likely insufficient to deal with potential climatic events of unknown magnitude which would require the development of novel solutions.

The climate-smart agriculture concept (FAO 2010) aims to encourage reflection on the transition to sustainable agricultural systems adapted to climate change. Our ongoing studies seek to promote climate-smart practices that are assessed according to three criteria—sustainable increases in productivity to equitably improve income and food security, adaptation to climate change and mitigation of its effects via a reduction in greenhouse gas emissions. These practices include technical practices, decision support tools and agroclimatic information.

Adoption of these practices would undoubtedly result in readjustments at the farm scale and necessitate renewal of existing research on the design of farming systems (Meynard et al. 2012). This research aims to systemically analyse the sometimes contradictory objectives of farmers and their families, while being hinged on multiple expertise (of farmers, researchers or technicians) to define and test solutions that foster synergies between these objectives. Solutions derived from this type of research are formulated through analysis of the current situation and participatory investigation of new solutions, sometimes with the help of modelling (Vall and Chia 2014).

Here we discuss the co-design of climate-smart farms based on a specific analysis of how to determine, with farmers, solutions to foster synergies on the farm scale between the sustainable increase in productivity, adaptation and mitigation. This chapter builds on the results of studies carried out in different projects aimed at investigating new solutions with farmers—climate information in Colombia in 2014 and manure production in Burkina Faso from 2008 to 2012, with the use of simulation tools in the latter case.

We outline our framework to analyse strategies used by farmers to cope with climate change and variability, followed by a review of the case studies and results obtained. Finally, the lessons learned from these two studies regarding the co-design of climate-smart farms are discussed.

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11.2 Framework for the Analysis of Farmers' Strategies

Through the analysis of farmers' strategies, it is possible to identify adaptation mechanisms they currently use so as to be able to determine further mechanisms that would promote the transition to climate-smart farms. Several frameworks for the analysis of strategies used by farmers to cope with climate change have been proposed. Vermeulen et al. (2013) distinguished—according to their scope or intensity—incremental adaptations based on continuous changes over long periods, systemic adaptations corresponding to changes within existing cropping or livestock systems, or adaptations based on radical transformation of farms. Other studies have focused more on decision-making and biophysical processes which support those adaptations, and have highlighted the diversity of types of flexibility (Nozières et al. 2011; Dedieu et al. 2008) or resilience (Lallau 2008) of farms.

The analysis framework we use distinguishes several scales of climate change adaptation used by farmers and their families, which may be associated with specific adaptation mechanisms (Andrieu et al. 2008; Chia and Marchesnay 2008; Pédelahore et al. 2011):

- farming systems, which are related to the schemes, choices and dimensions of cropping or livestock systems, to the management of trade-offs or synergies between these systems, and to mobility as a means to gain access to new productive resources;
- practices at the plot or animal scale, resulting in adjustments to the context through modification of the practices (e.g. modification of varieties used or sowing dates) or input volumes;
- activity systems (on-farm and off-farm), which are related to the management of trade-offs or synergies between agricultural and non-agricultural income, and can result in mobility to seek income-boosting resources.

Adaptation mechanisms associated with each of these scales may be activated for short periods (e.g. planting of an off-season crop to compensate for low income from rainfed crop harvests during the current year) or long periods (e.g. a gradual change in production strategy). This framework was applied to analyse mechanisms used by farmers in the two case studies considered here.

11.3 Materials and Methods

11.3.1 Case Study in Colombia

The aim of this study carried out in three areas in Colombia, i.e. El Espinal, Pompeya and Puracé, was to determine, with farmers, the type of agroclimatic information best tailored to their needs. The use of agroclimatic information can be considered as a specific category of climate-smart practice that may promote decision making and the implementation of adaptations at the practice, farming system, or activity scale. Two main farm categories were studied on a total of 30 farms—landowner farming (more hired labour than family labour) with cereal monocropping at El Espinal and Pompeya, and small-scale family farming with mixed crop-livestock farming at Puracé. The survey focused on the socioeconomic features of farms (education levels, total farm area), strategies used to cope with climate variability, the current extent of access to climate information, the use or not of this information, and desired improvements in the information. Data were coded for the purpose of performing a multiple correspondence analysis followed by hierarchical clustering to associate farming characteristics and strategies with agroclimatic information requests.

11.3.2 Case Study in Burkina Faso

We conducted a survey on the adaptation strategies of the three main farmer categories (crop farmers, crop-livestock farmers, livestock farmers) in western Burkina Faso and developed a simulation model (Andrieu and Chia 2012) to investigate, with farmers, the impacts of introducing practices that could improve food security. The production and use of compost was one of the practices identified by farmers. This practice may have related adaptation and mitigation benefits especially because of the reduction in chemical fertilizer purchases. The model simulates the effects of strategies of the three farmer categories on the performance of their farms (transhumance and/or forage purchases in case of forage deficits, sales of livestock in case of income deficits, fertilizer purchases in case of a negative soil nitrogen balance).

A baseline scenario without compost and a scenario with compost input were simulated for a 10-year dataset concerning rainfall, input prices (fertilizer) and product prices (milk, cotton, cereals) for which we virtually doubled the interannual variability in comparison to a real dataset. Three model outputs were used to analyse the impact of introducing the practice on the climate-smart agriculture criteria:

- improvement in the cereal balance of the farm (supply from cropping systems minus the family's cereal demand) as productivity indicator;
- decrease in the coefficient of variation for the farm income as adaptation indicator;
- improvement in the partial nitrogen balance of the farm (applied organic fertilizer minus the demand for all crops) as mitigation indicator.

11.4 Results

11.4.1 Diversity of Adaptation Mechanisms

The strategies used to cope with climate variability differed between farmer categories. In Colombia, Puracé farmers preserved traditional seeds to cope with the different seasonal conditions (Fig. 11.1), while Pompeya farmers mentioned resorting to farm relocation in response to a decline in production. Farmers on landowner farms at Pompeya and El Espinal mentioned fewer adaption mechanisms than Puracé family farmers. This could be explained by their high level of investment (especially mechanization) in one to two cash crops, thus making adaptations in practices or farming systems difficult.

In Burkina Faso, however, adjustments in practices were almost identical for all farmer categories, but livestock farmers mentioned using transhumance in response to a lack of water and forage resources (Box 11.1), while crop-livestock farmers with the greatest production resources mentioned diversifying income sources by

Fig. 11.1 Preservation of traditional seeds as a climate change and variability adaptation strategy in Colombia (© F. Howland/CIAT). A seed bank created by a farmer at Puracé (Cauca, Colombia). This illustrates one adaptation strategy based on native seed conservation (exchange, propagation, storage) outside conventional certification schemes. Farmers sow all varieties available in small quantities in order to preserve seeds to cope with the diversity in potential climate scenarios

beginning to intensify their livestock farming activities (Table 11.1). We will see later that the diversity in these strategies has an impact on farmers' interest for climate-smart practices and on farm performance with respect to climate-smart agriculture criteria.

Box 11.1. Adaptation of herd management to climate change in western Burkina Faso.

Éric Vall and Soumaïla Pagabeleguem

Livestock farmers in western Burkina Faso have been experiencing climate change for 10–15 years, as reflected by: a 1–2 month delay in the onset of the rainy season, an increase in the duration of 10–20 day 'drought pockets', an increase in rainfall in August, and earlier cessation of rains.

The farmers claim that this change is mainly due to the increase in agricultural encroachment. Farmers adapt their herd management strategies, as difficulties arise, by:

- dividing the herd, purchasing feed, transhumance to areas with greater rainfall when rains are delayed;
- grazing the herd in lowlands with greater grassy plant cover during prolonged or repeated drought periods;
- moving the herd to hilly areas, reducing the residence time in muddy paddocks, increasing pesticide treatments in case of heavy rains in August;
- short transhumance to areas favourable for annual herbaceous plants in case of early cessation of rains.

Adaptation strategies vary according to the agroclimatic zone (greater fodder storage in Sudanian and Sudano-Sahelian zones), herd size (greater feed and forage stocks for farmers with medium-sized herds) and locally available resources (short transhumances facilitated by the availability of areas without crops).

11.4.2 In Colombia—Information Required to Cope with Climate Change

In Colombia, we further refined the initial classification that differentiated landowner farming and small-scale family farming and identified five types of farmer characterized by their adaptation strategies (Table 11.1) and demand for specific climate information. Types 1 and 2 farmers (both from Puracé) used the highest number of adaptation mechanisms with regard to practices and farming system.

Table 11.1 Main adaptation mechanisms mentioned by farmers in Colombia and Burkina Faso

<table>
<tr><th></th><th>Activity system</th><th>Farming system</th><th>Technical practices</th></tr>
<tr><td>Crop farmers in western Burkina Faso</td><td rowspan="3">Seasonal work in mines and urban areas
Small business</td><td>Capitalization of cotton income via livestock farming</td><td rowspan="3">Adjustment of cropping system choices
Adjustment of cropped areas, livestock numbers, input volumes
Choice of varieties</td></tr>
<tr><td>Crop-livestock farmers in western Burkina Faso</td><td>Intensification of livestock farming activities via introduction of livestock fattening</td></tr>
<tr><td>Livestock farmers in western Burkina Faso</td><td>Beginning of investment in cotton cropping
Transhumance</td></tr>
<tr><td>Crop farmers at El Espinal</td><td></td><td>Irrigation</td><td rowspan="2">Adjustment of cropped areas and input volumes</td></tr>
<tr><td>Crop farmers at Pompeya</td><td>Abandonment of agriculture for another activity</td><td>Relocation</td></tr>
<tr><td>Crop farmers at Puracé</td><td></td><td>Transition to conservation agriculture
Preservation of traditional seeds
Mixed crop-livestock farming</td><td>Choice of varieties
Use of differences in land elevation
Staggered sowing
Use of hedges</td></tr>
</table>

Type 3 farmers were essentially located at El Espinal and had relatively few adaptation mechanisms to cope with climate variability. The same trend applied to type 4 farmers from El Espinal and Pompeya who had the highest educational level (engineers and academics) and were likely to have a better understanding of the value of climate information for decision making. Type 5 farmers were from El Espinal and Pompeya and mentioned having fewer adaptation mechanisms.

Farmers with the most adaptation mechanisms (types 1 and 2) were finally those who least requested climate information (type 1) but requested seasonal information (type 2) to help them cope with changes in the farming system. Those with the least leeway, because of their high level of investment, generally requested short-term daily and weekly information (types 3, 4 and 5). Some of them (types 4 and 5) nevertheless understood the value of seasonal information in the longer term to better prepare the cropping season. Type 5 included farmers who mentioned few adaptation mechanisms and whose capacity to use climate information for making adjustments to their farming system could be questioned. Farmers thus have a role to play in defining the most relevant type of information for their decision making.

11.4.3 In Burkina Faso—Compost and Climate-Smart Farms

In Burkina Faso, a whole-farm simulation model was used to analyse adjustments associated with the introduction of compost and their effects on climate-smart agriculture assessment criteria for different farmer categories. Introducing compost in crop-livestock farms increased the income variability since the higher demand for crop residue to produce compost led to a fodder deficit in years when rainfall was lowest, in turn leading to increased forage purchases. Cereal and nitrogen balances were nevertheless enhanced on the farms through the positive impact on soil fertility and cereal yields (Fig. 11.2). On crop farms, introducing compost enhanced the three assessment criteria. Due to the lower livestock numbers, crop residue

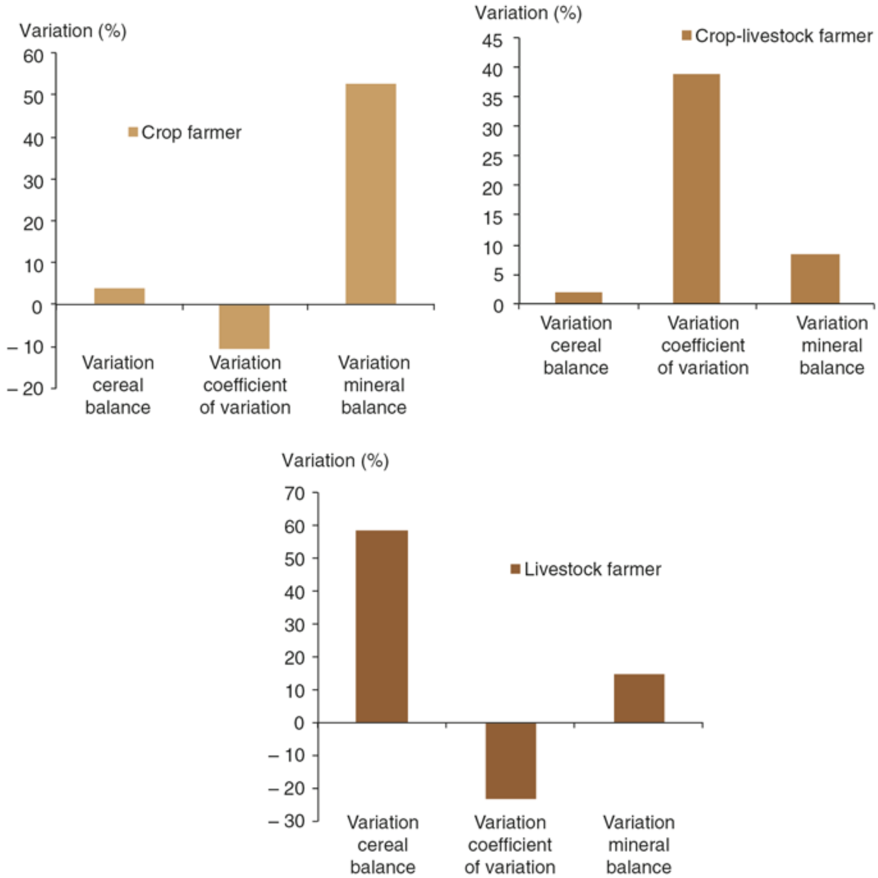

Fig. 11.2 Impact of the introduction of compost on cereal and nitrogen balances and on the coefficient of variation for income (variation between the baseline scenario and the scenario with compost)

produced on this type of farm was sufficient to meet fodder and manure needs and no forage purchases were required. On livestock farms, the three assessment criteria were also enhanced, but there was high reliance on crop residue produced by other farmers from the village (increase in simulated transhumance days). The introduction of compost thus had different impacts on the three assessment criteria.

11.5 Discussion

11.5.1 Diversity of Adaptation Mechanisms Used by Farmers

The results presented highlight the diversity of adaptation mechanisms currently used by farmers, some of which go beyond the farming system and are based on the development of off-farm activities.

In Colombia, some landowner farmers may give up their agricultural activities when the profitability of the farm decreases. This transition is facilitated when they also have off-farm activities. Pédelahore (2014) showed that involvement in multiple activities can also be a driver of farming system investments.

Three main mechanisms are used at the farm scale: spatial mobility of the farmer or her/his herds, diversification and specialization. For Pompeya farmers in Colombia, spatial mobility is reflected by their ultimate migration to newly cleared areas, giving them access to fertile soils, thus enabling them to maintain or even increase their monetary income. For livestock farmers in Burkina Faso, herd mobility in response to seasonal variability in water or forage resources is temporary. Diversification in farming systems on the family farms studied was based on mixed farming, sometimes associated with livestock farming, but also on the maintenance and enhancement of the diversity of environmental resources through, for instance, the preservation of traditional seeds or taking advantage of differences in land elevation. Conversely, on landowner farms, a high proportion of their farming system is associated with substantial artificialization of the environment (use of improved seeds, high level of equipment), which is how these farmers offset variability in their production results.

Finally, practices were the main focus of adaptation for all farmer categories and generally implemented on short time scales. This diversity of strategies amongst farmer categories calls for further research to compare their efficiency with regard to productivity, adaptation and mitigation.

11.5.2 Lessons for the Co-design of Climate-Smart Farms

The climate-smart agriculture concept encourages investigation of innovative practices—e.g. the use of agroclimatic information, as well as long promoted practices like compost use in Burkina Faso—from a different perspective using assessment criteria such as productivity, adaptation and mitigation. The results of the two case studies confirmed the importance of analyzing strategies used by farmers to deal with climate change and variability in order to define the types of existing adaptation mechanisms and solutions that are hinged on these mechanisms. For instance, climate information may not meet the current demand of some farmer categories. The impact of these solutions on climate-smart agriculture criteria also differs depending on the strategy (e.g. the effect differs for crop farmers, crop-livestock farmers or livestock farmers in Burkina Faso) and indicates that a broader range of solutions are necessary to address the diversity of situations.

The Burkina Faso case study also showed that the tested practices may not have a positive impact on all three criteria. Their relevance depends on the context and specific issues with regard to productivity, adaptation and mitigation.

The participatory approaches we used in the two case studies should be combined to be able to co-design climate-smart farms. Solutions should be formulated with farmers to strengthen existing strategies and simulate, with them, the short-

Fig. 11.3 Demonstration on organic manure production for farmers in Burkina Faso (© M. Rueff)

and long-term effects on climate-smart agriculture criteria. The models could serve as tools for discussion between researchers and farmers (Andrieu et al. 2012; Rodriguez et al. 2014). This simulation study could have been combined with a full-scale experiment to enhance farmers' knowledge on ways to put the solutions into practice (Fig. 11.3).

Changes in practice result in adjustments at the farm scale, e.g. introduction of compost led to an increase in the transhumance duration for livestock farmers in Burkina Faso. Specific support is therefore needed. This may be achieved by training advisers from public and private institutions on taking short- and long-term uncertainties into account, on multicriteria assessments, and on the use of simulation tools, with farmers, to investigate potential future trends.

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Chapter 12
Joint Management of Water Resources in Response to Climate Change Disruptions

Olivier Barreteau, Stefano Farolfi and Sylvain Perret

Abstract Climate change has a profound impact on the water cycle, causing gradual and sometimes marked changes in hydrosystems and natural hydrological processes. Societies and stakeholders are striving to adapt so as to manage and control their interactions with water. Current scenarios indicate, however, an acceleration in global climate change processes, yet with high local variability. In this chapter we present a selection of climate change related research studies focused on three major issues in the field of water resource management: characterizing change patterns, adapting to change via technological innovations and adapting governance to cope with change. These studies were carried out in partnership primarily with institutions in developing countries, with the full participation of local stakeholders in defining and running the projects and disseminating the results.

12.1 Water Cycle and Climate Change—The Issues

The water cycle is clearly the global biophysical process most affected by atmospheric temperature changes (modified evaporation, evapotranspiration and rainfall regimes, cryosphere melting). The forms, expressions and trends in this cycle are readily perceptible as they involve the atmosphere, oceans, terrestrial and aquatic ecosystems, as well as all living organisms. Significant changes in rainfall and

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Fig. 12.1 Irrigated rice cropping in Majes Valley, Peru (© B. Locatelli/CIRAD)

surface water flow volumes, sequences, durations, forms and intensities, as well as in inland and marine water quality, represent the bulk of the direct and indirect impacts of climate change on water resources.

Climate change therefore induces gradual and sometimes marked changes in hydrosystems and natural hydrological processes. It also disrupts water-dependent manmade systems such as livestock farming, rainfed and irrigated agriculture. Water and aquatic environments, as well as their users, are highly dependent on climate patterns: water resource availability and quality, spatiotemporal variability, extent of needs, especially agricultural. In return, irrigated agricultural activities, especially in submersion conditions, contribute substantially to the emission of methane, a powerful greenhouse gas (Fig. 12.1). It is hence estimated that irrigated rice crops emit 9–13 % of anthropogenic methane (IPCC 2014).

Societies and stakeholders strive to adapt to these interrelationships, in line with the intrinsic variability in these processes to which they are accustomed. This enables them to manage and control their interactions with water by altering flows via adjustments in their land use patterns or mobility. Current scenarios indicate, however, an acceleration in the intensity of this variability. Substantial scientific and lay skills, knowledge and know-how concerning practices, especially agricultural production and resource management practices, have turned out to be less relevant or insufficient to address these changes and should therefore be updated or revised.

In this change and uncertainty setting, we present a selection of climate change related research studies focused on three major issues in the field of water resource management:

- characterizing change, to gain further insight into modifications in natural and manmade systems induced by climate change, to model the short- and long-term impacts and risks, and to represent the interweaving of climate change with other socioeconomic, institutional and political changes under way;
- proposing technical solutions to support stakeholders in adapting their practices in order to achieve greater resilience to risks and identify technical solutions to cope with change;
- adaptation of governance to cope with change, to take emerging questions on water management and usage within territories into account.

12.2 Characterizing Change

The first major issue is to characterize change processes under way. A first series of studies focused on water resource availability, including characterization of the role of climate change in altering rainfall patterns. Regarding the current trend in the monsoon regime in Southeast Asia, for instance (Singhrattna et al. 2009), this weather pattern occurs later, while being more erratic and of harsher intensity. The development and combination of statistical climatic and mechanistic hydrological models confirmed that regional temperatures in the China Sea are robust predictors (at 1–4 months) of pre-monsoon rainfall and (at 6–12 months) of monsoon and dry season rainfall on a catchment scale in Thailand. The use of these predictors (by downscaling) paves the way for medium-term rainfall forecasting and management of related risks (floods and droughts).

This change in rainfall regimes may be perceived in different ways depending on the season and land-use pattern. Trends in the Sahel indicate that a decline in rainfall could result in an increase in flood peaks over a shorter period (Mahé et al. 2010). In addition to the increased intensity of storms, land-use changes have caused increased runoff, resulting in a faster concentration of flows along the main hydrological drainage lines. The impacts of flood recession on agriculture are greater than when only the trend is considered, indicating that increased water management is necessary. For a given production system, climate change thus leads to a change in water use conditions.

The characterization issue also applies to stakeholders through the identification of the importance of climate change relative to other global changes, i.e. all changes that occur in the context of a stakeholder's water use and for which the stakeholder has no direct control. This may involve changes in national or supranational agricultural or environmental policies, economic changes related to changing markets, demographic modifications or changes in land-use policies. Users do not always distinguish the effects of these changes in terms of their origin, e.g. the separation between signals associated with a change in energy policy resulting in closure of a dam or related to low rainfall (Box 12.1), whereas there is a causal relationship between climate change and land-use policy changes. Climate change is not always considered as the most important factor, at least in the short term. Farmers are aware of climate variability and argue that they can handle it most of the time (Faysse et al. 2014), resulting in less need for adaptation than taking other factors into account (Mertz et al. 2010). This leads to a higher response threshold (delayed reaction) for climate-related changes than for other changes.

Box 12.1. Large dams in West Africa—a climate change adaptation solution or a source of problems?

Bruno Barbier, Cirad, UMR G-EAU, Dakar

After a long pause, in the last few years West African governments and a few donors from emerging countries have indicated their willingness to heavily reinvest in large dams to meet the pressing demand for reliable and less expensive renewable energy and the development of irrigation. The latter is considered to be one of the best climate change adaptation instruments for rural communities. These arguments and the accompanying new funding only partly explain the renewed interest in dams. There is ongoing controversy on whether large dams are actually needed, and on the different impacts of these structures in West Africa.

The West African region is especially vulnerable to climate change. The still poorly understood high climate variability appears to be especially high in this region. Rainfall and flow forecasts are highly uncertain because of the coexistence of natural cycles and climate change related trends. In the past, the production of large hydroelectric and agricultural dams revealed a high vulnerability to climate variability. Irrigated areas in West Africa are still extremely limited in size, and their economic results disappointing, but there is considerable room for improvement and development. Some forms of irrigation can also be developed without building large dams. Moreover, dams have a negative impact on traditional riparian systems, especially on forage production, wetlands and downstream riparian ecosystems. The decline in traditional irrigated systems should be offset by more efficient irrigation.

Current knowledge and acquired experience indicate that large dams are not a panacea in the adaptation to climate change in West Africa. In addition to the climate change issue and the prevailing uncertainty, hydrological regimes required for efficient power generation are seldom sufficient in this region, and the provision of cheaper renewable energy is not guaranteed. Moreover, agricultural systems irrigated with dam water are not efficient. The development of new irrigated areas should be coupled with increased irrigation efficiency and agricultural system performance.

This perception of the relative importance of climate change and of the need to adapt to it varies in different parts of the world. It seems lower in the Sahel and North Africa, but higher in Nepal (Manandhar et al. 2011). In this highly agricultural country with extremely diversified environmental conditions, associated especially with a marked elevation gradient, studies have focused on perceptions of climate-related changes and on adaptive measures taken in small family farms. The results revealed accurate perceptions, in line with trends derived from a historical meteorological data analysis (1977–2006), concerning the decrease in rainfall, the increase in temperature (minimal) or the higher frequency of droughts and floods. Farmers develop multifaceted responses to changes with regard to both cropping and farming systems (Table 12.1). They are based mostly on stakeholders' knowledge and experience (human capital) but are constrained by the general lack of other capital. Moreover, they are individualistic, empirical and sometimes inefficient, highlighting the need for better action planning, greater reliance on external knowledge and technological solutions, collective action and approaches that will boost adaptation and resilience to change.

Table 12.1 Technical solutions implemented at the farm level in two regions of Nepal in response to locally-perceived climate change (from Manhandar 2010; Manhandar et al. 2011)

Types of change and perceived risks	Lowland regions (Rupandhei district)	Highland regions (Mustang district)
Reduced rainfall	Crop diversification shift in cropping calendars Implementation of simple water and soil management/conservation techniques (e.g. small stone walls, small-scale manual supplementary irrigation)	Development of domestic water recovery/recycling techniques crop diversification
Increased occurrence of flood and drought periods	Adoption of shorter cycle or more tolerant Indian rice varieties Introduction of small-scale aquaculture in lowland flood plains crop diversification	
Increased temperature, combined with increased pest attacks or more frequent fogs		Apple orchards moved to higher plots crop diversification

12.3 Proposing Technical Solutions

The second major issue is to propose and test technical solutions to cope with climate change, or rather spatiotemporal changes in water resource availability. We investigate three options: resource regulation, mobilization of alternative resources and technological innovations in water use. Dams provide a way to store water for use in shortage periods (see Box 12.1), but they also give rise to problems for users. These may not have relevant knowledge to foresee water releases or induced potential morphological changes (Ferry et al. 2012). Dam construction also generates changes in the hydrological regime such as fisheries (Cecchi 1998) or health effects. The management of dams also raises questions because it involves collective investments that are sometimes hard to implement and manage if they are not underwritten by legitimate authorities (Faysse et al. 2010).

Alternative resources such as brackish water, wastewater and groundwater can offset the increased variability in surface freshwater. However, despite their potential (Molle et al. 2012), tapping these resources still raises questions concerning technological development and assessment of their economic interest. They may also have negative impacts on environmental quality. Regarding uses, irrigation is still a good climate change adaptation solution, especially compared to other solutions specifically focused on crops (Santikayasa et al. 2014). The development of water-efficient technology is not entirely focused on adaptation to resource scarcity, it rather addresses the question of increasing production while not increasing water use. Drip irrigation is, for instance, an emerging technology developed as a response to climate change as well as in favour of various interests (Venot et al. 2014). These technical solutions are nevertheless a continuation of adaptation expertise acquired on past variability patterns for a change of intensity that is a priori not commensurate with the expected changes. This adaptation capacity based on previous patterns may be a hindrance when considering the changes to come.

Regionally, another approach involves predicting changes in land production potential according to regional current and future climate change patterns, for planning purposes, especially for large-scale plantations, e.g. tea, rubber and coconut in Sri Lanka (Jayathilaka et al. 2012). Spatial and temporal maps of climate and production patterns are plotted using historical data and compared. Relationships between crop yields and climate data are established by hierarchical multicriteria analysis and using simple crop models. An analysis of regional climate change patterns underlined the decrease in rainfall, especially in wet areas of the island, and the increase in the average temperature trend. Six agroecological zones were identified and their spatial analysis compared for two periods (1980–1992 and 1993–2007) revealed changes in climatic conditions and the risk of production losses due to shifts in the optimal climatic zones (Fig. 12.2). The maps produced were discussed with stakeholders in the concerned sectors to help guide future plantation planning and rural development overall.

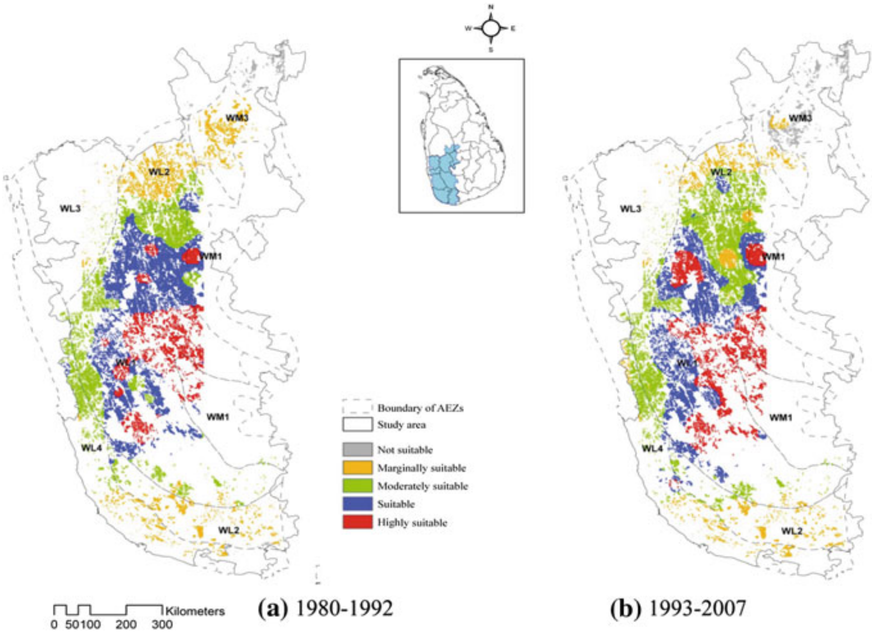

Fig. 12.2 Map showing zones suitable for tea cropping in Sri Lanka, according to climatic criteria and changes between two periods (from Jayathilaka et al. 2012). *Dotted lines* correspond to agroecological areas predefined at the beginning of the study and designated by the acronyms WL and WM, e.g. *WL1* wet area at low elevation no. 1, or *WM3* wet area at medium elevation no. 3, etc.

12.4 Adapting Governance to Cope with Change

The third major issue—an upshot of the previous issues—concerns the possibility of changes in the governance of hydrological areas. This should include non-technical adaptation solutions such as taking into account the increased migration to offset income variability (Mertz et al. 2011), the increased medium-term forecasting capacity (Diarra et al. 2013) or the economic assessment of alternative scenarios for water resource allocation in catchment basins (Hassan and Farolfi 2005). New methods are required to inform the decision making process for users and managers. The assessment of climate change impacts and adaptation options requires insight into the induced effects, particularly in terms of social justice. Although not directly related to climate change, the land-grabbing phenomenon currently affecting many poor countries is an example of the dynamics that should be monitored. Researchers, in partnership with water management stakeholders, are thus working towards developing methods and tools to facilitate the inclusion of heterogeneous viewpoints in development and adaptation choices.

The participatory modelling and simulation kit Wat-A-Game (WAG) supports all stakeholders for gaming and negotiation on water management and usage

(Fig. 12.3). Minority stakeholders are thus able to express their viewpoints on change and adaptation proposals (Ferrand et al. 2009). Its application in eastern and southern Africa has facilitated the involvement of all village communities and governments in preparing their collective development strategies (Legrand et al. 2014).

Fig. 12.3 A Wat-A-Game session in Kenya in 2014 (© N. Ferrand/IRSTEA)

12.5 Other Studies

Mitigating climate change via studies on greenhouse gas emissions by irrigated cropping systems and possible solutions, especially via irrigation water management, have also been the focus of many studies (e.g. Perret et al. 2013; Thanawong et al. 2014) which are discussed in Chap. 20 regarding environmental assessments through life cycle analysis.

Some studies have highlighted the indirect impacts of climate change on water resources. In particular, there is growing demand for alternative renewable energy resources. This demand is often politically promoted as a climate change mitigation measure in close interaction with water resources. The demand for biofuels induces changes in land use and in water demand. These modifications could have major consequences on the regional or local water demand (Gheewala et al. 2013, 2014), surface water flows and soil erosion risks (Babel et al. 2011). Moreover, the development of hydroelectric dams modifies river regimes and riparian hydroecosystems (see Box 12.1).

12.6 Conclusion

This non-exhaustive panorama was focused on adaptation to climate change with respect to water-dependent agricultural systems, their territories and water resource management and governance. The presented research studies were carried out in partnership, primarily with institutions in developing countries, in close collaboration with local stakeholders in developing and running the projects, as well as disseminating and using the results. Research activities are generally conducted locally, according to participation and action-research principles, with the involvement of farmers, decision makers, and development agents. Such investigations also take into account and compare different viewpoints, use co-construction approaches for analysis, assessment and solution-seeking, and also favour result sharing, training and capacity building throughout the research process.

These are the original features of the studies reported here. They help to better associate the different stakeholders involved in climate change adaptation processes. The aim is to form a continuum of scientific and lay expertise, know-how, local practices, external technologies and information to fuel decision-making channels involved in adaptation processes regarding rural populations, farms and public policies.

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Chapter 13
Agricultural Organic Waste Recycling to Reduce Greenhouse Gas Emissions

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Abstract Organic waste recycling in agriculture can enhance the efficiency of nutrient cycles and directly or indirectly reduce major and increasing sources of greenhouse gas emissions. It can also boost soil fertility and agricultural resilience to climate change. There is considerable potential for improving recycling that has been studied from the farm to the territorial scale. We present research results concerning the improvement and introduction of recycling practices on several scales and concerning associated biophysical processes allowing more reliable assessment of greenhouse gas emission balances. Whether concerning the resilience of agricultural systems or the mitigation of emissions, the agricultural waste recycling potential is highest on the territorial scale, especially when the spatial concentration of various wastes is high, e.g. in periurban areas around fast-growing

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megacities in developing countries. CIRAD has developed recycling management methods and support tools and is enhancing knowledge on processes that determine the climate footprint of recycling. The aim is to fill the many knowledge gaps regarding greenhouse gas emission factors and determinants of organic matter bioprocessing in tropical conditions.

13.1 Background

In recent years, the livestock farming sector has been singled out for its contribution to climate change, although the spotlight is actually focused on the entire agricultural sector. The causes of this situation are human-induced changes related to food—a growing population whose diet changes according to the level of development, with increasing segregation of places of production and consumption. These two changes have led to substantial increases in greenhouse gas (GHG) emissions that could be attributed to the livestock sector (Chap. 10). This sectoral focus makes it easy to draw a readily understandable picture of the situation, but other aspects could also be of interest in the search for solutions. A climatically relevant perspective shifts the focus toward what—during the second agricultural revolution—Marx, influenced by Liebig, referred to as the 'metabolic rift' (between humanity and the soil). This rift with regard to natural cycles has since been exacerbated by globalization, urbanization, dietary changes and spatially concentrated specialization of agricultural sectors. Initially criticized for its impacts on soil fertility, this rift, particularly through the accumulation of organic waste it entails, is a significant source of GHG emissions.

Organic waste recycling helps reduce this metabolic rift, thus contributing to ensuring sustainable and resilient soil fertility—and hence agriculture—while reducing environmental impacts associated with this rift, including the impact of climate change. Within the agricultural sector, the increased segregation of places of production and consumption is obvious in so-called intensive livestock farming sectors, whose effluents have long been the focus of our research. The search for sustainable recycling solutions has broadened the scope to encompass the territory, while respecting local specificities and highlighting the potential synergy between various types of waste.

There are many links between organic wastes—from their production to their final destination—and GHG emissions. Because of this multitude of links, there are also many direct and indirect ways of reducing these emissions that could be investigated with the recycling of such wastes. In the first part of this chapter, we present research on the identification and implementation of systemic changes required to achieve these reductions. As little is known about the biophysical processes involved, studies to gain further insight into and represent these processes in order to be able to more reliably estimate GHG emission balances are discussed in the second part of the chapter.

13.2 Waste Recycling Pathways of Climatic Interest

'Concentrated', rather than 'scattered', deposits of organic waste are usually managed within enclosed areas and at low cost for farmers, often to the detriment of the environmental balance. Substitutes are required when this organic matter is not returned to the agricultural area from which it originated, e.g. chemical fertilizer, whose manufacturing and use represent a substantial 'climatic' cost. However, the increase in these waste deposits and the increasing societal commitment to climate protection broadens the prospects for greater 'climate-responsible' management.

Some technical improvements enable waste producers to improve their climate footprint in some cases. However, there is much greater potential for improvement via careful linkage of farmers with their environment, e.g. greater chemical fertilizer substitution, reduced storage time, or access to economies of scale for the implementation of treatment processes like methanation. Energy recovery and agricultural recycling of waste can thus be complementary, and integrated management of agricultural recycling of urban, periurban (agroindustrial) and agricultural organic waste is possible. This recycling process may generate significant agroenvironmental benefits but which are hard to implement and assess.

13.2.1 Pathways Studied at the Farm Level

Most farms in tropical areas combine crop production and livestock farming activities, but the extent of integration of these two activities at the farm level varies considerably. One of the main keys to this integration is the use of the product of one activity as a resource for another activity (and vice versa) (Fig. 13.1). This integration can be analysed from the standpoint of biomass recycling and the nutrient cycle. Crops generally produce residue that can be recycled for livestock feed and in turn these animals produce organic manure that can be used to fertilize crops.

It has long been impossible to quantitatively assess this degree of crop-livestock farming integration. Methods such as ecological network analysis—inspired from trophic network analysis methods—have enabled quantification of the extent of crop-livestock integration in Réunion (Vayssières et al. 2011a), Madagascar (Alvarez et al. 2014) and more recently in Burkina Faso and the Caribbean. These studies revealed high diversity both between and within regions, indicating that there is considerable room for progress. In principle, nutrients are preserved to a greater extent on farms with high crop-livestock integration, hence they have lower GHG emissions.

A participatory modelling study was conducted in Réunion from 2003 to 2007. The GAMEDE computer model was co-built with a group of six dairy farmers to simulate the functioning of dairy cattle farms that included grasslands and sugarcane fields. These six farms were located in different agroecological zones on the

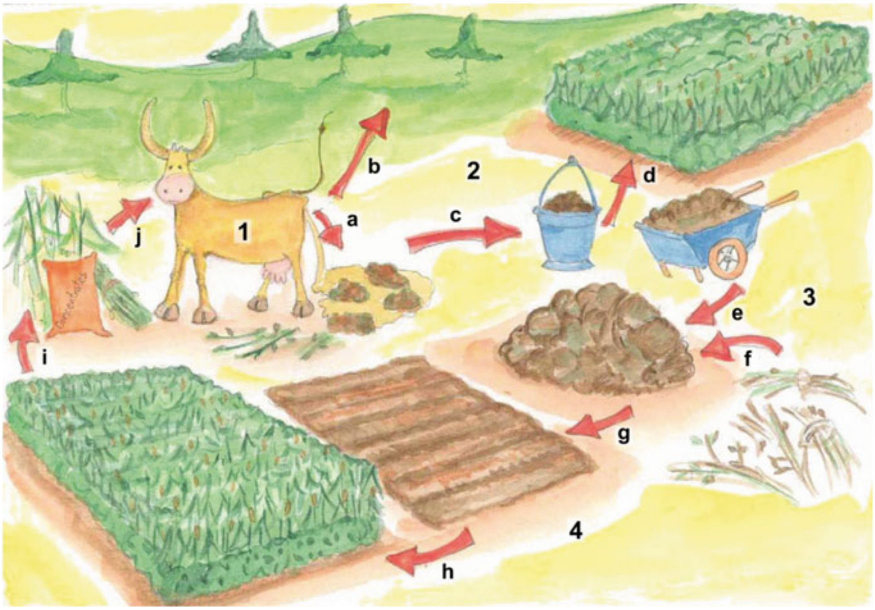

Fig. 13.1 Biomass recycling on mixed crop-livestock farms (from Rufino et al. 2006). Numerals (*1–4*) correspond to the main biomass management and transformation processes and letters (*a–j*) indicate the main biomass flows studied to promote the integration of crop and livestock production. (1) Digestion by livestock: crop products (including residue) can be used as livestock feed (flow *j*). Dung resulting from their digestion is stored in buildings (flow *a*) and/or spread on rangelands (flow *b*). (2) Organic manure collection: dung is collected (flow *c*) and spread directly in crop fields (flow *d*) or stored before spreading (flow *e*). (3) Organic manure storage and curing: crop residue (including feed waste in troughs) may be mixed with dung (flow *f*) before storage or composting. (4) Decomposition in soil and biomass production by plants: organic manure is spread on cultivated plots (flow *g*) and the nutrients from manure are gradually made available to plants. Part of these nutrients are used by plants (flow *h*), and the biomass produced is distributed between the seeds and residue (flow *i*)

island and were representative of the diverse range of farming practices. The GHG balance varied between farms (Vayssières et al. 2011b). Participatory use of the GAMEDE model enabled assessment of three environmental impact reduction strategies: substitution of chemical fertilizers by organic manure produced on the farm, substitution of part of the feed concentrates by fodder available on the farm, and improvement of the reproductive performance of female dairy cows. The simulations showed that enhanced crop-livestock farming integration led to a reduction in the environmental impact while increasing the economic gross margin of the farm (Fig. 13.2). For all farms in Réunion, the three strategies potentially represent an average 12.3 % reduction in the dairy farming contribution to climate change. The increased labour time is the main hurdle for the adoption of these practices.

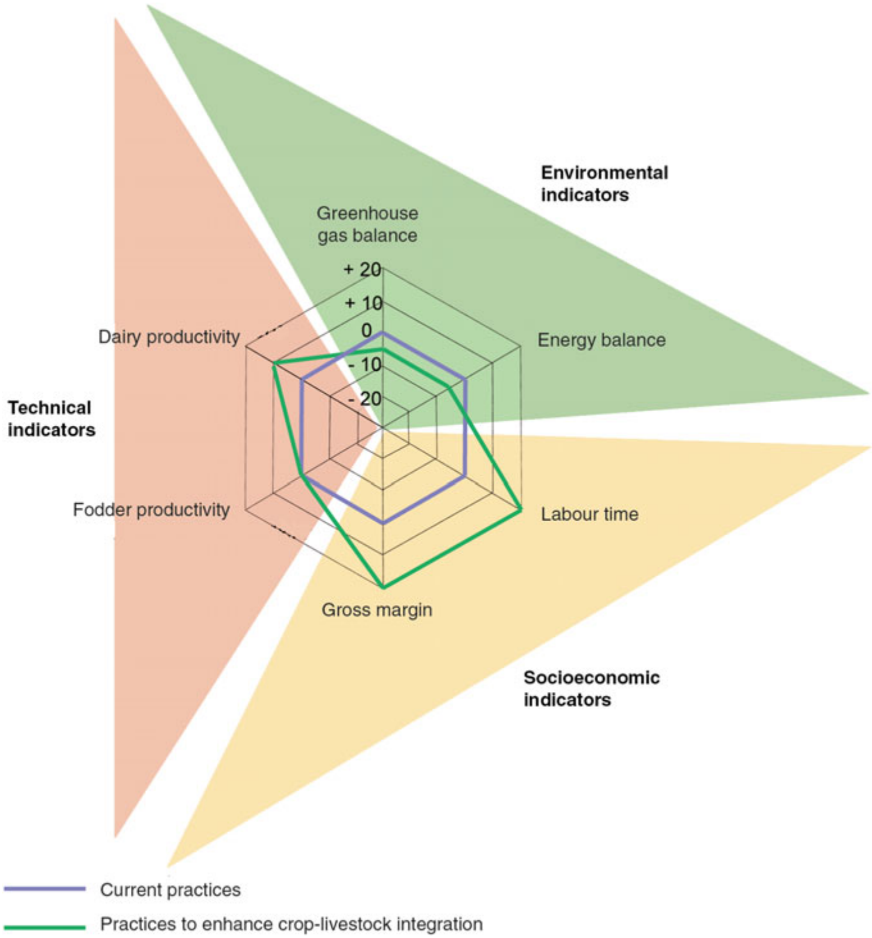

Fig. 13.2 Effect of better crop-livestock integration on the environmental, technical and socioeconomic sustainability of a dairy farm at Plaine-des-Palmistes in Réunion (% variation in reference to practices monitored in 2004). The radar chart indicates the percentage change relative to current practices for different variables

13.2.2 Pathways Studied at the Farmers' Association Level

In intensive livestock farming regions, high surplus amounts of nitrogen are often applied to crops in organic or chemical form. Nutrient losses (partly in GHG form) resulting from these surplus inputs represent an agricultural and climatic cost, especially as there is generally very little synthetic fertilizer substitution by organic inputs. In this setting, farmers' associations have emerged in an effort to improve waste recovery by proposing collective spreading solutions in areas remote from places with surplus soil nitrogen levels that were previously partially fertilized with synthetic fertilizer applications. CIRAD conducted a project at Ille-et-Vilaine (France) with the aim of developing methods for agronomic and environmental assessment of collective slurry spreading and studying the constraints (Paillat et al. 2014). A life-cycle analysis was carried out to compare a scenario in which pig slurry was spread on fields 40 km away from farms where the slurry had been produced to a scenario involving aerobic slurry treatment conducted 12 km, on average, from livestock farms (Lopez-Ridaura et al. 2008). The feasibility of the spreading plan was studied using the COMET model (Collective Management of Effluents on a Territory scale; Paillat et al. 2009).

The findings of the life-cycle analysis suggested that the spreading scenario would emit a higher total amount of GHG than the total emitted under the aerobic treatment scenario due to the emission of methane (CH_4) during storage and nitrous oxide (N_2O) after spreading, despite the higher energy consumption under the second scenario. Dynamic simulation of the relationship between farms enabled an assessment of the actual situation, while providing insight into variations between farms and measurement of the extent of their dependence on collective slurry spreading. The COMET model simulation results showed, for instance, that the collective spreading plan is never complete on winter cereal crops (spreading in March) because of the soil and climate conditions, leading to an increase in CH_4 and ammonia (NH_3) emissions due to the high storage time.

Different technical or organizational solutions were tested with the COMET model to reduce the potential environmental impacts. The simulations demonstrated that these solutions often affect many emission sources and sometimes in opposite ways. The size of the storage facilities and spreading capacities could be tailored to the specific structure of each farm so as to improve synchronization of the spreading and storage dynamics and reduce occasional surpluses. GHG emissions during storage and spreading are barely modified but the reliance on synthetic fertilizers is slightly decreased. The logistics of the collective spreading plan are crucial for individual spreading operations. If the number of delivery trucks is insufficient, deliveries and spreading cannot be achieved in the best time slots for the crops, thus markedly increasing the need for supplementary fertilizer applications.

13.2.3 Pathways Studied at the Territorial Level

Collective waste management is generally geared solely towards enhanced logistics, which usually results in the reduction of the waste load on nearby land and partial substitution of fertilizer inputs on land further away. These two changes improve the climate balance as compared to individual management. Such improvements could be much better if this management were also to provide access to collective treatment whereby a batch of waste is transformed into fertilizer products tailored to needs, thus substantially reducing high emissions from on-farm storage and raw waste spreading. Transition to integrated organic waste management at the territorial level could enhance its climate footprint in two different manners. First, regarding agronomic and agricultural needs, advantage could be taken of the complementarity between waste of various origins and types for the substitution of chemical fertilizers and amendments, thus avoiding emissions associated with their manufacture and delivery. Secondly, this would theoretically enable recovery of carbon (C) and nitrogen (N) contained in the waste, which are usually eliminated in processes that passively, or even actively, promote GHG emission.

A participatory approach involving all stakeholders would be required to fulfil this objective, including waste producers, consumers (present and potential) of waste and derivatives, potential processors, as well as representatives of local authorities. From 2011 to 2014, CIRAD pooled its expertise in agronomy and in the co-design and modelling of management systems in a research project on the island of Réunion (Wassenaar et al. 2014), where the growing problem of organic waste deposits encouraged stakeholders to get involved in a participatory approach to find solutions.

The research group, as one of the stakeholders, was expected to propose not only locally tailored solutions—i.e. addressing farmers' needs and waste producers' constraints, while remaining economically and logistically realistic—but also being in the public interest, including the reduction in GHG emissions. The term 'propose' is essential here. This did not involve technology transfer. Research identifies the possibilities, but the stakeholders at the territorial level make the collective decisions. The search for solutions thus involves a difficult trade-off between many options in which, in the absence of their monetization, the climatic benefits are generally indirectly taken into account, which also comes with agronomic benefits. The overall results of the many changes induced by implementing an integrated co-designed management scenario are hard to assess, and this is further aggravated by the high uncertainty in the estimation of the main emissions (see the next section) and by the difficulty of assessing the results of a change of activity (Fig. 13.3).

The fact remains that an integrated management scenario where livestock waste is co-composted with ground green waste and concentrated distillery vinasse, thus generating a complete fertilizer that is especially valued in market gardening, represents a climate benefit—despite an increase in GHG emissions caused by fuel consumption for transport or handling. The climate balance of more elaborate scenarios, where such 'organic bases' are transformed into real fertilizer, is even more positive due to the higher rate of substitution of imported chemical fertilizer.

13.2.4 Implemented Organic Waste Recycling Strategies

Organic waste methanation is recognized as a key solution for reducing GHG emissions in agricultural and agroindustrial sectors. It combines many positive effects on the environment with the reduction in CH_4 and N_2O emissions during storage and spreading, while avoiding GHG emissions through the production of

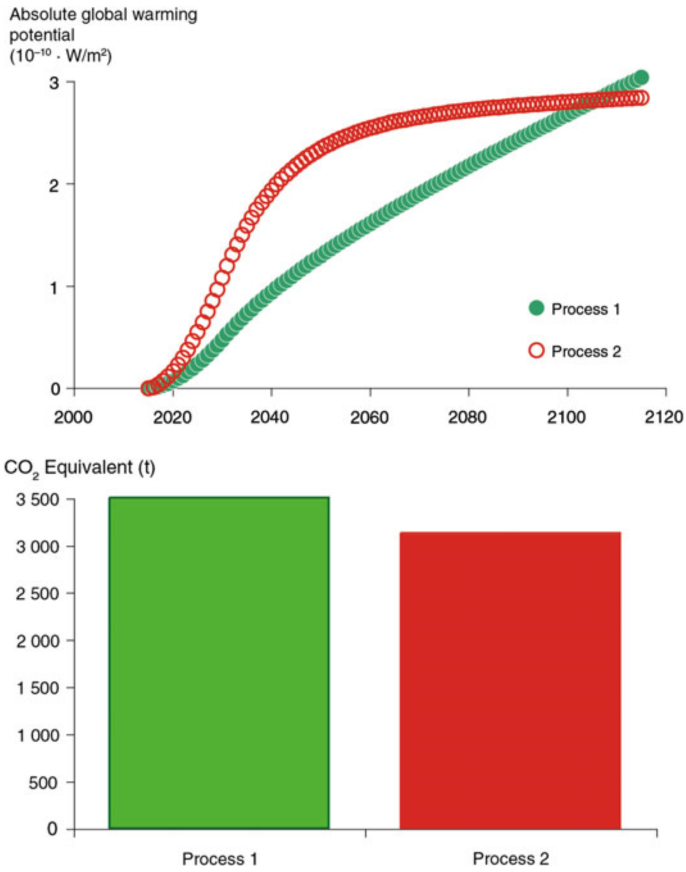

Fig. 13.3 A dynamic assessment to determine the climate footprint of an activity. From a temporal inventory of two processes, it is possible to calculate the CO_2 equivalent (warming potential in CO_2-eq in 100 years time, *upper diagram*) or to estimate the actual impact at different time horizons. Here we see that a stakeholder preference for a time horizon differing from that considered in the conventional approach (*lower diagram*) can alter the conclusions of the analysis (from Dumoulin et al. 2014)

renewable energy without loss of the fertilization potential of waste, which is also partially sanitized. In tropical regions, this waste recovery process is especially interesting since the high temperatures enhance its performance and electrical energy production is not yet fully centralized. However, despite its considerable interest, broadening experimental projects to include full-scale operations is far from being easy because of the lack of project supporters and capital. Interdisciplinary approaches that account for the dynamics and specific relationships between the different stakeholders are also necessary. Mobilizing quantitatively and qualitatively sufficient organic waste deposits is a major problem when they are to be provided by local authorities or smallholders. Since the 1990s, CIRAD has specifically focused on the methanation of agroindustrial waste produced in large quantities at one place.

In Africa, for instance, cattle farming is generally an extensive activity. The slaughterhouse is practically the only place of concentration of animals where it is possible to actually collect and recycle waste. CIRAD participated in two projects on this continent, i.e. in Senegal[1] and Egypt (Farinet and Forest 2003), to demonstrate the technical and economic feasibility of slaughterhouse waste methanation. A plug flow reactor is required for continuous methanation of this solid waste. Biogas is recovered within the slaughterhouse in Egypt for hot water production and in Senegal for combined heat and electricity generation. After methanation, the digestate is composted by leaving it to cure and dry in heaps in the open air. Due to its residual content of stable organic matter and mineral elements, it is preferentially targeted for application on vegetable crops.

Another example of CIRAD's involvement in agroindustrial waste methanation concerns the palm oil sector. Palm oil mills are self-sufficient in thermal energy through the recovery of by-products (fibre, shells, rachis), but they are still dependent on fossil energy for electricity. However, extraction operations also result in the production of an effluent with high organic matter and mineral element contents. This waste is conventionally treated in huge open-air lagoons and it emits up to 38 kg CH_4 per tonne of produced oil. Since 2011, CIRAD has been collaborating with a private group to carry out methanation of these effluents in covered lagoons in three oil mills in Gabon, Ghana and Nigeria—a technique that is especially well adapted for local application. By 2020, the use of biogas in these three mills will lead to a reduction of 4 million t/year in diesel fuel consumption. Hence, combined with the reduction in GHG emissions compared to the previous situation, the emission of 73,700 t of CO_2 equivalent will be avoided every year.

13.3 Production of Knowledge on Greenhouse Gas Emissions During Recycling

The major biophysical processes involved in recycling organic waste products are linked with gas emissions that occur during storage, processing and soil application. These emissions mainly involve CH_4, associated with anaerobic biodegradation of organic compounds, N_2O, associated with ammonium nitration and nitrate denitrification, and indirectly NH_3, associated with its volatilization, its chemical interaction in the atmosphere and its redeposition in ecosystems. For prediction purposes, CIRAD is studying the still insufficiently understood factors that determine these complex processes and their interactions.

[1]http://uved-matorg.cirad.fr.

13.3.1 Estimation and Modelling of Emissions During Processing and Storage

Composting is an aerobic organic matter stabilization process that, through a marked thermophilic phase (rapid digestion phase that elevates temperatures to within the 60–70 °C range), sanitizes compost. After field application, it then supplies plants with nutrient elements and improves the soil's chemical, physical and biological qualities. During the active composting phase, biological heat production and organic matter transformation lead to gaseous NH_3, N_2O and CH_4 emissions. The variety of practices, differences in the substrate nature and the climate modify the organic matter degradation rate, the final quality of the produced compost and the extent of emissions in the form of gaseous pollutants. Research carried out over the last 10 years by CIRAD, INRA and INSA Toulouse on livestock waste composting (e.g. Paillat et al. 2005; Oudart et al. 2012) have led to the analysis of interactions between major biological, biochemical, physicochemical and thermodynamic processes responsible for the stabilization of organic matter and gas emissions. These studies are based on small windrow composting experiments with passive aeration and on dynamic semi-empirical modelling of the process.

The study in controlled conditions enabled a classification of the effects on the kinetics of gas emissions of key composting factors, including C biodegradability, N availability, moisture and porosity. The combined effects of porosity and moisture have a major role in the regulation of organic matter transformation and gas emissions, which was validated for windrow composting of poultry litter. A dynamic composting model was developed that simulates the kinetics of various transformations and exchanges in order to gain further insight into the impacts of these key factors on physicochemical and biological processes (Oudart 2013). During the thermophilic phase, N availability was found to be the factor that most quickly limits organic matter transformation into biomass. This unique result contrasts with the preconceived idea that N is abundant in livestock waste and highlights the potential for the reduction of NH_3 emissions (and thus indirectly GHG) through organic N production. The initial fractionation of organic matter and the initial microbial biomass content are needed to predict the kinetics of C and N uptake by microbial organisms. The specific CO_2 emission parameters are related only to the nature of the substrate, whereas those of NH_3, H_2O and N_2O are also related to the initial windrow physical characteristics.

Given the low N_2O emissions, the difference between simulated and observed emissions is much greater than the differences noted for CO_2, H_2O and NH_3 emissions. Further modelling studies should thus focus on improving the calibration and statistical analysis of the simulation results so as to be able to relate the initialization parameters to the windrow physicochemical characteristics. However, the modelled effects of porosity, moisture and structuring agent with respect to organic matter transformation already indicate that the model could be used to qualitatively optimize livestock waste composting.

13.3.2 Estimation and Measurement of Emissions After Field Applications

Recent studies have highlighted the lack of benchmarks on emission factors and the need for a regional approach, as the soil-climate conditions impact the level of emissions. They stress the need to acquire local benchmarks to be able to assess the different potential mechanisms for reducing GHG emissions.

Carbon storage and GHG emission factors are being studied in the field in Réunion. The wide variety of soil types on the island (over 50 % of the world's soils represented), climatic conditions and land-use patterns make it a good candidate for filling knowledge gaps on GHG emission factors under tropical conditions, as well as identifying the main determinants of C storage. In 2013 and 2014, CO_2 and N_2O emissions were monitored via two series of measurements from March to June on temperate grassland plots (1,600 m ASL, Andosols) to assess the relationship between emission levels and different organic fertilization treatments. A long-term trial on a highly instrumented site, which belongs to the French SOERE-PRO long-term field experiment network for research on the recycling of organic residues in agriculture, was set up by CIRAD in Réunion and focused on sugarcane (Fig. 13.4).

Field trials are useful for measuring the effects of organic matter inputs—including GHG emissions—under real conditions and can provide a good support for assessing organic fertilization practices. However, they are complicated to set up and monitor as they generally require long-term monitoring to measure the effects of organic matter inputs exhibiting slower transformation dynamics than chemical fertilizer inputs, which makes them expensive. They are also subject to climatic variations, even when sheltered, and the measured effects could depend on the soil conditions, such as the clay content or pH. Overall, this does not facilitate the acquisition of benchmarks on the transformation dynamics of organic inputs of different natures. 'Standard' methods should thus be used that are independent of climatic variations to measure the transformation dynamics of soil organic matter inputs. Laboratory methods were developed for this purpose—soil and organic matter incubations in microcosms (<1 kg of soil) under controlled conditions. CIRAD contributed to the standardization of these methods (AFNOR-XPU44-163 2009). Incubations under controlled conditions demonstrate that the C/N criterion used alone can lead to errors in assessing organic matter transformation dynamics. It is nevertheless useful for revealing the impact of composting on the stabilization of organic matter from organic amendments because the latter stabilizes with the composting time. Once applied to a soil, a composted organic amendment will emit less GHG than the same compost collected and applied at a very early composting stage (Fig. 13.5). Incubation under controlled conditions can also be used to estimate the N_2O emission potential of soils that have been amended or not (Rabetokotany et al. 2013). Some models for predicting organic matter transformation capacities—such as TAO (transformation of organic inputs), developed by

Fig. 13.4 The long-term SOERE-PRO agronomic trial on sugarcane set up in the municipality of Sainte-Marie, Réunion. In 2014, it was the only trial of this type set up in a tropical environment. The fertilizer materials studied included pig slurry, poultry litter and sludge from a sewage treatment plant. It included a control plot with chemical fertilizer application. GHG emissions are measured continuously

IRD and CIRAD (Thuriès et al. 2001), validated for organic matter in West Africa and the Indian Ocean region—can also predict nitrogen gas emissions, including N_2O.

13.4 Research Outlook

There are considerable prospects for the two avenues of research described in this chapter. The path towards gaining sufficient knowledge to obtain a robust representation of GHG emission related processes is still long. Experimental sites like that of SOERE-PRO will provide valuable benchmarks and, above all, help establish links between laboratory measurements of 'potentials' and field data. Continued modelling of composting and validation via new experiments will also contribute. European bioeconomy provisions provide a framework for exploring new avenues (Box 13.1).

While awaiting these advances, and in the light of the issues, it is essential that the research achievements of agricultural recycling of organic waste be applied at

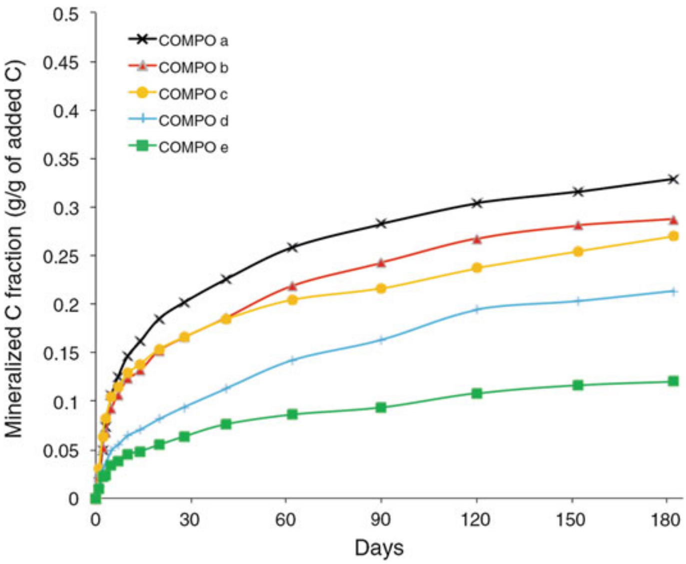

Fig. 13.5 Mineralized C fraction (C–CO_2 in g/g of added C): organic amendments collected at different composting stages. COMPOa: non-composted, to COMPOe: highly composted (from Thuriès et al. 2001)

sites with a high GHG emission reduction potential, while striving to develop more climate-smart and resilient agriculture systems. Periurban areas around megacities in developing countries are prime areas where the concepts presented here could have a high impact.

Box 13.1. Bioeconomy development.

Jean-Yves Grosclaude

The bioeconomy refers to the non-food development of agriculture and forestry products and by-products via the processing of plant material into food, materials, elementary chemicals, organic fertilizers and bioenergy. It can partially overcome the reliance on exhaustible fossil resources (oil, gas, coal). The European Union is already betting on the bioeconomy through the development of biomass uses for material, chemical and energy sectors—this choice is aimed at reducing the carbon footprint of the economy, strengthen the energy independence of countries, find new green growth pathways and create new diversified markets, while favouring innovation, employment and territorial development.

Presently the development of bioeconomy supply chains includes:

- traditional materials (wood materials, reconstituted wood, textiles, rubber) and their recycling sectors (waste paper and reclaimed wood). These materials form the basis of non-food recycling and are having an increasing impact in the housing sector by competing with high energy-intensive materials (plastic, steel, aluminium and even concrete);

- plant-derived biomolecules (solvents, lubricants, surfactants, chemical intermediates), which are already expanding and diversifying traditional chemical life-science sectors (soap, starch, pharmaceutical), but a genuine innovation effort from the industrial agriculture sector is needed to ensure their full development and enable them to take a foothold on the petro-chemistry market;
- organic fertilizers and amendments. Although well known (compost), these should be improved, standardized and promoted (metha-compost, ashes) to fully reveal their fertilizer value relative to their mineral competitors, and developed to help address agricultural and environmental challenges;
- energy or heat conversion, which encompasses biomass processing into heat and electricity, methanation processes resulting from fermentation of organic by-products and waste and biofuel production.

In France, for example, transformed biomass represents 5 % of global material chemical and energy markets, and these proportions are much higher with regard to wood and paper (10 % of construction materials and 20 % of packaging). By 2050, the target set by the European Union could boost the 'biosourced' product development targets to 20–25 % of the market share in the overall 'material, chemical and energy' supply sectors.

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Chapter 14
Will Tropical Rainforests Survive Climate Change?

Bruno Hérault and Sylvie Gourlet-Fleury

Abstract Tropical forests account for over 50 % of the global forested area and forest carbon stock. Although the deforestation rate is tending to decline, forests are confronted with climate change, which could profoundly modify their functioning. The migration of species that took place during the Pleistocene is no longer possible because human activities have markedly altered tropical landscapes. Forest species will thus have to adapt (or not) particularly to the increased water stress. Forest management methods must incorporate new knowledge on the vulnerability of species and evolve in order to reduce potentially negative interactions between disturbances and the water deficit. A key challenge is to identify trade-offs between logging in water deficit situations and the increased forest fire risk. In drylands, factors related to climate change are meshed with other change factors, but innovations in the management of woodlands could ensure their long-term persistence.

14.1 Background

Humid and dry tropical forests—which account for over 50 % of the global forested area—have long been described as the Earth's green lungs. While over the last three decades society's attention has been focused on the deforestation of large tropical forests in the Amazon, Southeast Asia and Central Africa, climate change is another and even more insidious threat that could quickly and profoundly modify the functioning and dynamics of these ecosystems. Forest ecosystems stand out from other terrestrial ecosystems (e.g. fields and grasslands, savannas, deserts, tundras) by the high quantity of carbon stored in the vegetation. Out of an estimated global

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forest carbon stock of 861 ± 66 Pg C,[1] more than half (55 %, 471 ± 93 Pg C) is stored in tropical forests, which represent only 10 % of the global land area. Tropical and boreal forests store the most carbon per unit area (240 Mg C/ha vs. 155 Mg C/ha in temperate forests), but their structures are fundamentally different —in tropical forests, 60 % of the carbon is stored in aboveground biomass, whereas in boreal forests 60 % is stored in the soil (Baccini et al. 2012). Why is carbon stored in tropical forests arousing so much interest? Because, due to deforestation, it could be emitted in high quantities into the atmosphere, thereby boosting atmospheric concentrations of carbon dioxide (CO_2), the main cause of ongoing climate change. Deforestation and land-use changes in tropical areas are currently responsible for 10–15 % of global greenhouse gas emissions (Houghton et al. 2012). While the overall deforestation rate in intertropical areas has slowed down in recent years, particularly thanks to the marked decline observed in Brazil, the fact remains that net carbon emissions associated with deforestation are estimated to have been 1.0 Pg C/year over the last decade (Baccini et al. 2012).

14.2 From a Turbulent Climate History to Current Global Change

Climate fluctuations in the Late Pleistocene (−126,000 to −11,700 BC, marked by successive glaciation periods) highly impacted environmental conditions in the intertropical region (Morley 2000). Major changes occurred in mountainous areas, with successive ups and downs in isotherm elevations, whereas it is likely that lowland areas remained subject to tropical climatic conditions (Liu and Colinvaux 1985). It was long considered that these glacial periods, with colder but especially drier climatic conditions, had led to significant shrinkage in the spatial distribution of tropical rainforests, followed by episodes of expansion during the more favourable interglacial periods. This picture has become more nuanced since the 1990s, with the hypothesis of a spatiotemporally continuous forest cover, as supported particularly by pollen analysis and genetic reconstruction findings. However, climatic conditions during glacial periods were probably much different from those that prevailed during the interglacial periods, with temperatures several degrees lower than at present. Forest species had to adapt to these changing conditions or migrate to follow their climatic optimum (Liu and Colinvaux 1985). This turbulent history contributed to the high local diversity of species that are presently found in tropical rainforests.

Climate change problems are therefore not insurmountable for tropical species. The problem is that current changes are occurring in a landscape setting that has been highly modified and occupied by humans. In other words, in most tropical

[1]Including 383 ± 30 Pg C (45 %) in soils, 363 ± 28 Pg C (42 %) in living biomass, 73 ± 6 Pg C (8 %) in dead wood, and 43 ± 3 Pg C (5 %) in litter; 1 Pg (petagram) = 1 billiard (a million billion) grams.

regions, species will be unable to migrate to follow their climatic optimum as they did in the past as they will be blocked by man-made areas. By modifying the availability and distribution of favourable microclimates, climate change will cause unavoidable supplementary stress on tropical trees. Why supplementary? Because tropical forests are already affected by other major local and global issues. They represent a reserve of land with potential for agriculture, mining resources, various timber and non-timber resources in areas of high population growth (Malhi et al. 2008). The diversity of threats is the main problem for tropical forests. Not only forests are located in modified and occupied landscapes, but human pressure on forests is growing. In the Amazon, the combined effects of climate change and land-use change could lead to major changes in vegetation throughout over 80 % of the forest. In the Congo Basin, it is estimated that 35–74 % of the forest is concerned by the climate threat and logging activities (Asner et al. 2010). In Asia-Oceania, land-use change could affect up to 75 % of the forest area. Finally, Asner and colleagues estimate that 55–82 % of the tropical rainforest biome will be degraded by 2100 (Asner et al. 2010). The combined effects of climate change and land-use change on the tropical forest distribution will thus likely constitute one of the greatest anthropogenic terrestrial ecosystem modifications of the next century. Macrogeographical and regional differences in these effects represent both challenges to be addressed and local opportunities for drawing up bold policies to preserve large tropical forests.

14.3 From Today's Climate to Tomorrow's Projections

Overall and over a 1-year period, the average rainfall recorded in tropical forests was found to be 2180 mm, with a mean temperature of 25.4 °C and solar radiation of 16.5 GJ (Malhi and Wright 2004). However there are considerable regional variations. Regarding rainfall, part of Malaysia and the northwestern Amazon region get over 3000 mm/year, while most of Central Africa is drier than the pantropical average. These variations are less marked for temperature and solar radiation, although African forests generally have somewhat lower average temperatures due to their slightly higher elevation. Another important feature of tropical forests is the seasonality of rainfall, especially the frequency of dry periods. This seasonality is less marked in so-called dryland tropical areas but is still a key factor for explaining species distribution and ecosystem functioning in tropical rainforests. Overall, African tropical rainforests seem to be most commonly affected by seasonal water deficits, contrary to Asian forests. In the Amazon, there are sharp differences between the northwest, with very little seasonality, and the southeast, where there are often harsh dry seasons that may last several months. Evapotranspiration, the amount of water that goes from the forest ecosystem into the atmosphere via transpiration from trees, other plants, animals and the soil, is also an important variable to consider with regard to a change in rainfall regimes. The average evapotranspiration of rainforests is 100 mm/month, which means that an equivalent amount of water should at least enter the ecosystem monthly via rainfall. However, these forests are able to function for a few weeks to a few months a year without this water quantity, during the dry season.

The dry season, often with a temporally regular rhythmicity, plays a key role in tropical forest functioning. It is the period when trees preferentially renew their leaves and halt their diameter growth (Wagner et al. 2013). Many forests, especially in Africa, even undergo a double dry season. Global climate models suggest that these regular cycles, which are so important for the internal rhythm of forest ecosystems, could be modified or at least accentuated. The latest climate model projections predict that tropical climates, forced by anthropogenic CO_2 emissions, will mainly suffer an increased water deficit (Sherwood and Fu 2014) (Fig. 14.1). These projections are in line with the trends observed in the Amazon region, where there seems to be an increase in the frequency of harsh drought years (1998, 2005, 2010) (Phillips et al. 2009). The soil water deficit is indeed the main climate limiting parameter with regard to forest dynamics (Fig. 14.2) and a determining factor in the distribution of tropical forests worldwide (Zelazowski et al. 2011). Some forests seem to be especially vulnerable because the present rainfall level is close to the minimum evapotranspiration threshold. There can thus be a real local risk of change in the plant composition in favour of dry tropical forests.

Fig. 14.1 Sand banks at the outlet of the Malebo Pool which gradually clog the Brazzaville river port. The river flows from left to right, with Brazzaville in the foreground and Kinshasa on the other side (© A. Laraque/IRD)

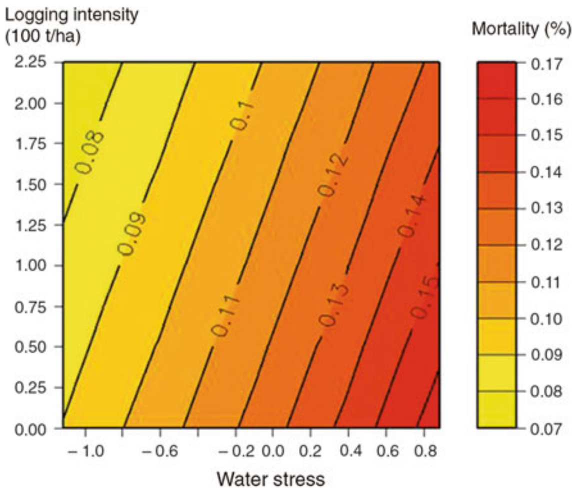

Fig. 14.2 *Dicorynia guianensis* is the main commercial tree species in French Guiana. Its annual mortality rate is represented according to two variables, i.e. the logging intensity on the y-axis (biomass lost during logging) and the water stress on the x-axis (normalized value). The mortality rate increases sharply with the water stress (© H. Fargeon)

14.4 How Can the Vulnerability of Forest Species to Water Stress Be Assessed?

Climate models indicate that increased water stress in forest ecosystems seems inevitable, so finding measureable and efficient indicators of the susceptibility of tropical trees, especially commercial species, to this ecophysiological factor is a major challenge (Fig. 14.3). Two approaches are currently the focus of interest, one based on the hydraulic properties of wood and the other on the response capacity of leaf cells to water stress. These two indicators, or 'functional traits', seem more relevant than other more conventional biological traits (wood density, leaf mass surface, seed size, etc.), which are not directly associated with ecophysiological processes of response or adaptation to water stress (Wagner et al. 2014).

Regarding wood properties, the reduced soil water supply induces an increase in sap tension in the conducting vessels of trees, as measured by a highly negative leaf water potential. Beyond a certain threshold, these tensions trigger the transformation of water into the gas phase—cavitation occurs, whereby air bubbles appear in the xylem as well as cavities in the water column (Choat et al. 2012). The upward flow of sap in the tree is thus reduced and its metabolism affected, leading to growth failure or even death of the tree (McDowell et al. 2013) (Fig. 14.2). Tropical rainforest species best adapted to water deficit conditions can withstand high sap tensions, so little or no cavitation occurs in their vessels. To identify these species, xylem cavitation vulnerability curves must be drawn while estimating the safety margin of species with regard to this phenomenon. This margin is the difference

Fig. 14.3 Installation of a micrometeorological station to quantify water stress in a tropical forest in French Guiana (© F. Wagner)

between the minimum leaf water potential in the dry season and the xylem pressure at 50 % cavitation. Species with the highest safety margins have the greatest chance of survival in a drier climate (Choat et al. 2012).

Another way to assess the vulnerability of species is based on the response strategy of leaf cells to water deficits. During the dry season, cell dehydration affects the cell structure, metabolism, and finally the overall performance of the tree. In living cells, internal adjustments occur, such as an increase in the osmoticum concentration (molecules that supplement osmotic pressure) or increased cellular elasticity, and help reduce tissue dehydration (Bartlett et al. 2012).

14.5 Adapting Production and Management Strategies

Four hundred million hectares, or half of the global tropical forest area, are now devoted to timber production. In order to ensure the long-term persistence of this production, the potential consequences of logging practices on the resilience of these logged forests to climate change should be taken into account. But these consequences could be contradictory. On the one hand, the resilience of logged forests to climate change would decline since pioneer species that emerge in the

Fig. 14.4 A logged forest overrun by umbrella trees (*Musanga* sp., a pioneer species) in southeastern Cameroon (© S. Gourlet-Fleury/CIRAD)

logged gaps (Fig. 14.4) and along skid trails (Gourlet-Fleury et al. 2013) could be vulnerable to drought (Ouédraogo et al. 2013). On the other hand, this resilience would increase because the removal of trees reduces the overall level of competition between species with regard to water, light and nutrient resources—trees would become less susceptible to climate stress with the reduced competition. A strategy to decrease competition in production forests is seriously considered for tropical regions and has already long been applied in temperate forests via thinning (Puettmann 2011). Initial results indicated that forests in which silvicultural treatments were most intense were also those that had the best resistance and resilience during water deficit periods. However, this positive effect was only observed during the first 50 years after treatment, thereafter it was nullified and ultimately became negative (D'Amato et al. 2013). A reduction in competition is indeed inevitably accompanied by an increase in growth, which generates very tall trees after a few decades. But it is now clear that very tall trees are much more vulnerable to stress due to their high demand for water resources (Nepstad et al. 2007).

Under the dual constraint of climate change and increasing market demand for wood from tropical rainforests, it seems that the production of these forests will have to be boosted while also increasing stand management interventions. It will thus be particularly important to take their potentials into account so as to be able to tailor interventions.[2] In some areas that are deemed more fragile with regard to ongoing climate change, such as forests growing on poor soils, silvicultural interventions should be limited to avoid inducing further stress. In other areas that are considered more favourable, production should be stepped up through the use of post-logging silviculture practices to ensure the renewal of commercially valuable species—thinning, clearing around valuable saplings, enrichment. Another consequence of logging will be the increase in forest fire susceptibility, which will be a key factor to take into account. This increased susceptibility is due to the greater amount of dead wood in the forest, the lower relative humidity in the underbrush, which increases the dead wood drying rate, and the higher human encroachment in forests. For instance, an opening in a forest canopy resulting from logging operations generates faster air movement. Fires in logged Amazon forests, for instance, are estimated to spread at a twofold faster rate than in intact forests (Cochrane and Barber 2009). The forest area that burns every year in the Amazon is thus increasing exponentially, and some authors think that, although the medium-term threat is climate change, it is likely that most forests will have burned long before the trees would be killed by water stress.

14.6 Outlook

Many uncertainties remain on the future of tropical rainforests, which currently must meet the growing needs of people who rely on them for their livelihood, while adapting to ongoing climate change, all in the context of landscapes altered by human activities. Long-term forest monitoring systems and the improvement of knowledge on the physiological functioning of trees will help to better understand and predict how forests could evolve, but full-scale field research is lacking. At the tree level, recent studies suggest that the carbon budget could be substantially modified in response to climate stress—changes in short- and long-term carbohydrate management, different allocations for storage, support and reproduction functions, etc. In these conditions, current indicators of carbon stocks and flows, based mainly on tree height and diameter, show obvious limits. There is an urgent need to explicitly model the different tree compartments and climate-dependent allocation trade-offs. In doing so, the developed models would enable, for instance, prediction (according to the different climate scenarios) of wood production patterns—a key element in sustainable forest management in many intertropical areas. At the stand level, identifying trade-offs between the decreased competition in stands to reduce their water deficit susceptibility and the increased forest fire risk is

[2] http://www.coforchange.eu/products/policy_brief.

an especially important challenge. But there is also an even greater challenge—to design an economic model that will help finance the implementation of these new production and management strategies. In addition to setting up new field experiments, the development of models of forest dynamics that incorporate the ecological functioning of forests, scenarios concerning climate change and the economics of logging businesses are promising avenues of research currently being pursued at CIRAD. In dryland areas, climate change related factors are closely intertwined with the impact of humans and their land-use practices. Some studies have shown the good resilience of wooded savanna ecosystems in West Africa, and innovations in woodland management may foster their long-term persistence (Boxes 14.1 and 14.2).

Box 14.1. Climate change and semiarid West African savannas.
Denis Gautier

The impact of climate stress on West African savannas has long been marked by the major droughts of 1973 and 1983–1984, which led to political awareness of this widespread phenomenon. Many authors have focused on the southward shift in isohyets resulting from these major droughts during the period from 1960 to 1990 or 2000, along with regional variations (Nicholson 1993; L'Hôte et al. 2002). The consequences of this southward isohyet shift on vegetation have also been the focus of a number of studies, which revealed the negative impact of climate change on natural vegetation (Gonzalez et al. 2012) and on agroforestry parklands (Maranz 2009) until the early 2000s. However, not all of the studies concluded on a degradation in plant cover. For instance, Nicholson et al. (1998) showed that there was very little change in plant cover in the Sahel between 1984 and 1998, nor was there a reduction in plant productivity.

Maps showing isohyet movements have not been updated and discussions on climate change in semiarid West Africa are still very marked by the major drought periods. This tends to minimize the importance of extensive agricultural practices and the fuelwood demand on climate change. (Taylor et al. 2002). However, scientific advances have been achieved following a few very rainy years. Although the drought period did not yet seem to be over in 2000 (L'Hôte et al. 2002), a more rainy period could have started in the early 2000s, but it is still hard to identify a change in rainfall patterns in favour of more humid conditions or the continuity of the drought period (Ozer et al. 2003).

Moreover, it is now recognized that the beginning and end of the rainy season are especially important for overall biomass production in this region. The rainy season begins earlier and ends later as one moves south. However, interannual variation in the structure of the rainy season is just as important as this spatial variation in rainy season characteristics. Contrary to the north-south variability associated with the intertropical front, the beginning and end dates are independent events. At a given site, the length of the season is virtually determined by the rainfall onset date.

Regarding biomass production, it is therefore essential to not only take water quantities into account, but also the structure of the rainy season (beginning and end dates), which has basically not changed over the last 40 years, and whose duration has remained quite steady (to within 4–5 days) before and after major drought periods (Barbe and Lebel 1997). The decline in biomass production that could have resulted from the decreased rainfall between 1970 and 1990 was in some ways partially offset by the fact that there was very little change in the length of the rainy season.

In this Sudano-Sahelian region, it is currently hard to determine the impact that climate change and variability will have on the natural vegetation, especially woody plants, since very few studies have been carried out to date on the resilience of woodland ecosystems and since it is hard to differentiate changes linked with the climate impact and those linked to the impact of humans and their land-use practices. However, some recent studies provide evidence that woody vegetation is resilient in areas that have not been impacted by human activities. Studies of Pierre Hiernaux and collaborators are particularly instructive in this respect (Hiernaux et al. 2009). They showed that, at 24 sites around Gourma (Mali) that were monitored for over 20 years from the last major drought from 1984 to 2006, woody plant recruitment occurred everywhere as of 1985, by successive cohorts, beginning with pioneer species like *Acacia* spp., which benefitted from the reduction in grass cover and the decrease in woody plant competition following the droughts. They then show that, beginning with a plant composition adapted to arid conditions, some plant diversification has occurred since the mid-1990s. This could indicate a potential return of the plant diversity that prevailed before 1970 according to the type of ecosystems, thus providing arguments in favour of the relatively high resilience of Sudano-Sahelian vegetation to climate change.

This resilience is nevertheless still generally hard to confirm, given the impact of anthropogenic pressures, which make it difficult to assess. Here the natural vegetation is gradually disappearing in arable regions as a result of agricultural clearing. Elsewhere it is disturbed by wood cutting activities, especially for fuelwood supplies, with an increase in demand due to growing urbanization (Gazull and Gautier 2014). Although the impact of extensive livestock farming and the use of fires as a savanna management practice are more complex to assess, despite the abundant literature on the topic, these four change factors make it hard to analyse the impact of climate change and variability on Sudano-Sahelian vegetation.

Box 14.2. Urban fuelwood supplies and climate change—experience in the Sahel.

Pierre Montagne, Aboubacar Ichaou, Ibro Adamou, Mamoudou Hamadou

There is growing urban and rural demand for fuelwood and charcoal from Dakar to Ndjamena in the Sahel. The challenge addressed by initiatives in the fight against climate change is to ensure that the harvesting of fuelwood from natural periurban stands is sustainable and that the aboveground carbon stock remains stable through the regeneration of harvested trees and shrubs, as well as planting. At Niamey in Niger, Ouagadougou in Burkina Faso and Bamako in Mali, efforts have been under way over the last 20 years to improve the organization of this fuelwood extraction. A specifically tailored policy has been drawn up in the three countries. It is based on the development of rural markets in Niger and Mali and on forest management working sites in Burkina Faso.

In Niger, several experiments have highlighted the value of forest management—tools for the sustainable management of periurban forest ecosystems. In the rural district of Makalondi, an innovative triad was developed that combines the local level through the creation of rural wood markets (responsible for the management of local forest resources), the rural district level (which oversees decentralized forest control), and the government level through its central and deconcentrated forestry administration. This transfer of resource management is based on the assumption that sustainability (and thus preservation of the carbon stock) can only be achieved if woodcutters comply with the forest operation criteria outlined in the management and development plans, which set (after inventory) annual marketing quotas so that wood cutters are only allowed to market the annual increase of biomass of these tree and shrub stands. Compliance with these forest operation standards by woodcutters, whose livelihoods are dependent on wood cutting and marketing, is essential—income from sales is generally used to purchase food, especially during serious food shortage periods (depletion of food stocks from the previous season) due to insufficient rainfall in year $n - 1$. Forest control—a sovereign task of the government forestry administration—has always failed due to the lack of sufficient human and material resources. The GESFORCOM project, carried out between 2007 and 2011, tested a system whereby rural districts were responsible for covering the costs (dedicated personnel, transportation) of a decentralized forest control system through a financial arrangement involving tax levies at the source.

In the same country, south of Maradi, a recent study demonstrated the benefits of managed forests and rural wood markets for the conservation of forest ecosystems. In the Baban Rafi forest, the creation of around 20 rural markets as of 1993 by the forestry administration contributed to preservation of the forest despite an increase in urban fuelwood consumption from 39,000 to 65,000 t/year. Forest operation by external traders and woodcutters who were not from the local village communities—a situation which prevailed in the early 1990s—has almost disappeared since the rural wood markets were set up. These markets considerably strengthened the capacities of empowered local people. The funds generated were used to set up organizational resources and technical expertise for sustainable management of forest resources. This management initiative also led to an increase in wood prices from FCFA 1.9–7.2/kg, a decrease in individual consumption and the beginning of an energy transition in favour of gas.

Wood markets also generate income of several hundreds of millions of CFA francs, to which local communities had no access 20 years ago, either individually (forest operation income) or collectively (rebates collected by municipalities). The administration also profits via the collection of taxes that cover its functioning. Twenty years ago nobody would have imagined that this forest would still exist, but it seems that even though the forest area has decreased from 90,000 to 60,000 ha, it is still there and continues to play its carbon storage role.

The fight against climate change is thus part of a global context of sustainable forest ecosystem management, but also fight against poverty and population growth. Forest management initiatives, associated or not with plantations, are implemented within the framework of fuelwood supply master plans to guide periurban forest operation. Aboveground carbon stock could remain stable if the quotas are respected. They could thus be effective tools in the fight against climate change.

Based on the results obtained over the last 20 years, the French Development Agency and the French Global Environment Facility have, since March 2014, been supporting the implementation of a project focused on the management of natural fuelwood stands in the Sahel. The aim is to develop the same strategy and move towards the harmonization of forest policies for sustainable energy supplies in these three African capitals (Niamey, Ouagadougou and Bamako).

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Chapter 15
Adaptation and Mitigation in Tropical Tree Plantations

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Abstract Tropical tree plantations are rapidly expanding to meet the growing demand for wood and nonwood forest products. Current research—combining ecophysiology, genetics and functional genomics—aims to enhance the climate

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change mitigation role of these plantations and their adaptation. The positive effect of the increase in atmospheric carbon dioxide concentration on photosynthesis could boost biomass production, but the higher water and nutrient needs will have to be fulfilled to ensure the sustainability of this positive effect. Multispecies plantations benefitting from positive interactions between species could help maintain production in tropical tree plantations against a background of increasing biotic and abiotic stress.

15.1 Issues

Global demand for forest products has significantly increased in recent decades and plantations are meeting this demand to a markedly increasing extent. While forest plantations represented only 5 % of the global forest area in 2000, they fulfilled 33 % of the world demand for wood (Millennium Ecosystem Assessment 2005). The areas of these plantations are rapidly expanding, with a mean annual increase of around 5 million ha over the 2000–2010 decade. The production of high quantities of wood (lumber, timber, fuelwood) and non-wood (rubber, gum, etc.) forest products by tropical tree plantations greatly reduces the pressure on tropical forests,

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thus contributing to their conservation (Paquette and Messier 2011). These plantations also play an important role in carbon sequestration and in the preservation of soil fertility and water resources. The sustainability of these ecosystem services is thus a major challenge.

Competition with other types of land use limits the possibilities for expansion of tropical plantations because most future available areas are located in regions with less favourable growing conditions. To fulfil the needs of a growing global population, it will be necessary to maintain or even increase current productivity in a context of increased biotic and abiotic constraints. Of the latter, the expected increase in the frequency of extreme climate events (harsher droughts, storms, etc.) and in fertilizer costs will likely have a heavy impact on productivity. Recent studies show that the increased atmospheric carbon dioxide (CO_2) level will only have a positive effect on photosynthesis if water and nutrient supplies for trees are increased (Norby et al. 2010). The rapid propagation of new pathogens at the global level and the propagation of diseases that could be fostered by the increase in commercial trade and abiotic constraints also represent a significant hindrance regarding the sustainability of these systems.

Current research aims to improve the adaptation of tropical tree plantations to climate change through experimental and modelling approaches. Multidisciplinary research is required to address these complex issues and design production systems adapted to major expected changes in tree growth conditions. Understanding the biological and physical laws that influence these agroecosystems is thus a major challenge for designing sustainable management approaches to deal with climate change.

In this chapter, rather than proposing a comprehensive review of ongoing studies, we decided to briefly present the research results and prospects concerning eucalypt plantations, as a tropical forest plantation example, and natural rubber plantations, as an example of a tree plantation managed mainly for the production of non-wood products. These two types of plantation are managed both by large industrial companies and smallholder farmers. Eucalypt plantations currently cover an area of around 20 million ha worldwide, while natural rubber plantations represent 10 million ha.

15.2 Main Results and Recent Trends

15.2.1 Climate Change Mitigation Role of Tropical Tree Plantations

Tree plantations accumulate high quantities of carbon in biomass. Carbon is stored in products harvested for more or less prolonged periods depending on the type of production, e.g. longer term for timber than for rubber from natural rubber plantations. The impact of these plantations on soil carbon sequestration also varies greatly depending on the original ecosystem considered for comparison. Many studies have shown that the soil carbon stock under tropical tree plantations does not markedly differ from that of the pre-existing natural forest vegetation or of well managed grasslands (Paul et al. 2002; also see Chap. 10). However, the soil carbon stock tends to increase when plantations are set up in cropping areas or on unproductive grasslands. The reference method for quantifying carbon and water exchanges between plantation ecosystems and the atmosphere requires the installation of instrumented towers above the tree canopy. This type of study has been carried out by CIRAD over the last 10 years to gain further insight into the processes driving carbon and water fluxes depending on management strategies and tree age in rubber plantations in Thailand and in eucalypt plantations in Brazil and the Congo (Fig. 15.1).

Tropical tree plantations can also contribute to climate change mitigation via the production of fuelwood or charcoal, thus helping reduce fossil carbon consumption. About a quarter of eucalypt plantations in Brazil serve the steel industry through the production of charcoal as a replacement for fossil coal (Fallot et al. 2009). Considerable quantities of fuelwood from smallholder fast-growing tree plantations managed by local communities are used in tropical areas. The high evapotranspiration from these plantations could also contribute to climate change mitigation by

Fig. 15.1 A tower where carbon, water and energy exchange between a rubber plantation and the atmosphere have been measured since 2008 within the framework of the Hevea Research Platform in Partnership (HRPP), Thailand (F. Gay/CIRAD)

recycling water into the atmosphere, thus promoting rainfall, increasing the relative humidity of the air and reducing temperatures over plantation stands (Spracklen et al. 2012).

Plantations devoted to the supply of nonwood products (e.g. rubber) also contribute to climate change mitigation. For 20 years, natural rubber plantations have been developing especially in areas where the climate and soil conditions are relatively unfavourable (Fox and Castella 2013). In some countries such as China, natural rubber trees are sometimes planted at the expense of secondary forests, thus causing a reduction in the soil organic carbon stock (de Blécourt et al. 2013). Fortunately, the situation is different in Thailand, where 3 million ha are devoted to rubber plantations and where new stands have been set up over the last 20 years in regions traditionally devoted to intensive crops like sugarcane and cassava. In this setting, afforestation via rubber plantations increases the soil organic carbon stock. Recent studies have shown that soil carbon is also more stable under rubber trees than under cassava plants. Researchers from CIRAD and the French *Institut de recherche pour le Développement* (IRD), their Thai partners of the Hevea Research Platform in Partnership (HRPP) and the joint international Land Use and Soil Ecosystem Services (LUSES) laboratory, set up networks of monitoring plots in rubber plantation regions with contrasting climatic conditions, especially in terms of rainfall. Two sites are currently equipped with a flux tower (to measure water and carbon exchange between plantations and the atmosphere) and a third site is being installed to represent the country's main plantation areas. These studies are used to calibrate models predicting the main fluxes of the carbon and water cycles in these plantations from climatic data. These models will then be used to assess the impact of climate change scenarios on a local scale. The importance of the atmospheric evaporative demand in regulating transpiration fluxes of trees (Isarangkool Na Ayutthaya et al. 2011) and the high susceptibility of fine roots to water stress (Chairungsee et al. 2013) have been demonstrated.

15.2.2 Development of Genetic Improvement to Promote Adaptation to Climate Change

15.2.2.1 Taking Ecophysiology into Account in Breeding Programmes

New criteria need to be incorporated in plant improvement schemes used in tropical tree plantations to deal with climate change. Recent breeding programmes include resource use efficiency (water and nutrients) and product quality criteria, which were given little attention in the past (Dvorak 2012). The length of rotations (6 years for the shortest eucalypt rotations to 25 years for rubber plantations) is, however, a major constraint for the selection of the most adapted plant material in a setting of rapidly changing growing conditions.

Breeding programmes are generally based on multi-location experimental set-ups, including sites with limited resources (water, nutrients) and higher temperatures than in current plantation areas. In this way, clones/varieties can be selected in conditions representative of future climate conditions. The development of high-throughput sequencing and genotyping technologies and the availability of reference genomes, e.g. for poplar and eucalyptus, help clarify the relationship between quantitative trait variation and the underlying functional genetic variability. These techniques should facilitate the identification of candidate genes involved in complex traits of agronomic and adaptive interest.

15.2.2.2 A Few Recent Studies

Several research projects have been initiated by CIRAD to improve our understanding of the genetic determinants of *Eucalyptus* adaptation to abiotic stresses so as to be able to include these criteria in breeding programmes.

In the Congo, a project currently under way (WUEtree) aims to gain further insight into the genetic and environmental determinism of water use efficiency in order to define an ideotype and design a tailored selection method. A large-scale field experiment was set up in this project to study the functional relationship between water use efficiency in leaves and that in the whole tree for different clones. Quantitative genetic models are used to assess the genetic variance components and environmental indicators of water use efficiency. Genetic association studies are also under way to determine what genomic regions underlie genes associated with water use efficiency. The information obtained will be used to test two selection methods—conventional phenotype-based selection and genomic selection based on high-throughput genome marking. As part of a previous project on tree plasticity under water stress in the field, a molecular plasticity analysis revealed the specific strategies of two eucalypt clones in response to water stress (Villar et al. 2011). A unique experiment monitoring radial microvariations in 250 *Eucalyptus urophylla* × *E. grandis* hybrids (ABIOGEN project) also demonstrated different genetic control dynamics in response to water and soil constraints.

In Brazil, the impact of fertilization on the drought response of a *E. grandis* clone was studied in a partial rainfall exclusion scheme under different nutrition (potassium chloride or sodium chloride inputs) and water supply conditions (Fig. 15.2). A high throughput study of genome, transcriptome, proteome and metabolome products is under way at this site, through a partnership between the University of São Paulo and CIRAD. Genomic and ecophysiological data are analysed integratively. The aim is to identify relevant molecular markers that explain the mechanisms of eucalypt adaptation to water stress and nutrient deficiency. These markers will then be validated in populations for breeding purposes.

In rubber trees, the first quantitative traits locus (QTL) map of the Wickham rubber family genome was drawn up (GENMAP project) based on the progeny of a cross between two of the most cultivated clones. Phenotyping carried out in Thailand from 2002 to 2009 revealed two QTLs highly related to latex production for one and to trunk circumference growth for the other. On the basis of these highly promising results, a pilot marker-assisted selection experiment has been

Fig. 15.2 A rainfall exclusion experiment set up at the Itatinga research station in Brazil within the framework of the SOERE F-ORE-T through a cooperation between CIRAD and the University of São Paulo (ESALQ). The impact of the exclusion of a third of the rainfall on the tree functioning (ecophysiology, biogeochemistry and functional genomics) is assessed for contrasting fertilization practices (© Eder Araujo da Silva)

carried out since 2011 on two rubber tree populations in Africa under contrasting ecological conditions. Ecophysiological studies are simultaneously under way to gain further insight into the determinants of rubber tree tolerance to water stress. The CrHyd project carried out in Thailand aims to assess the potential use of ecophysiological traits—combining xylem hydraulics and water use efficiency—as early indicators of growth performance under water stress. The first step involves field characterization of the extent of variability of ecophysiological traits in 20 clones of the Wickham family. The second step will analyse relationships with the growth rate by incorporating the whole tree functioning. Forecasts on temperature increases in the main rubber growing areas, as well as recent extensions into areas at colder latitudes, prompted a study on the impact of temperature on photosynthesis (Kositsup et al. 2009). The results clearly show that photosynthesis of rubber tree leaves is reduced beyond an optimal temperature slot of 25–30 °C (Fig. 15.3). These studies also showed that the optimal temperature range for photosynthesis depends on the temperature during the leaf growth period. Hence, leaves that have grown at 18 °C have an optimum of around 25 °C, compared to 30 °C for leaves of trees grown at 28 °C.

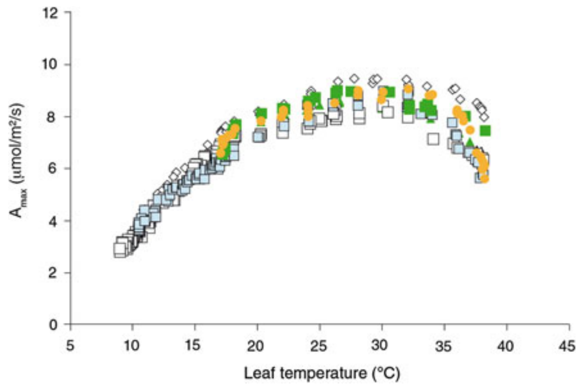

Fig. 15.3 Example of the net CO_2 assimilation response (A_{max}) to temperature in rubber trees. The different symbols represent different leaves (from Kositsup et al. 2009)

15.2.3 *Changes in Cropping Practices to Promote Adaptation to Climate Change*

The adaptation of cropping practices requires a greater understanding of the response of trees to environmental changes. Specific experiments were set up to study the effects of the main abiotic stresses on the functioning of trees. Atmospheric CO_2 enrichment performed in a greenhouse and in forests for several years showed that stimulating photosynthesis by increasing the CO_2 availability could boost production in the short term, but the nutrient or water availability soon turned out to be a limiting factor (Norby et al. 2010). This type of information is essential for improving models that simulate the response of trees to climate change and for identifying cropping practices best adapted to benefit from the increased atmospheric CO_2. Studies coordinated by CIRAD (MACCAC project) are being carried out in forest plantations and agroforestry systems to simulate, using an ecophysiological model, how the changes proposed by plantation managers to adapt silviculture to climate change could affect tree functioning and associated environmental services.

The rainfall exclusion experiment installed in a eucalypt plantation in Brazil has shown that the drought response of trees is closely dependent on fertilizer inputs (Fig. 15.4). Root colonization of deep soil layers has a key role in the hydrological functioning of trees during drought periods (Battie-Laclau et al. 2014). The water use efficiency was also observed to sometimes differ when making comparisons on leaf and whole tree scales. These studies revealed the limits of simple indicators of water use efficiency on the leaf scale such as isotopic measurements for the selection of germplasm in a context of water stress. Despite the positive effect of potassium fertilization on the response of stomata to environmental conditions, unfertilized trees (low productivity with a small leaf area) better withstand exceptionally harsh droughts than fertilized trees. Indeed, the lower water demand of potassium deficient trees fosters water recharge to deep soil layers in the rainy season, thus increasing the water supply available for trees.

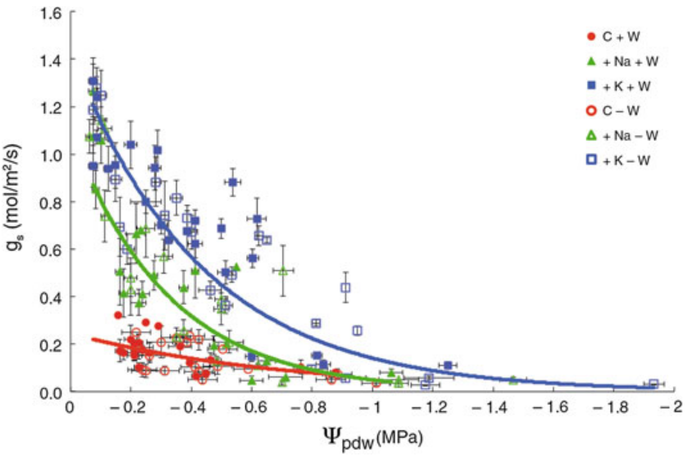

Fig. 15.4 Comparison of stomatal conductance (g_s, indicating water loss in leaves) depending on the predawn leaf water potential (Ψ_{pdw}, high absolute values indicate a low soil water availability) for trees fertilized with potassium chloride (+K), sodium chloride (+Na) and unfertilized (C) receiving around 1400 mm/year of rainfall (+W, *closed symbols*) or a reduction of around a third of the rainfall (–W, *open symbols*) over the first 3 years after planting (Battie-Laclau et al. 2014)

Genetic and environmental controls have been demonstrated for most eucalypt wood properties (Hein et al. 2012). Cambial activity is affected by abiotic stress, which alters the anatomy of wood, particularly with a decrease in vessel diameter in response to water stress. Wood properties such as density, chemistry and mechanical resistance (Searson et al. 2004) will therefore be affected by climate change, with technical and economic consequences depending on the end use. Studies carried out in Brazil in partnership with the University of São Paulo help guide silvicultural practices when there are risks of drought that could lead to tree mortality. They show that a reduction in fertilization could be interesting for limiting water stress, while keeping in mind that wood production would also be affected. Although often overlooked, efficient weeding to remove the herbaceous understorey seems essential after canopy closure in order to maximize the soil water stock accumulated during the rainy season. A reduction in the planting density to reduce between-tree competition during the dry season could also be recommended, although the more time needed to reach canopy closure makes it hard to control the herbaceous layer just after its emergence.

Rubber plantation yields are mainly determined by the latex harvesting conditions during tree tapping. Soil fertility management is also very important, especially in the immature phase during which latex is not harvested. Studies carried out by CIRAD and IRD aim to clarify how soil fertility management affects the functioning of rubber plantations while assessing agricultural practices that could optimize tree nutrition and performance in the long term. These studies are focused on all processes affecting the fertility of the soil-tree system, especially the biological component. The effect of management between rows during the tree immature phase is thus studied in sandy soils in northeastern Thailand. Introduction of the legume *Pueraria phaseolides* in rubber plantations enhanced the nitrogen nutrition and growth of trees in comparison to a rubber tree-grass association. The susceptibility and resilience of biological agents involved in litter degradation to environmental changes (climate, agricultural practices, etc.) are also being studied.

15.2.4 Consequences of Global Pathogen Dissemination

Eucalypt plantations were little affected by pest and disease problems in the past, but the situation has rapidly changed in recent years with the emergence of new pathogens able to inflict substantial production losses. With the increase in global trade, phytosanitary issues are likely to become a major constraint to the sustainability of these plantations. Rapid adaptation of genetic improvement programmes has so far enabled the selection of resistant plant material. Biological control has also been effectively used in some situations to reduce damage due to the introduction of exotic insects. New technologies based on molecular tools for disease and insect detection and monitoring are rapidly developing. Sustained investment to incorporate phytosanitary features in plant material selection programmes should help ensure the long-term sustainability of these plantations (Wingfield et al. 2013).

The main phytosanitary risk for natural rubber crops is associated with the fungus *Microcyclus ulei*. This leaf disease is endemic to South America, where *Hevea brasiliensis* originated, and does not affect Southeast Asian countries, which account for 90 % of global natural rubber production. Accidental introduction of *M. ulei* in this region would be catastrophic since the cropped rubber varieties are all highly susceptible to this pathogen. CIRAD is studying the biology of this fungus and is striving to develop resistant clones. The QTL approach is being used to study the genetic determinism of the resistance (Le Guen et al. 2011). This research is under way in French Guiana, in partnership with the Michelin company. Meanwhile, CIRAD, with the joint research unit PIAF and financial support from the French Rubber Institute (IFC) has, since 2008, been developing a programme to study the fungus *Corynespora cassiicola*, the causal agent of a rapidly spreading rubber leaf disease (Déon et al. 2014). This programme aims to identify genetic factors that influence the pathogen virulence and host susceptibility and the findings will be used to improve breeding programmes.

15.3 Conclusion and Outlook

15.3.1 Enhance Multidisciplinary Research

The challenge of adapting tropical tree plantations to biotic and abiotic constraints associated with climate change can only be met by increasing our understanding of the ecophysiological functioning of the trees. It is essential to design adapted silvicultural management strategies to ensure the sustainability of production systems. The rapid development of tools to analyse genome activity in response to biotic and abiotic stress should help speed up the selection of efficient plant material in this new setting, provided that progress in functional genomics is accompanied by a better understanding of the physiological features of the trees. Research should therefore be focused on multidisciplinary approaches that incorporate recent advances in genomics, functional ecology and plant pathology in order to formulate an integrated response to climate change.

15.3.2 Developing Multispecies Plantations

Species mixtures can enhance the resilience of forest plantations to biotic and abiotic stresses (Jactel et al. 2009). Growers could benefit from positive interactions between species (complementarity and facilitation) by planting genotypes with different functional characteristics. Ecological studies suggest that the benefits of these positive interactions are more obvious under stress conditions than in favourable growing conditions. Multispecies plantations should thus be encouraged in the context of climate change. While genetic improvement programmes have so far mainly been focused on monospecific plantations, selection of ideotypes adapted to associations could help maintain biomass production by maximizing positive interactions between species.

15.3.3 Analysing the Adaptation Capacities of Village Plantations

Village plantations account for over 80 % of the global natural rubber cropping area. In Thailand—the top natural rubber producing country—rubber trees are grown on 1.5 million family farms that cultivate less than 4 ha on average. Rubber cropping is much more profitable than annual crops like rice, but also comes with a much higher risk for farmers due to their long-term investment in this crop. Environmental and socioeconomic conditions may radically change over the 25 year rubber tree rotation period. A multidisciplinary approach combining social and biophysical sciences has just been launched to gain insight into how smallholder rubber growers perceive risks associated with global changes and adapt their farms accordingly (HeveaAdapt project).

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Chapter 16
Coffee and Cocoa Production in Agroforestry—A Climate-Smart Agriculture Model

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Abstract Agroforestry should be a major climate-smart agriculture option as it combines sustainable production with adaptation and mitigation of climate change. In recent decades, cocoa and coffee cultivation have been responsible for the loss of more than 30 million ha of primary and secondary forests, and thus for increased greenhouse gas emissions. However, they also have a substantial mitigation potential via the 20 million ha currently in production, only part of which is managed under agroforestry. These agroforestry plantations are more stable over time and resilient against climate change and price volatility of agricultural products, by combining ecological services with diversified production. This chapter illustrates these features through research results obtained on three continents and proposes recommendations on the management of these systems and on public policies—from the farm to the territory.

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16.1 Background

Agroforestry is an agricultural production activity that combines, on the same plot, annual or perennial crops with trees—generating wood, fruit, medicinal and other products as well as ecological services. This traditional land-use pattern has been practiced on all continents for centuries. It can be a sustainable agriculture model if all production factors and interactions between crops and associated trees are carefully managed. Although often criticized for its lower productivity than monoculture systems, agroforestry is less input and energy intensive. By combining ecological services and diversified production, it is more stable and resilient over time than monocultures with respect to climate change and price volatility of agricultural products. Agroforestry provides an opportunity to reduce greenhouse gas (GHG) emissions by sequestering carbon (C) in trees and soil and by reduced reliance on synthetic fertilizers. It should thus be considered as a major climate-smart agriculture tool, which significantly contributes to the food security and development objectives of tropical rural societies.

This chapter provides an overview of these features on cocoa and coffee agroforestry systems. Cocoa and coffee cultivation are mainly practiced by smallholders (around 80 % of global production comes from farms of a few hectares or less). These smallholders (around 50 million rural households worldwide) are highly vulnerable to variations in international market prices and to the negative impacts of climate change. With 10 million ha for each of these two crops and values of around US$11 and 12 billion/year for coffee and cocoa, respectively, they represent prime sources of currency for producing countries (FAO 2014). This chapter also puts forward recommendations for the ecological intensification of these systems and the implementation of incentive public policies.

16.2 Impact of Climate Change on Coffee and Cocoa Producing Regions

By 2050, simulations based on 19 global climate models and on the business-as-usual scenario (no mitigation of GHG emissions) of the Intergovernmental Panel on Climate Change (IPCC) show a significant reduction in the geographical area favourable for cocoa and coffee production.

According to Läderach et al. (2013a), this reduction in cocoa producing areas in Côte d'Ivoire and Ghana (around 60 % of the current world production) is mainly due to the drier climate conditions rather than to increasing temperatures (around +2 °C by 2050), to which cocoa plants are not very susceptible. The drier climate will result in enhanced evapotranspiration caused by increasing temperatures not offset by annual rainfall, which is declining slightly. This would reduce water available to cocoa plants and lead to the disappearance of cocoa in lowland (<200 m) coastal and forest-savanna transition zones. A limited geographical area at higher elevation (200–400 m) could marginally benefit from this increase in temperature.

For arabica coffee (*Coffea arabica* which represents 65 % of world coffee production), Läderach et al. (2013b) showed, by modelling, that climate change would lead to a reduction in the geographical area for coffee production to higher elevations in regions such as Central America (Fig. 16.1). The main factors explaining this pattern are the increase in mean and maximum temperatures and the reduction in rainfall during the dry season. These two parameters combined would cause heat and water stress that would be too high for lowland arabica coffee plants. These conclusions are backed by studies in Costa Rica which showed that the lengthening of the dry season is a highly limiting factor for coffee production, whereas the reduction in rainfall in the rainy season would have little or no impact (Cannavo et al. 2011).

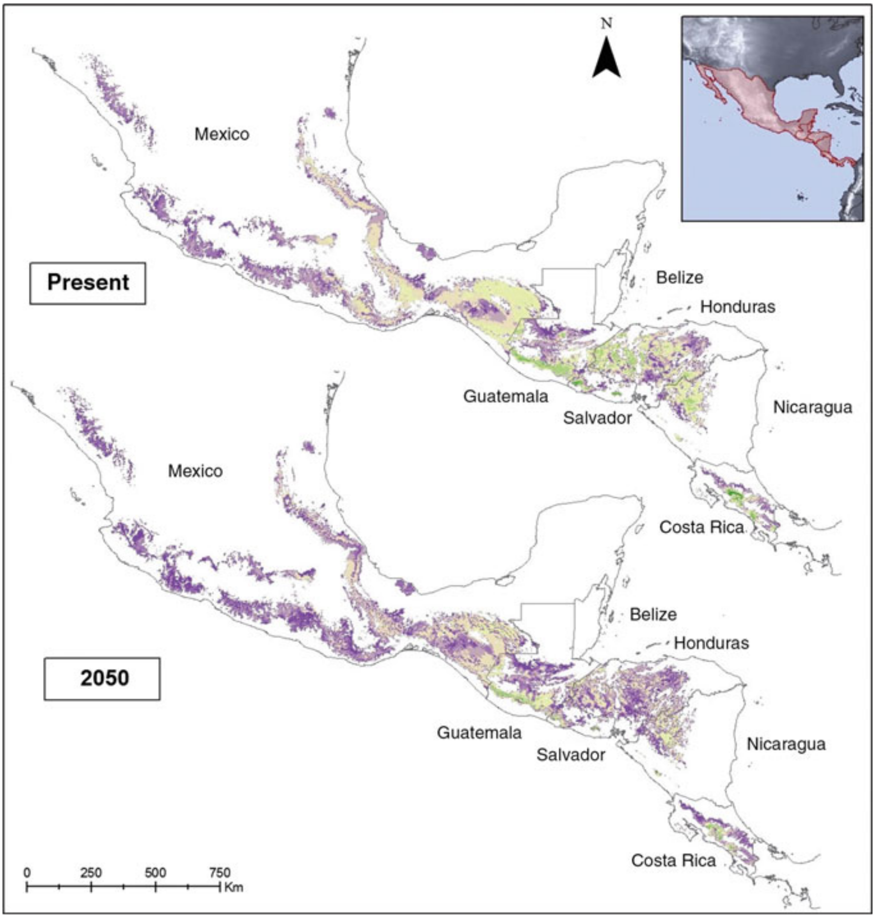

Fig. 16.1 Reduction in areas favourable for coffee cultivation in Central America due to climate change by 2050 (adapted from Läderach et al. 2013b). *Dark green* highly favourable; *pale green* favourable; *violet* slightly favourable; *dark violet* marginally favourable

These studies were nevertheless limited to determining the geographical area 'favourable' for cocoa and coffee crops and did not incorporate the negative or positive impacts of climate change on the development and incidence of cocoa and coffee pests and diseases (Chap. 6). They also did not include modifications in agricultural practices that some farmers would make to adapt to the changes.

16.3 Mitigation

Forest to agriculture conversion is one of the main sources of GHG emissions in the humid tropics, which hosts 55 % of the global biomass. Cocoa and coffee cultivation are responsible for part of this deforestation. According to Clough et al. (2009), the shift in cocoa pioneer fronts led to the disappearance of 14–15 million ha of tropical forests worldwide (around 2 million in Côte d'Ivoire, 1.5 million in Ghana and 1 million in Sulawesi, Indonesia) over the last five decades, while 9–10 million ha are currently under cocoa production. Global coffee cultivation—covering an area of around 10 million ha—has also participated in the deforestation of tropical forests. This deforestation occurred over a longer period and on smaller areas than that associated with cocoa cultivation, because coffee plantation management is more stable over time and the renewal of plants on the same area is more frequent than for cocoa plantations. The main challenge in the pursuit to mitigate GHG emissions from cocoa and coffee plantations is thus to stabilize these cropping systems.

The transformation of forest into a cocoa or coffee plantation does not systematically result in the total elimination of forest trees. Many farmers preserve, replant or deliberately leave trees to regenerate in plantations because of their agronomic, economic or cultural value, especially fruit trees or fast-growing trees for timber and fuelwood production. These are called 'shade trees' because they are taller than cocoa or coffee plants and maintain a microclimate for these perennial crops. It is estimated that this coffee- and cocoa-based agroforestry accounts for 60–70 % of the area under cocoa and coffee in the humid tropics (Clough et al. 2009; Jha et al. 2014). Tree diversity varies from a single tree species to several dozen associated species per hectare (Deheuvels et al. 2014). Their management intensity varies from harvesting in zero-input plots to systematic use of pesticides, insecticides and chemical fertilizers at levels similar to those used for intensive monocultures. The current trend is marked by a decrease in the number of trees in cocoa plantations in West Africa (Ruf 2011) and coffee plantations worldwide (Jha et al. 2014).

Cocoa- and coffee-based agroforestry has significant potential for mitigating agricultural GHG emissions in the humid tropics through C sequestration in biomass and soil. This can also be achieved in agroforestry by implementing practices geared towards reducing nitrogen (N) inputs and losses in the form of nitrous oxide

(N_2O) via better management of N inputs or substitution of these inputs by introducing legume trees in the plots. Nygren et al. (2012) reported that the N fixation potential of legume shade trees is under-used in these systems as N fixation can reach over 100 kg/ha/year and could offset annual N exports via cocoa or coffee beans which are in the 20–50 kg/ha range. This technical potential should, however, be weighed against the impacts of these practices on the costs and income of farmers, most of whom cultivate small areas and have insufficient resources to put these innovations into practice. The following examples illustrate this potential.

16.3.1 Cocoa Agroforestry in Cameroon

In a study of 58 cocoa agroforestry plantations in the Central province of Cameroon, Saj et al. (2013) showed that C storage in the aboveground biomass of the cocoa system is dependent on its species composition and on the ecosystem that preceded the cocoa plantation (Fig. 16.2). Much lower C storage was observed in savannas, and cocoa plants only contributed 2–12 % of C to the total aboveground biomass (Table 16.1).

Fig. 16.2 A cocoa agroforestry plot in Cameroon, with cocoa plants growing in the understorey of different shade tree species in the upper canopy (© P. Jagoret/CIRAD)

Table 16.1 Carbon stock (in t/ha) in the biomass of different categories of shade trees and cocoa plants in various ecological zones in Cameroon (from Saj et al. 2013)

System component	Original ecosystem		
	Savanna	Forest	Gallery forest
Cocoa plants	7.0	3.3	5.3
Trees (timber)	1.6	18.8	16.8
Fruit trees	24.0	20.3	33.7
Service trees	14.6	29.6	15.1
Trees of medicinal and cultural value	0.3	4.3	5.0
System total	47.5	76.3	75.9

16.3.2 Coffee Agroforestry in India

In the Western Ghats region (Karnataka) in India, Vaast et al. (2011) showed that associations of arabica coffee plants with local trees (>300 trees/ha and >30 species/ha) maintained C stocks at levels equivalent to those in surrounding forests (Fig. 16.3; Table 16.2). However, associations of robusta coffee (*Coffea canephora*) plants in a plot with less shade and consisting of over 80 % of the exotic species *Grevillea robusta*, accumulated much less C (Table 16.2). The aboveground biomass of trees and soil biomass (down to 1.5 m depth) were the two largest C stocks, representing over 90 % of the total C, while the contributions of coffee plants and litter were minimal.

Fig. 16.3 Measuring tree growth in a robusta coffee agroforestry plot in the Western Ghats region, India (© P. Vaast/CIRAD)

Table 16.2 Carbon stored (t C/ha) in various compartments of reference forests (Forest) and in agroforestry (with arabica or robusta coffee) with local or exotic tree species in the Kavery catchment, India

System	Tree	Coffee	Soil (0–1.5 m)	Litter	Total
Forest	97	–	97	2.4	196
Arabica + local trees	88	4.8	112	1.6	206
Arabica + exotic trees	73	3.3	105	2.2	183
Robusta + local trees	78	13.0	90	1.8	182
Robusta + exotic trees	47	10.1	78	1.9	138

16.3.3 Coffee Agroforestry in Latin America

A meta-analysis on C stocks in coffee agroforestry areas in Latin America based on 21 studies showed that aboveground biomass depended on the species and planting density (Harmand et al. 2007; Hergoualc'h et al. 2012). Ten years after planting, the average C stock in aboveground biomass in monoculture systems was 8.5 t C/ha, whereas it ranged from 15 to 30 t C/ha in agroforestry depending on the shade type (service or timber species) (Figs. 16.4 and 16.5).

Fig. 16.4 An arabica coffee agroforestry plot in association with *Cordia alliodora* as shade tree in Costa Rica (© J.-M. Harmand/CIRAD)

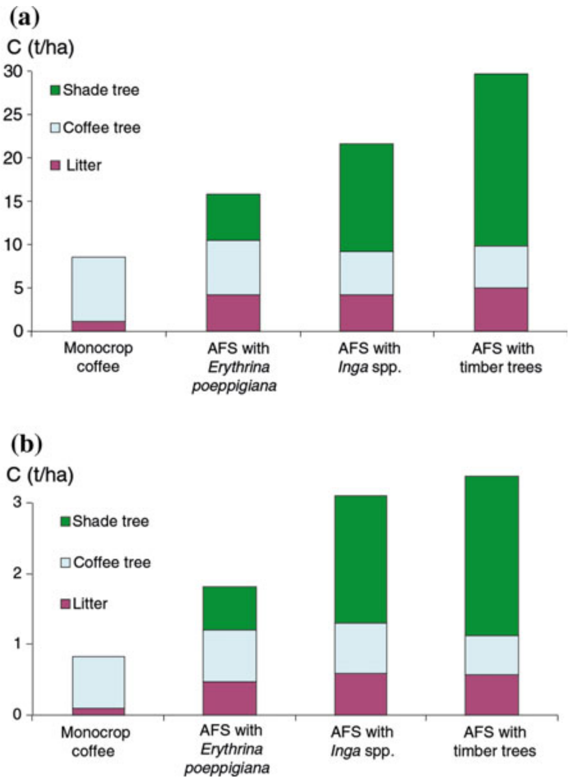

Fig. 16.5 **a** Accumulation of C (t C/ha); **b** average annual increase (t C ha/year) in aboveground biomass + litter in a coffee monoculture and different agroforestry systems. Summary of 21 studies: 16 coffee monoculture plots, 13 coffee + *Erythrina poeppigiana* plots, 5 coffee + *Inga* sp. plots and 138 coffee plots associated with timber species. AFS: agroforestry system (from Harmand et al. 2007)

16.3.4 Example of the Coffee Agroforestry Impact on Greenhouse Gas Emissions in Costa Rica

In Costa Rica, Hergoualc'h et al. (2008) compared a coffee plantation in full sun (monoculture) and an association of coffee plants with the leguminous tree *Inga densiflora* and showed that under intensive fertilization conditions (250 kg N ha/year) N_2O emissions were slightly higher in agroforestry plantations (5.8 kg N–N_2O ha/year) than in monoculture plantations (4.3 kg N–N_2O ha/year), with fertilization being the main emission factor. Net GHG emissions at the soil level—taking N_2O, and methane (CH_4) emissions, and changes in soil C stocks into account—indicated that the soil was a net GHG source (Hergoualc'h et al. 2012). At the plantation scale, C storage in biomass and ground litter represented 4.6 t ha/year in agroforestry plantations, and 2.0 t ha/year in coffee monoculture plantations. Overall, coffee monoculture conversion to agroforestry increased GHG fixation by 10.8 t CO_2-eq/ha/year over 7 years.

Despite their obvious contribution to deforestation and GHG emissions during their installation, these examples illustrate the high potential of cocoa- and coffee-based agroforestry systems to store more C than monoculture, and hence to play a role in mitigating climate change. This potential varies markedly depending on the tree species used, the previous land-use and local soil and climate conditions. However, the C storage potential could be ranked in the 10–100 t C/ha range for cocoa agroforestry and 10–150 t C/ha for coffee agroforestry.

16.4 Adaptation

Agroforestry can facilitate farmers' adaptation to climate change through different pathways:

- microclimatic. Interception of solar radiation by the tree canopy helps buffer the minimum and maximum daily temperatures; rainfall and wind interception also modify some climate change impacts, but not always positively;
- ecological. Species associations generally enhance the use of available natural resources, especially when the species occupy distinct spatial or temporal niches: different species whose root systems colonize different soil horizons; shifted or inversed phenological features (growth and fall of leaves and other organs);
- socioeconomic. Agroforestry enables diversification of agricultural income sources and reduces climate change risks. The different agroforestry species are potentially affected differently by extreme climate events, thus enhancing the resilience of the agroforestry systems.

These dimensions are illustrated by the examples and research results presented hereafter.

16.4.1 Impacts of Agroforestry Practices on the Microclimate, Water Availability, Production and Quality

16.4.1.1 Microclimate and Water

Agroforestry practices reduce water and thermal stress in cocoa and coffee plants grown under shade tree protection. Studies in Central America showed that the presence of shade trees can reduce the air temperature around coffee plants by 2–5 ° C, while increasing the ambient humidity (Siles et al. 2010). The same applies to cocoa plants, where a reduction in air and soil temperatures was observed under shade combined with higher humidity, thus reducing water stress (Lin et al. 2008). Many farmers recognize this protective feature of some trees and classify them as 'hot' or 'cold' trees according to their beneficial or negative effects on the underlying crops (Cerdán et al. 2012).

Shade trees may, however, compete with cocoa or coffee plants under limiting water conditions, especially when the dry season is longer than usual (Cannavo et al. 2011). Moreover, trees intercept 5–15 % of the rainfall, which therefore does not reach the ground, although water infiltration into the soil is improved. Transpiration of coffee and cocoa plants under shade is lower than that of plants grown under full sun, but total evapotranspiration of agroforestry systems is higher than that of monoculture systems. However, a beneficial effect of trees is often noted, even in water limiting conditions. This may be explained by the complementarity between crops and shade trees for water use, thanks to the marked differences in root colonization patterns in the soil horizons. Cocoa and coffee plants tap water from surface horizons where their roots are concentrated, while some shade tree species tap water at greater soil depths, as demonstrated in Sulawesi between cocoa plants and *Gliricidia sepium* trees (Schwendenmann et al. 2010) or in Costa Rica between arabica coffee plants and *Inga densiflora* trees (Cannavo et al. 2011). A redistribution of soil water from deep roots of shade trees to superficial cocoa and coffee roots could also enhance this complementarity between trees and associated crops. Under marginal conditions, tree choices should focus on species that lose most of their leaves in the dry season (e.g. *Ceiba pentandra* in a forest-savanna transition zone in central Cameroon), which therefore consume little water, or on windbreaks to limit the drying effect of winds (e.g. Harmattan winds in West Africa).

16.4.1.2 Production and Quality

In optimal agroecological conditions, shade reduces the flowering intensity, coffee cherry load and thus arabica production by 15–30 % compared to intensive monocultures (high fertilizer inputs and systematic pesticide treatments). However, shade reduces the alternate bearing pattern between high and low years by 20–30 %, while increasing the plantation longevity. In suboptimal ecological conditions, shade has a beneficial impact on productivity (10–50 %) by maintaining coffee plants in a microclimate that is more suitable for their development and limits fruit abortion and drop as a result of climate stress during the production cycle.

Shade also has a beneficial impact on coffee quality with regard to the bean size, chemical composition and cup quality (Vaast et al. 2006). In optimal conditions, shade reduces the coffee cherry load and, as a result, competition between cherries for nutrients and assimilates, leading to the formation of larger and denser beans due to better bean filling. In optimal and suboptimal conditions, shade reduces the temperature and solar radiation around cherries, which delays pulp ripening by several weeks, thus enhancing bean filling and improving cup quality.

Little research has been conducted on the impact of shade on cocoa productivity and quality. The current trend is generally to eliminate trees or limit shade to stimulate cocoa plantation productivity. However, it is recognized that the presence of shade trees can extend the longevity of cocoa plants, which means they can produce for over 60 years as compared to 20–30 years in monoculture systems (Jagoret et al. 2011). Moreover, the presence of trees improves soil fertility and the nutrient cycle, especially the bioavailability of phosphorus, a key element in flowering and fruit set of young pods. By modifying the microclimate, shade trees also reduce physiological pod drop, but an excessively humid microclimate can also promote the development of black pod disease. No published studies are available on the effects of shade on the size of beans, their chemical composition and cocoa quality.

16.4.2 Effects of Agroforestry Practices on Household Income and Diversification

16.4.2.1 Example of Pepper and Wood Production in Robusta Coffee Agroforestry Plantations in India

A study carried out in Kodagu district (India) showed that growing pepper on trees associated with robusta coffee plants can generate as much as 20–25 % of the net annual income of coffee, with forest products (timber and fuelwood) generating 10–15 % and cardamom and Areca palm nuts around 1–5 %. This production diversification enables farmers to buffer production fluctuations that could result from climate variations, while boosting their resilience to shocks related to coffee price volatility (Chethana et al. 2009).

16.4.2.2 Example of Timber Production in Coffee Agroforestry Plantations in Costa Rica

In Costa Rica, a study demonstrated that the sale of timber originating from *Eucalyptus deglupta*, *Cordia alliodora*, *Terminalia amazonia* and *Cedrela odorata* could represent 15–35 % of the total value of coffee income pooled over 25 years, which corresponds to the age at which tree species (apart from eucalyptus) can be logged (Fig. 16.6; Vaast et al. 2013). Despite its lower market value, eucalyptus can be more interesting than high quality timber species because of its faster growth, with two to three rotations in 25 years, and thus more frequent income.

Fig. 16.6 Wood produced in an arabica coffee plantation in Costa Rica stacked alongside a road for sale (© P. Vaast/CIRAD)

16.4.2.3 Examples of Cocoa Agroforestry Plantations in Cameroon

Jagoret et al. (2011, 2012) monitored the performance of old cocoa agroforestry plantations that had been maintained for several generations, thus demonstrating the agroecological and socioeconomic sustainability of these multispecies systems. These cocoa plantations are managed by continuous regeneration via coppicing or replacement of dead cocoa plants, which leads to gradual rejuvenation and stabilizes the cocoa density and yield. They include 25 tree species on average, preserved or deliberately introduced by farmers for fruit and timber production, shade, pest control and fertility maintenance. These plots have a key role in the sustainability of farms, where they occupy up to 60 % of the cropping area. Although the sale of cocoa is the major source of income—accounting for around 75 % of their total annual income—farmers also attach particular importance to income from other products (up to 36 % of their total income), as well as to other functions and ecosystem services of these complex systems (Jagoret et al. 2014).

16.4.2.4 Example of Cocoa Agroforestry in Central America

In Central America, Cerda et al. (2014) analysed the contribution of cocoa agroforestry systems to household income and consumption. Fruit products accounted for over half of the total income, including self-consumption, particularly bananas (24–33 % depending on the farm type) and oranges (19–37 %). However, timber contributed little to the total income (2–6 %), but represented an important capital that could be tapped whenever needed. By taking very few economic risks (low reliance on purchased inputs), some farmers are able to generate substantial net income and make more effective use of their household labour.

16.5 Recommendations for Research and Agroforestry Practices

Among research priorities to reduce the vulnerability of coffee and cocoa cultivation to climate change, ecological intensification of agroforestry is a major one to promote. Current production levels are very low compared to their potential and there is significant scope for increasing global productivity of agroforestry systems while preserving their role in providing ecosystem services and diversified agricultural and tree products. There is also scope for the genetic improvement of cocoa and coffee plants in the agroforestry management context, which has yet to be targeted by improvement programmes (Chap. 7). The focus should also be on developing shade regulation techniques by pruning tree crowns during critical periods, or by combining species with different phenological features (leaf fall staggered over the production cycle and seasons). The development of integrated pest management methods is also needed to foster, in addition to choices of tree species, the conservation of functional biodiversity (biological control by natural enemies, pollination, etc.). It is hoped that this increase in productivity and sustainability will help stabilize current production areas and thus curb their movement to new agricultural frontiers, which are responsible for massive deforestation, as observed in cocoa farming in recent decades (Ruf 2011). However, it is unlikely that technical improvements alone can change this pattern—they should be accompanied by effective policies to promote agroforestry and the protection of forest areas.

Moreover, improving the provision of ecosystem services—another component of ecological intensification—should also be possible. In many cases, the systems have not reached a level where one service is provided at the expense of another. More C sequestration is possible while sometimes even improving, but not jeopardizing, the productivity of the main crop and thus farmers' income. This necessitates the development of plot management strategies to help develop or preserve a diversified tree composition. For example, local species could be used to increase the functional diversity—pollination, C sequestration, soil erosion control, drought resistance, suppressive effects on pests and diseases—and combined with species with more specific functions, e.g. legumes to ensure N fixation and soil fertility, or tree species to produce high added value timber. This species selection and combination approach should be implemented in collaboration with farmers, by taking traditional practices and knowledge of these species into account to come up with innovations specifically adapted to local conditions and likely to be widely adopted (Vaast and Somarriba 2014).

Coffee and cocoa plantations often predominate in the landscapes where they are located, as in the case of cocoa in Côte d'Ivoire and Ghana, and coffee in the Western Ghats region in India. The landscape approach is thus relevant, but there are still lively debates between proponents of the 'land sparing' and 'land sharing' approaches in the management of rural areas (Fischer et al. 2011; Phalan et al. 2011). The more or less majority stance in the cocoa sector is that the land sparing strategy is the best option via cocoa intensification, mainly in monocultures, thus ensuring a substantial increase in productivity per unit area. This option would free up areas within the landscape to diversify production while setting aside protected areas. On the other hand, the land sharing approach, promoting agroforestry which is less intensive and more environment-friendly, requires more cropland. The coexistence of these two approaches in the same landscape should be an interesting alternative. This would mean adopting intensive monoculture—provided that agrochemical inputs are used soundly—in areas that are deemed less sensitive, while favouring agroforestry in priority ecological areas, such as slopes prone to heavy erosion, gallery forests and buffer zones along rivers and springs, as well as areas in contact with protected areas or serving as corridors between protected areas. Increasing tree cover in these landscapes, combined with the development of a spatially arranged mosaic interspersing monocultures, agroforestry and protected forest areas, could increase the resilience of coffee and cocoa plantation landscapes to climate change.

16.6 Policy Recommendations

Incentive public policies are essential for the promotion of agroforestry practices and the financial support of farmers. These policies should be targeted towards smallholder farmers using extensive practices, who are the most exposed to climate change. These farmers, without any capacity to invest in technical innovations, have significant leeway for boosting the productivity of their agroforestry plots. For farmers using more intensive cropping strategies, the introduction of trees along the edges of plantations is a model to be promoted, combined with moderate use of inputs. Current mechanisms implemented to curb deforestation, protect existing forests and reduce GHG emissions (REDD+; Chap. 25) could be extended to agroforestry, given its C sequestration potential, by prompting farmers to convert their full-sun plantations into agroforestry, by enhancing the quantity of C stored in existing agroforestry systems, or simply by stabilizing the plantations. According to Noponen et al. (2013), the implementation of these mechanisms is complex because of the high transaction costs related to the high number of smallholders involved and current C prices, i.e. US$10–15/t CO_2-eq. This financial compensation should be combined with other mechanisms such as eco-certification and payment for other environmental services (pest control, soil conservation, nutrient cycle and water regulation, biodiversity preservation, etc.) so as to make these policies more attractive.

These incentive policies will be more efficient if they are supported by more conventional policies (drawing up and applying strict regulations) which are the only ones effectively protecting forest areas. Unfortunately, policies formulated for protecting these areas that have been promoted in recent years all have major drawbacks: they are seldom applied in the most remote regions, which are the most interesting for conservation; and when they are, they have, especially for agroforestry systems, at least as many negative as positive impacts. It is often so difficult and costly to legally log agroforestry species that they lose their value, and farmers one way or another end up eliminating them or preventing their regeneration. There are some exceptions, but it seems to us that a radical review of conservation policies, with the aim of promoting timber production and ecosystem services in agroforestry systems, is urgently needed.

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Part III
Stimulating Change

Chapter 17
Impact of Climate Change on Food Consumption and Nutrition

Michelle Holdsworth and Nicolas Bricas

Abstract This chapter focuses on the complex interrelationships between nutrition and climate change. After a brief review of the main nutritional problems globally and their determinants, we begin by showing how the dietary changes associated with agricultural and food sector industrialization and urbanization contribute to both climate change and malnutrition in all its forms. Consumption of animal products is discussed, but we show that livestock farming needs to be addressed as well as to consume animal products. We then illustrate how climate change affects food and nutrition. Finally, we review areas where more research is needed, to inform debate on some poorly understood aspects of the relationship between climate change and nutrition, and conclude that there is a need for an ecological nutrition science drawing on several complementary disciplines.

17.1 Background

A number of nutrition and public health issues arise at the global level collectively termed malnutrition.[1] The figures speak for themselves—some 805 million people do not have enough to eat and suffer from hunger[2] (FAO 2014). Although the number of undernourished people in low and middle income countries (LMICs) has been declining in recent years, progress in some regions has been slow, in particular

[1]Malnutrition refers both to undernutrition and overnutrition. It is defined as 'poor nutrition, caused by a lack of food, inadequate intake of nutrients required by the body, or the inability to assimilate the food consumed.'
[2]The words 'hunger' and 'undernourishment' may be used interchangeably.

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sub-Saharan Africa, the Caribbean, southern and western Asia (FAO 2014). Today, the highest incidence of hunger is in sub-Saharan Africa, where it is closely linked with poverty. However, the greatest number of undernourished people is still found in Asia.

Alongside nutritional problems related to height and weight, two billion people suffer from a micronutrient deficiency (iron, vitamin A, zinc, etc.), in part because their diet lacks sufficient variety. All micronutrient deficiencies affect children's development as well as women's health and hamper nations' economic development because of their impact on human capital[3] (Webster-Gandy et al. 2012).

Long-standing undernutrition problems are now compounded by obesity and diet-related non-communicable diseases (NCDs), such as type 2 diabetes and cardiovascular diseases (Popkin et al. 2012), which are increasingly becoming public health problems in LMICs. They now account for a third of the disability-adjusted life year burden (Ebrahim et al. 2013). The problem is particularly evident in urban areas because of changing dietary habits and sedentary lifestyles (Delpeuch et al. 2009), particularly among women and increasingly among the poor (Popkin et al. 2012), reinforcing the intergenerational transmission of poverty. The nutrition transition takes the form of a dietary shift toward greater consumption of energy-dense foods (especially those high in added fat and sugars) and of highly processed foods and animal protein, with less consumption of high-fibre starchy foods, fruits and vegetables and, more generally, a higher food intake (Delpeuch et al. 2009). These trends show that food security and nutrition issues are no longer only cereal-related, but that attention must now be paid to other products, including fruit and vegetables (Fig. 17.1). Demographers expect the world population to rise from 7 billion to some 9 billion by 2050, the bulk of the increase being in urban areas. That will accelerate the nutrition transition and affect the food system's ecological footprint.

17.2 Climate Change and Diet-Related Non Communicable Diseases: Same Determinants

Societies that suffer the most from NCDs are clearly also those that emit the most greenhouse gases—uncoincidentally. Both result from the same phenomenon, one that has led to increasing non-renewable energy use (coal, then oil) (Fig. 17.2).

Use of these energy sources has spurred industrialization and has resulted in an increase in agricultural production outstripping population growth, contrary to Malthus's predictions. Production of heavily petroleum-based nitrogen fertilizer, together with the use of other mineral fertilizers, phosphate and potassium, has resulted in a rapid and marked increase in crop yields. Mechanization too has

[3]'Human capital' refers to a comprehensive economic view of human beings based on their biological, social, cultural and psychological contributions to the economy.

Fig. 17.1 A fruit stall in the market in Belém (Pará), Brazil (© E. Torquebiau)

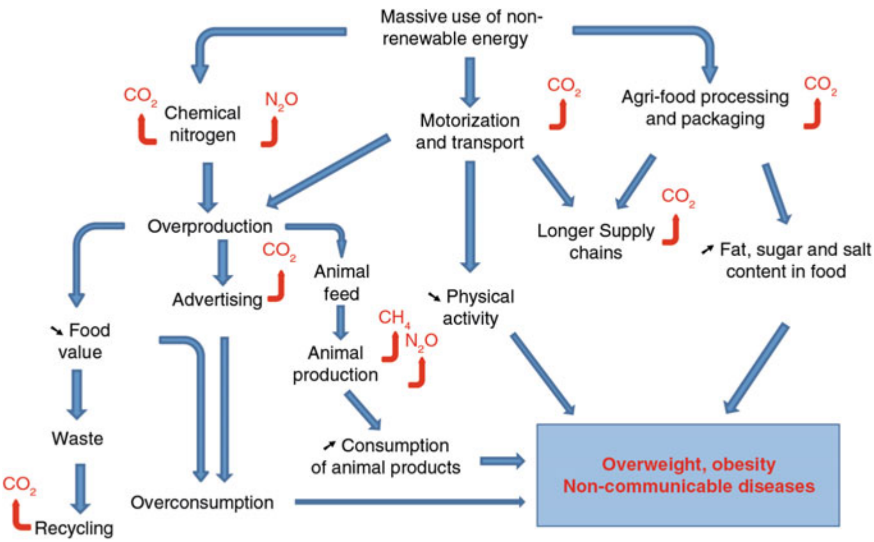

Fig. 17.2 Greenhouse gas emissions and food-related non-communicable diseases have the same determinants

become widespread thanks to fossil energy use, leading to a significant increase in labour productivity. Long-distance trade, facilitated by motorized transport by sea, land and air, has put distant markets within reach. Agriculture, relieved of its functions of generating energy (wood and draught animals) and materials production (wood again, straw and some fibres) is now able to concentrate on food production. Livestock production has grown to absorb the increased crop production and to meet the growing demand for meat, dairy products and eggs as a result of increased purchasing power. However, this rapid increase in livestock production has also spurred consumption as prices have fallen. The growth of agrifood processing industries has been based on food production that incorporates more and more services and offers food for consumption everywhere and in every season. The food needs packaging which, in terms of fossil energy, is costly both to manufacture (plastic, metal) and to transport, as well as marketing and trade promotion, which also consumes a lot of energy. Food overproduction has also led to a sharp increase in waste, not so much because of the supply chain's poor technical performance, but because food is devalued in affluent societies. Not only is much of the energy that goes into food production wasted because some of it is unused, but the more waste is processed, the worse the environmental impact becomes—a vicious cycle whose consequences are twofold.

First, it causes significant greenhouse gas (GHG) emissions. Given the production patterns, the emissions come from fossil fuel burning (carbon dioxide emissions), animal production and waste fermentation (methane emissions), as well as overuse of nitrogen fertilizer (nitrous oxide emissions). Agriculture and the agrifood sector (processing, distribution, catering) are heavy GHG producers (Griffiths et al. 2008).

Other consequences of overproduction are dietary changes that predispose to NCDs. Mechanization of work and transport motorization have cut individual energy requirements by around a third relative to livelihoods involving manual labour, or from 3000 to 2000 kcal/person/day (Egger 2008).

The increasing demand for ultra-processed convenience foods leads to higher carbon dioxide emissions from their production and (often petroleum-based plastic) packaging (Stern 2006; Fig. 17.2). The rise in demand for ready-made meals spurs the adoption of a diet that is more energy-dense, and so more carbon-intensive and obesity-producing than before. Reducing consumption of energy-dense foods would significantly reduce carbon dioxide emissions as these types of foods are carbon-intensive in that they have often travelled many 'food miles'; whereas food preparation from scratch is likely to produce less carbon dioxide. The case is not totally clear-cut, however, as data from France indicate that a highly nutritious diet can actually have a greater carbon impact (Masset et al. 2014).

17.2.1 Meat Consumption and Climate Change

The issue of meat over-consumption illustrates this phenomenon of escalating GHG emissions in the food system. Concerns have been voiced about the impact of the strong worldwide growth in meat consumption on climate change and health (McMichael et al. 2007). It has been suggested that red meat consumption should be limited, first because it increases the risk of certain cancers, particularly bowel cancer, but also because eating red meat is associated with heart disease because of its fat content. Average world meat consumption is 100 g/day/person, but that average figure masks wide disparities in consumption. Thus, average daily meat consumption is half as much in LMICs (47 g/day) and five times as high in high-income countries (HICs) (224 g/day) (McMichael et al. 2007). The increase in meat consumption is worrying (Fig. 17.3), particularly in transition countries where consumption was previously low, such as those of South and East Asia. China's meat consumption has doubled over the last decade and is expected to triple by 2030 (Fig. 17.3).

The inefficiency of meat production is another concern. Livestock must on average consume 7 kcal of plant fodder to produce 1 kcal of meat. Intensive livestock farming uses the equivalent of 9 kcal of grain to produce 1 kcal of beef. The equivalent ratio is 4:1 for pork and 2:1 for poultry (Delpeuch et al. 2009). Hence, when a country becomes prosperous enough for a large part of its population to eat meat regularly, the amount of grain to be grown rapidly increases, with obvious implications for GHG emissions and NCDs. McMichael et al. (2007) add that a global solution to reduce the climate and health impact of red meat consumption would be to reduce individual consumption to 90 g/day in HICs (including less than 50 g/day of meat from ruminants), which would allow lower-income countries (LICs) to converge towards that level. That would of course

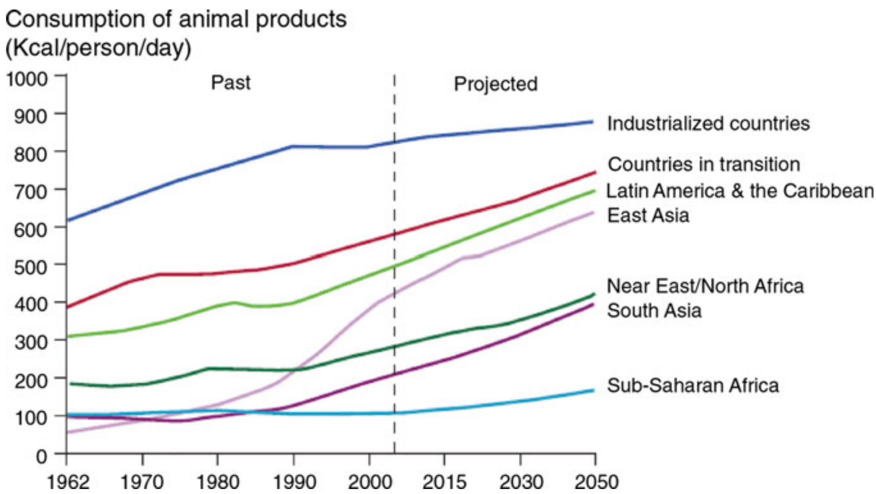

Fig. 17.3 How worldwide consumption of animal products is changing (McMichael et al. 2007)

require an unprecedented shift in the eating habits of most inhabitants of HICs, which is unlikely to happen without major policy change. Red meat consumption does have health benefits—it protects against iron deficiency, which is the world's most widespread micronutrient deficiency, affecting more than a billion people, and which may, if untreated, lead to anaemia. Consequently, any policy solution needs to take the many coexisting nutritional problems into account.

17.2.2 Are Vegetarian Diets Part of the Solution?

Comparisons between vegetarian and meat-based diets have highlighted differences in environmental impact—a meat diet uses 2.9 times more water, 2.5 times more primary energy, 13 times more fertilizer, and 1.4 times more pesticides than a vegetarian diet (Marlow et al. 2009). Animal-based foods also generate more GHG emissions than plant-based foods, with the exception of greenhouse-grown fruit and vegetables (González et al. 2011).

Some argue that a vegetarian diet is not good either for human health—because of inadequate nutrient intake—or for the environment—because of the important role of grazing lands in carbon sequestration (Chap. 10). Thus, the way meat is produced should also be a priority, as well as whether it should be eaten or not. The way different livestock farming systems affect GHG emissions largely depends on the scale and type of the system used for animal rearing (Friel et al. 2009). Even so, the future sustainability of current protein sources such as meat and fish remains one of the biggest challenges for a sustainable food system. Tailoring dietary recommendations to regional contexts, i.e. promoting healthy, resource-efficient foods that can be produced locally, could provide better outcomes for the environment, nutrition and public health (Clonan et al. 2012).

17.3 Effects of Climate Change on Food and Nutrition

17.3.1 Potential Impact of Climate Change on Undernutrition

There is evidence that climate change is worsening existing undernutrition problems by undermining current antipoverty initiatives, particularly in sub-Saharan Africa. Undernutrition also has an impact on vulnerable populations' resilience, impairing their ability to cope with and adapt to the consequences of climate change, as well as their capacity for economic growth (Fig. 17.4). Droughts in Africa have triggered famine (e.g. in Somalia) and food crises in other countries. That is a likely indicator of what the future may hold, with extreme weather events becoming more frequent as a consequence of climate change.

Rising food prices are one of the most notable effects of environmental change and may precipitate food insecurity. Climate variability may cause serious civil

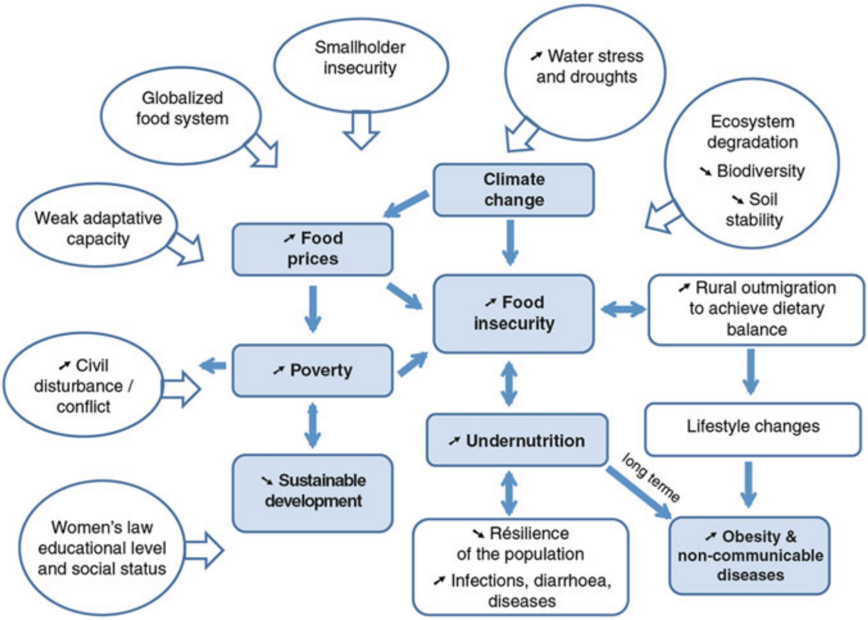

Fig. 17.4 Potential impact of climate change on food and nutrition security

unrest due to food price volatility (Godfray et al. 2010), particularly in households that spend a large part of their income on food. In 2007–2008, soaring food prices caused governments and consumers deep concern. Urban riots became widespread, and in addition to the social unrest, concerns focused on the growing number of people suffering from hunger in the world's poorest countries. Data gathered in the Congo during a period of economic crisis (1986–1991) showed that food prices can increase the incidence of overweight (including obesity) among urban women and also increase the number of underweight people (Cornu et al. 1995). The uncertainty as to the effects of recent food crises illustrates the need to implement nutrition surveillance systems in all countries, to monitor the health status of populations in terms of undernourishment or obesity—something that is all the more crucial in the context of extreme climatic events.

17.3.2 Climate Change Impacts in Communities Dependent on Agriculture

Agriculture-dependent economies will be most affected by climate change as acute climate shocks, seasonality (Tirado et al. 2012), and long-term climate trends will have an impact on households' access to resources, resulting in an unstable food supply. Such events will force households to adjust their livelihood strategies and diversify their income sources in order to survive (DFID 1999). Any significant livelihood loss due to drought could be a major cause of rural exodus, which in turn could hinder access to food (Confalonieri et al. 2007) and give rise to an upsurge of obesity and NCDs alongside urban undernutrition (Fig. 17.4).

Climate change and extreme weather events will affect all aspects of food security, namely access, availability, utilization and stability. Changes affecting ecosystems—and they are already happening—will bring shifts in livelihoods, food production, water availability, health and ultimately nutritional status (Fig. 17.4). Empowerment of women is also considered an important means of mitigating the impact of climate change on nutritional status due to their specific roles in social and economic resource management (Tirado 2011). Women will have to adapt their livelihoods as a result of ecosystem changes that could adversely affect health and nutrition security through a lack of access to drinking water and safe sanitation, a lack of time to care for children, e.g. to breastfeed, and a reduced availability of certain foods caused by water scarcity (Tirado et al. 2012). In East Africa, for example, young children born during drought are twice as likely to be malnourished as children born at any other time (Watkins 2007). Access to clean water also affects sanitation and is influenced by climate and rainfall change. Hence, climate change is a key driver of water availability and therefore a risk factor for diarrhoeal diseases (Fig. 17.3), which have an impact on undernutrition (Boko et al. 2007).

Soil degradation and pollution caused by agriculture are also likely to contribute to biodiversity loss (Godfray et al. 2010) and food insecurity as food production capacity falls (Fig. 17.3). There is clear evidence that conflict and war are more likely to occur in response to such environmental degradation, due to the scarcity of food and water. Some have suggested, for example, that climate change and environmental degradation were partly responsible for the conflict in Darfur and are likely to spark new wars across Africa (UNEP 2007). War can suddenly put whole regions at risk of starvation. The FAO has recognized that armed conflicts are on a par with poverty as one of the main causes of the hunger that continues to afflict certain parts of the world.

17.4 Future Research Opportunities

The issue of the effects of climate change on food and nutrition has only recently begun to be addressed, and there are still many grey areas.

17.4.1 Broad Multidisciplinary Approaches

Multiple research approaches are needed given the complexity of nutritional problems in LMICs. Research should focus on both over- and under-nutrition, and the relationship between the two. The SUNRAY study in Africa (Holdsworth et al. 2014;

Lachat et al. 2014) appraising priorities in nutrition research showed that it is important to focus research on the prevention of malnutrition in all its forms by assessing community nutrition interventions. The public health landscape is likely to become even more complex in the coming years as LMICs, particularly in Africa, face looming environmental threats from climate change, water scarcity and socio-demographic changes. Under these circumstances, nutrition research efforts need to be focused (Holdsworth et al. 2014). When well targeted, research can play a crucial role in improving nutritional status. However, researchers need to undertake more objective analyses of the impact of actions that incorporate both health and environmental sustainability objectives.

17.4.2 Research that Takes an Ecological Approach to Public Health

The research agenda needs to broaden and include the impact of what is eaten on the environment as well as the impact of environmental and climate change on all aspects of food security. The goal is not just to evaluate each type of food, from the standpoint both of nutrition and the environment, but also to assess the accessibility, sensory, social and cultural qualities of a balanced diet. All of these elements are found in the conclusions of the SUNRAY project in Africa (Holdsworth et al. 2014), which stressed the importance of ecological nutrition research. It is important to fund behavioural and environmental nutrition research, which will require interdisciplinary collaborations between nutritionists, social scientists, and agricultural and climate change scientists.

While ecological approaches in public health are important, there is evidence to justify targeting research towards changes in individual behaviour by looking into consumers" knowledge, attitudes and beliefs, but also by analysing the external factors that influence and determine behaviours in various cultural, social and environmental contexts. There appears to be a consensus on the need for such research to be done concurrently (Lachat et al. 2014) and for our definition of the environment to be broadened to include the natural environment, including climate change.

17.4.3 Prioritizing Research on the Role of Women

There is a need to examine the links between nutrition, gender and climate change, and especially women's role in mitigating climate change and GHG emissions, as they are often responsible for gathering firewood, felling trees and supplying the household with food. Can responsibility for climate change mitigation really be borne by poor women, as advocated by the World Food Programme and other stakeholders (Tirado 2011)?

17.4.4 Impact of Rural to Urban Migration on the Sustainability of Urban Diets

Rural to urban migration and its environmental, economic and health impacts on sustainability of diets needs to be studied in LMICs. That would involve assessing the dietary impact of changes in lifestyle and in people's physical, economic and social environment, looking also at the effects of such changes on the global environment and perhaps quantifying the impacts of traditional (rural) vs modern (urban) dietary patterns on their carbon footprint (waste, GHG emissions, water, use of packaging, phosphorous and fossil fuels). Policy options for a more sustainable food system could be assessed in a range of different LMIC contexts.

17.4.5 Research on the Organization of Food Systems in Response to Climate Change

Little is known about how shifts in agricultural production zones caused by climate change affect food availability in various parts of the world. Such shifts will mean not only that production of certain crops will move from places where they are no longer viable to others that are now better adapted, but that planting of some crops will decline while others will be more widely grown. For example, rising sea levels will lead to delta salinization that could favour the development of fish farming, so farmed fish availability may increase. The relative share of local production and imports will presumably change the world over, but the dietary and nutritional consequences of such changes cannot yet be assessed.

Food system preparedness must be a priority as more frequent and serious adverse climatic events may be expected. Should each society boost its resilience by diversifying its diet and hence its sources of supply, keeping its storehouses full, and ringing the changes on genetic modes of production to withstand greater climate variability? Or should international trade instead be expanded so that imports can be relied on when adverse climatic events affect domestic production, thus sharing the risk between several nations?

17.4.6 Monitoring and Surveillance Systems Are Crucial

Nutrition monitoring systems will be indispensable in tracking climate-related factors in Africa, especially to assess the impact of seasonality and the concomitant changes in undernutrition. The World Health Organization has stressed the need for health institutions and climate change modellers to collaborate to assess whether climate and environmental change influences the nutritional status. For example, a changing climate necessitates consistent nutritional status prediction models, particularly in Africa (Tirado et al. 2012), to better assess the impact of climate change on diseases that can lead to undernutrition.

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Chapter 18
The One Health Concept to Dovetail Health and Climate Change Policies

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Abstract Health strategies and policies must be adapted in response to climate change within a broader context of global change involving increasing demand for animal products, globalization of their trade, and the impact of multiple environmental, socioeconomic and climatic determinants of human and animal health. In that setting, there is a greater risk that parasitic and infectious animal and zoonotic diseases will emerge, persist or spread, so livestock production and health sectors must become more resilient while reducing countries' vulnerability to climate-sensitive diseases through adaptation measures. These will involve ranking diseases by severity and evaluating and then minimizing risks (surveillance, prevention and control) pursuant to ad hoc legislation based on the One Health concept.

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18.1 Background

Recent literature extensively describes the impact of climate change on diseases and health in general (ECDC),[1] with particular reference to human and animal infectious diseases (Morand and Waret-Szkuta 2012; OIE[2]; FAO).[3] Climate and its variations have an impact on pathogens (resistance, selection, etc.), hosts (immunity, movement, including migration, etc.), vectors (ecological niches, vectorial capacity) and epidemiological dynamics. Climate can notably influence and change pathogen transmission rates and dispersal routes, networks of contact between individuals and groups of individuals that may belong to different species, the structures of communities and farming methods (Fig. 18.1), but also biodiversity and its ambivalent role in disease emergence. The most climate-sensitive diseases are parasitic (cycles with external phases), vector-borne, and diseases transmitted by

Fig. 18.1 Young cowherds lead the family herd to water at the lake, Burkina Faso (© D. Louppe/CIRAD)

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[1]European Centre of Disease Prevention and Control, 2014: http://ecdc.europa.eu/en/healthtopics/climate_change/pages/index.aspx.

[2]World Organisation for Animal Health, http://www.oie.int/en/for-the-media/press-releases/detail/article/climate-change-has-a-considerable-impact-on-the-emergence-and-re-emergence-of-animal-diseases/.

[3]Food and Agriculture Organization of the United Nations, World Livestock 2013—Changing disease landscapes, Rome, http://www.fao.org/ag/againfo/resources/en/publications/World_livestock/2013.htm.

water and small mammals. Many of these diseases can occur simultaneously during extreme weather events. Finally, these are frequently zoonotic diseases: "diseases and infections that are naturally transmitted between vertebrate animals and humans" (World Health Organization, WHO).

Climate change may increase the frequency of contact between wildlife, humans and their livestock by altering the natural habitats of animals harbouring pathogens and changing the animals' movement patterns. By increasing food insecurity, it may also lead to changes in behaviour, for example the search for alternative food sources such as bushmeat. The Ebola epidemic in West Africa in 2014 revealed the urgent need to strengthen early detection and management of emerging zoonotic diseases (Tambo et al. 2014) and the need to better determine how they are transmitted between species.

Climate change increases the risk of infection for human and animal populations, thus highlighting the need to strengthen, harmonize and adapt health systems and policies (Figs. 18.2 and 18.3). To improve prevention and monitoring, an ad hoc institutional and regulatory framework will need to be developed, as well as scientifically established methods of gathering climate and health data and organizing the response.

Weather patterns, including extreme events, have an impact on health system organization, particularly in the most vulnerable countries, because they affect the social and environmental determinants of health (air, water, food, security, etc.) and alter the emergence, spread or endemicity of diseases.

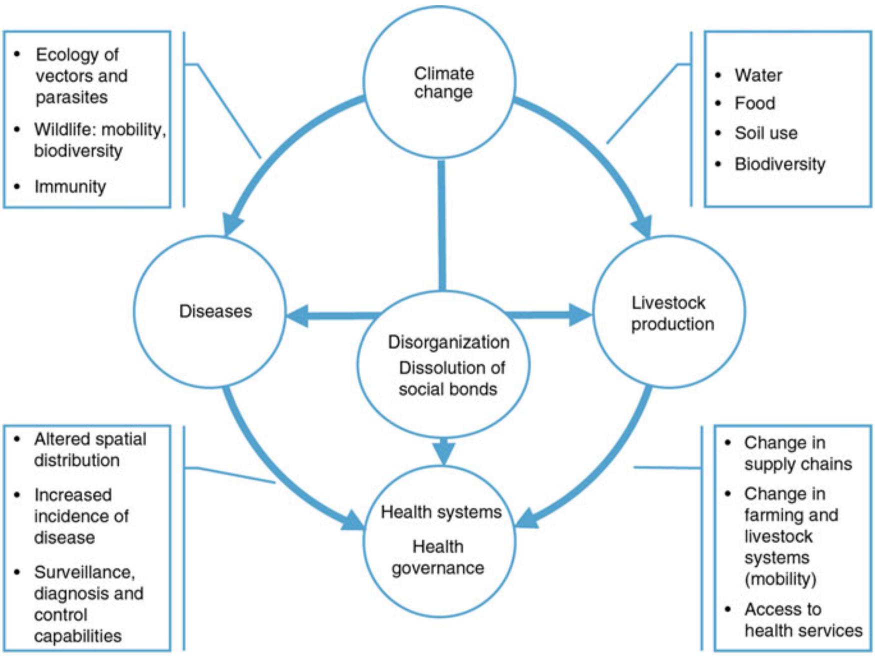

Fig. 18.2 Mapping interrelationships between climate change, diseases, animal production and health management systems

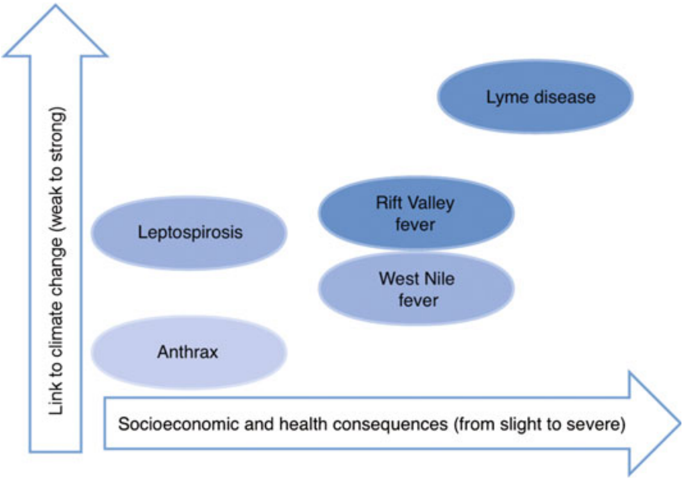

Fig. 18.3 Impact of climate change in Europe on some zoonotic diseases. Diseases in *dark blue*: revised monitoring to be considered (adapted from Lindgren et al. 2012)

Whereas the evidence of links between climate change and biological or sociotechnical systems—including vector pathosystems (Chap. 8), biodiversity (Chap. 19) and modes of production (Chap. 10)—is clear, fewer studies have been focused on the links between climate and animal health policy (Cáceres 2012).

The overall approach proposed for the preparation of strategies and health policies related to climate change derives from a four-stage health risk analysis (Fig. 18.4): rank diseases in order of importance; analyse the risks arising from

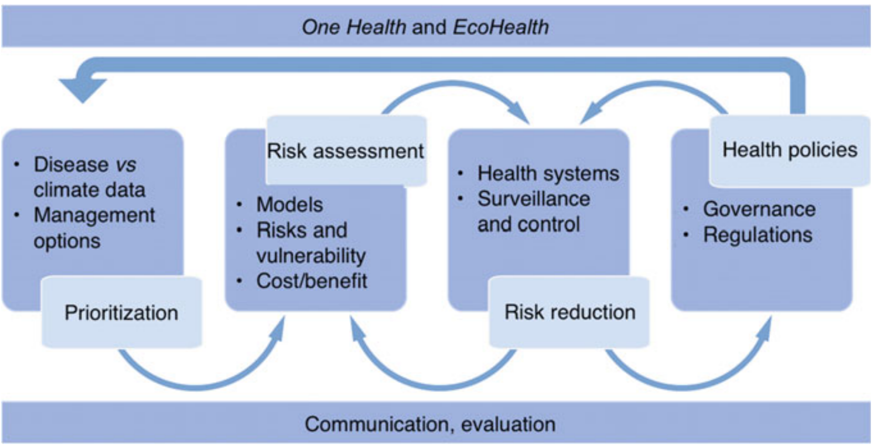

Fig. 18.4 A comprehensive approach to developing strategies and health policies to address climate change

climate change and identify and prioritize options for managing them; adapt and strengthen health systems and management methods, i.e. disease monitoring and control; propose targeted, flexible health policies and regulations and evaluate responses.

The comprehensive One Health approach enhances interactions between the environmental, medical and veterinary sectors as well as cross-cutting communications between scientists, managers and the relevant target groups.

18.2 General Framework: The 'One Health' Concept

The One Health concept ('One Health' and 'EcoHealth') posits that the epidemiological dynamics and stakeholders' actions that determine the health of animal and human populations need to be studied in their ecological, socioeconomic and political contexts at the interface of human health, animal health and ecosystem health (Fig. 18.5).

The One Health approach is driven by international standards institutions (OIE, FAO, WHO; Box 18.1) and is supported and recognized by the donor community

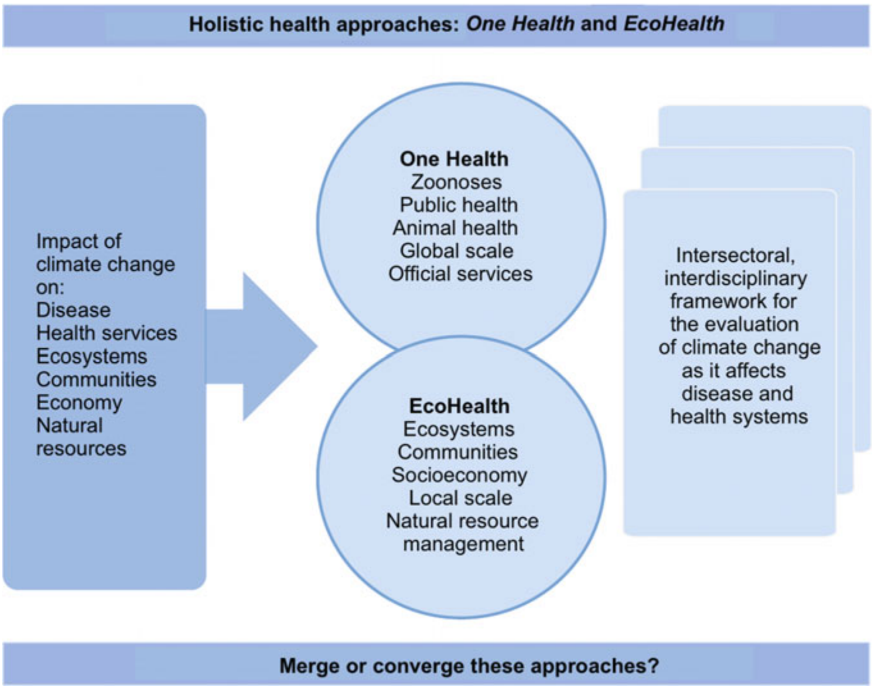

Fig. 18.5 Mapping the One Health and EcoHealth concepts, which are integrated frameworks designed to study the impact of climate change on health

(MAEDI[4] and the French Development Agency, AFD). The EcoHealth concept (Ecosystem Approaches to Health), which derives from the nature conservation sphere, takes a broader view of health and links public health to the areas of natural resource management, ecology, geography and other social sciences.

Box 18.1. International organizations, animal health and climate change.

Muriel Figuié

When the climate issue came to prominence on the international stage, with the creation of IPCC in 1988, it was essentially dealt with from an environmental and economic standpoint.

Its extension to health issues was formally put on international organizations' agenda in 2008 with the organization by WHO of a World Health Day on the theme 'Protecting Health from Climate Change', then the establishment, in 2009, of a climate and health programme (Debil 2013). In this programme (WHO 2008[5]), WHO stresses the impacts of climate change on air and water quality, agricultural production and human infectious diseases.

Prior to the emergence of recent infectious diseases (SARS, H5N1, etc.), animals were mentioned in the international debate on climate change mainly in regard to biodiversity (threatened by climate change) or the possible role of livestock production in climate change (deforestation, greenhouse gas emissions) or as victims of that change (e.g. drought).

However, the emergence of new infectious zoonoses is an opportunity to juxtapose the climate change issue with that of animal and human health. In 2010, on the occasion of the review of its strategic plan, the World Organisation for Animal Health (OIE) fully integrated the problem into its mandate by adopting a new mission: "to provide expertise in understanding and managing the effects of environmental and climate changes on animal health and welfare" (OIE 2010[6]).

While international organizations agree on the existence of a link between climate change and the evolution of certain diseases, such as vector-borne diseases (FAO-OIE 2014[7]), they still have difficulty in making concrete decisions on the actions to be taken, given the complexity of the processes at work.

In the present context of 'systemic' risks and uncertainty (OCDE 2003), the international organizations' actions in connection with animal health and climate change are part of a comprehensive policy based on the One Health

[4]French Ministry of Foreign Affairs and International Development, http://www.diplomatie.gouv.fr/fr/photos-videos-publications/publications/enjeux-planetaires-cooperation/documents-de-strategie-sectorielle/article/position-francaise-sur-le-concept.

[5]http://www.who.int/world-health-day/toolkit/2008_whd_issues_paper_summary_en.pdf?ua=1.

[6]http://www.oie.int/fileadmin/Home/eng/About_us/docs/pdf/5th_StratPlan_EN_2010_LAST.pdf.

[7]http://www.fao.org/news/story/en/item/232597/icode/.

concept, one that considers climate change as an emerging health factor among others, such as globalization, the evolution of antibiotic resistance, land use changes, etc. The opportunity now arises to renew general recommendations towards better international coordination and strengthening of national human and animal health services and epidemiological surveillance.

The One Health and EcoHealth approaches constitute a functional framework for an integrated and interdisciplinary way of addressing the impact of climate change on diseases, health and health systems. In addition, they are particularly suited to the context of the least developed countries, which can use them to pool human, informational and financial resources.

The geographical groupings whereby these approaches may be put in practice are varied in their nature and scope—they may for instance be international health networks like CORDS,[8] or regional ones such as the Indian Ocean Commission's health watch project (based on the SEGA public health surveillance[9] and AnimalRisk animal health monitoring networks),[10] or the Caribbean region's CaribVET network[11]; there are also national or regional research platforms such as RP-PCP in Southern Africa,[12] GREASE in Southeast Asia,[13] and Madagascar's "Forests and Biodiversity" partnership.[14] These initiatives are all inclusive spaces for studying the determinants of climate-dependent diseases in tropical areas and risk reduction strategies and policies to be implemented, with particular emphasis on the environmental aspect.

Finally, education, training and awareness of health professionals and scientists through the 'One Health' concept (Paul et al. 2013) are also a way to strengthen these comprehensive approaches while adding the climate dimension.

18.3 Prioritization of Diseases and Risk Assessment

To keep policy makers and stakeholders in the health sector informed, disease prioritization methods need to be developed, while taking climate and its variations into account (Morand et al. 2013) alongside other biotic and abiotic determinants.

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[8]Connecting Organizations for Regional Disease Surveillance, http://www.cordsnetwork.org/.

[9]Epidemiological monitoring and alert management, http://www.reseausega-coi.org/.

[10]http://www.animalrisk-oi.org.

[11]http://www.caribvet.net/fr.

[12]Research Platform "Production and Conservation in Partnership" http://www.rp-pcp.org.

[13]Management of emerging epidemiological risks in Southeast Asia http://www.grease-network.org.

[14]http://www.cirad.mg/DpForetBiodiversite/.

A number of methods are used, including classical 'expert opinion' methods[15] and new quantitative ones. The H-index, for example, is a quick, simple index, calculated in a transparent and automatable way, that can be used to rank, then prioritize, infectious diseases by their real health impact and track their evolution (McIntyre et al. 2014). Other multicriterion-based approaches are being explored that explicitly incorporate climate change considerations (Cox et al. 2013). OIE supports the development of these methods and is preparing guidelines and recommendations in that regard for member countries.

Risk analysis (Fig. 18.6) is a powerful modelling tool that can be used to forecast the risk of introduction, dissemination or transmission of diseases in order to take appropriate management measures. It enables risks to be interpreted as probabilities, preferably spatially defined (Goutard et al. 2007)—one preferred tool is the risk map, which factors in climatic parameters and their variations.

Risk communication should be better understood (Figuié and Fournier 2008). Indeed, risk analysis implies that scientists will appraise the risk and develop decision support tools, but also that managers will develop control strategies. Hence, communications on climate-dependent diseases are a priority, between epidemiologists and modellers who gauge the risks, on the one hand, and policy-makers, farmers and the general public on the other.[16]

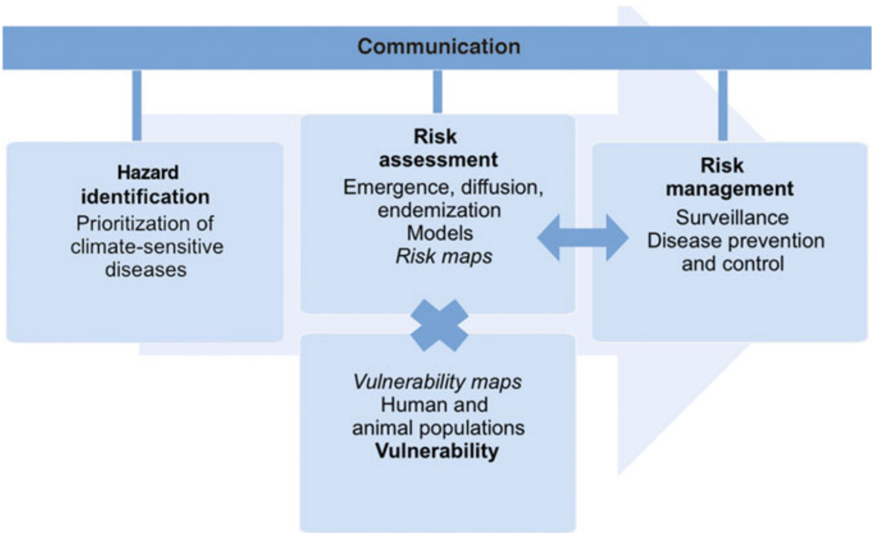

Fig. 18.6 General framework for risk analysis (identification, assessment, management and communication) and estimation of the vulnerability of populations, with the relevant maps being combined with risk assessment maps

[15]At the European level, IFAH (the International Federation for Animal Health) has developed a decision support tool: http://www.discontools.eu/Diseases.

[16]Cf. bluetongue management in France: http://www.senat.fr/rap/r07-460/r07-46024.html.

18.4 Risk Reduction: Enhance and Adapt Health Systems

The overall objective is to increase the resilience of human and animal populations —and the underlying economic systems—to the impacts of climate change. The resilience of a socioecological system is its ability to absorb natural or anthropogenic disruptions and reorganize itself to maintain its functions and structure (Mathevet and Bousquet 2014). This applies for example, to livestock production sectors that may be 'disrupted' by diseases (Renard and Bonnet 2010), in particular as a result of climate change.

In addition to the need to strengthen surveillance systems for diseases in order to consolidate official services worldwide, particularly in the poorest countries (Roger et al. 2014), it is important to monitor and record climatic parameters and associated change indicators. Early warning systems based on climate information can improve epidemic management (Morand et al. 2013). However, with a few exceptions, such as Rift Valley fever monitoring in East Africa (Anyamba et al. 2010) and entomological surveillance, surveillance systems do not simultaneously gather environmental, climatic and health data. Such data are generally collected and combined a posteriori via other, indirect sources (remote sensing, meteorological databases, big data) in the course of statistical, ecological and epidemiological analyses. Better designed cooperation with institutions and climate research centres (e.g. French National Centre for Space Studies, CNES; US National Aeronautics and Space Administration, NASA, etc.) would facilitate convergent gathering of surveillance data on diseases and climatic parameters. Surveillance data integration and analysis methods are needed (Salman 2013) and require the development of time series analyses, multivariate analyses, meta-analyses and spatial and dynamic modelling.

Surveillance optimization can benefit from methods under development, such as social network analysis, which is a valuable tool for modelling contacts, and their variations, among populations or groups of stakeholders (sectors, markets, interspecies contacts). The cost and operation of various types of surveillance systems in response to disruptive factors such as climatic variations can also be analysed by these methods.

Disease control also depends on improved biosecurity on livestock farms (Fig. 18.7), particularly in low-income countries (Conan et al. 2012). In that context, climatic variables should be integrated into epidemiological assessments.

Prevention and control also require the preparation of vaccine banks[17] that can respond quickly to the risks identified and monitored in connection with weather events.

Non-medical mechanisms may be proposed to enhance farmers' adaptation to climate change. This includes index-based insurance, written to cover weather events and certain diseases and developed by several institutions: the International Livestock Research Institute (ILRI), the International Union for Conservation of

[17] http://www.oie.int/en/support-to-oie-members/vaccine-bank/.

Fig. 18.7 A villager and her water buffalo, Ba Be National Park, Province of Bac Kan, Vietnam (© M. Peyre/CIRAD)

Nature (IUCN), the Rockefeller Foundation, and the World Bank[18]; CIRAD and its Senegalese partners have started working on index-based insurance for trypanosomiasis (Dicko et al. 2014). In the livestock production sector, however, experiments reported so far are limited by a minimum risk—a trigger index—that is never reached, and by a premium per head of livestock that is scarcely affordable. For other agricultural sectors, it has been found that these programmes work only in countries that can subsidize the premium (Binswanger-Mkhize 2012).

Animal health systems are structurally underfunded in low-income countries, where climatic conditions are endured rather than anticipated (Van den Bossche and Coetzer 2008). Extreme weather events also require rapid response systems that are not always available. For instance, rapid response in both public health and animal health would be required to deal with outbreaks of Rift Valley fever in East Africa due to an ENSO effect (El Niño southern oscillation). FAO and WHO propose a joint action plan for the Rift Valley fever based on the One Health concept, but the response is often hampered by many financial and human constraints.[19]

Some official veterinary services are developing a body of legislation whereby an emergency may be declared for health phenomena caused by environmental and climatic changes. The risk of an outbreak of Rift Valley fever in the Mediterranean area is one example. Monitoring of environmental and climatic changes and

[18]http://elibrary.worldbank.org/doi/pdf/10.1596/1813-9450-4325.

[19]http://www.cdc.gov/mmwr/preview/mmwrhtml/mm5604a3.htm.

forecasting of the socioeconomic consequences (Peyre et al. 2015) could lead the countries concerned to include specific monitoring for Rift Valley fever and emergency preparedness in the event of outbreaks in their regulations.

18.5 Conclusion

If an animal and human health geography can be developed—a health-oriented social science that integrates animal health and is in line with the One Health and EcoHealth approaches—an integrative interdisciplinary framework will be available to analyse the impact of climate change on health systems and territories (Curtis and Oven 2012). Geography, as a discipline, would help to draw vulnerability maps for human and animal populations. These, combined with risk prediction maps (Fig. 18.6), could be used to rank zones and populations to target for prevention, monitoring and control initiatives.

Alongside non-climatic determinants, climate variations and change add complexity and uncertainty to disease epidemiology, health ecology and health risk management (Fish et al. 2011). The impact of climate change, whether gradual or sudden (during extreme events), may be direct, disrupting economic and social networks, or indirect, through increased disease outbreaks. Climate and its variations can thus disrupt health facilities and limit human and animal populations' access to health systems. Cross-sectoral and interdisciplinary collaborations on analysis, modelling, and risk management—which are feasible within the overall One Health and EcoHealth framework—will allow joint development of decision support tools to help implement integrated health strategies and policies in response to climate change.

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Chapter 19
Impact of Climate Change on Ecosystem Services

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Abstract The ecosystem services concept has been proposed as a response to threats to biodiversity. It is based on a utilitarian view of nature, complementing other conservation strategies—ecosystem services are seen as a way of mitigating climate change and as an adaptive strategy for societies. However, the question remains as to how ecosystems will continue to provide those services in a time of rapid climate change. Most biological communities are disappearing due to climate change combined with other anthropogenic pressures, affecting the functionality of ecosystems that are close to collapse. Rather than maintaining existing ecosystems intact, the focus should be on recognizing their dynamic nature and protecting the functions and services they provide.

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19.1 The Ecosystem Services Concept

The ecosystem services concept partially reflects the relationship between ecosystems and human societies. It is an attempt to capture the 'benefits' provided to humankind by ecosystems, which arise from ecological functions and biodiversity (Costanza et al. 1997; Cardinale et al. 2012). From that perspective, ecosystems directly or indirectly provide a wide range of vital goods and services, such as air and water purification, water and nutrient cycling and regulation, soil formation and retention, atmospheric carbon sequestration, decomposition of matter, and primary and secondary production (Table 19.1). 'Supporting' services are the prerequisite for three other sets of ecosystem services (provisioning, regulating and cultural). All of these services do not constitute a stable whole. There is debate as to their definitions and typologies, while some authors go so far as to question the relevance of the service concept.

The ecosystem services concept has enjoyed success recently. It has stimulated thinking on the economic mechanisms available to conserve biodiversity by assessing its various value components, which may translate into economic benefits (Millennium Ecosystem Assessment 2005). Some see assignment of a value to services as just a tool to raise awareness of their importance, not an attempt at their monetization or commodification. Others see that the goal is to identify goods and services within the ecosystem, to quantify their value and, where possible, to give them a monetary dimension, so as to link biodiversity conservation to the market economy. Taxation of natural resource consumption could potentially be a way to achieve that. Many of these services have thus been appraised in economic terms, i.e. mainly in terms of their worth based on the utility we derive from them (The Economics of Ecosystems and Biodiversity 2009). For example, the value of the service produced by pollinators of major crops has been estimated at €150 billion globally (Gallai et al. 2009).

One of the main criticisms levelled at the ecosystem services concept is that it may lead to a purely economic and utilitarian vision of nature, rather than preservation of nature for its intrinsic value (McCauley 2006; Adams 2014; Maris

Table 19.1 Typology of ecosystem services (based on Costanza et al. 1997 and Millennium Ecosystem Assessment 2005)

Supporting services	Soil formation and retention, nutrient cycle, trace elements cycle, carbon cycle, primary production, oxygen production, necromass recycling, natural habitats
Provisioning services	Food, fresh water, bioenergy, fibre, useful molecules, genetic resources, soil, air
Regulating services	Climate regulation, disturbance regulation, hydrological flow regulation, water purification, air purification, disease regulation, erosion control, biological control, pollination, carbon sinks
Cultural services	Inspiration, aesthetics, education, recreation, sense of belonging, cultural, scientific and educational heritage, spiritual benefits

2014). Such commodification may also lull us into a belief that natural resources and other economic resources are interchangeable, whereas nothing can recreate biodiversity once it is destroyed: there is a risk that the conservation approach will serve the interests of markets rather than vice versa. While they do reflect a utilitarian view of nature, approaches based on ecosystem services should still be seen as complementing, not supplanting, biodiversity conservation strategies already being pursued. Hence, they are not necessarily mere market tools (Schröter et al. 2014).

Ideally, a concept such as this, because it reconciles biodiversity conservation with economic considerations, could help guide policy development both regionally and globally. Its use for that purpose is limited, however, by a lack of basic knowledge, in particular of ecosystem functioning, but also of the potential effects of conservation policies on societies' economic development at different temporal and spatial scales. We still do not know, for instance, how biodiversity affects an ecosystem's ability to provide goods and services (Worm et al. 2006; Naidoo and Balmford 2008). What we do know is that the most species-rich biological communities provide a greater range of ecological functions than those that are species-poor, and that those services are stabler (Cardinale et al. 2012).

Again, there is still debate as to how to measure all ecosystem services, as their direct or indirect role in human well-being remains quite vague: one example would be the role played by the majority of animal and plant species in the functioning of ecosystems and ecosystem service production. Studies have shown that most rare or endemic species play no major role in the community where they are found, unlike common species (Cardinale et al. 2012). And yet it is the first group of species that requires priority conservation initiatives. The same is true of some ecological functions that may be seen as unimportant inasmuch as they confer no direct benefit on humans, a perception that can be detrimental to the preservation of biodiversity. For example, even though floods and epidemics play a vital role in maintaining the dynamics of many ecosystems, substantial resources are deployed to control them (Brouwer et al. 2007) (Box 19.1).

Box 19.1. Climate, ecosystem services and health.

The profound changes that ecosystems have undergone, particularly through the amplifying effect of climate change and the imbalances between humans and nature, have led directly to the emergence of new diseases. The health crises that have shaken the international community in recent years (e.g. SARS, bird flu, Ebola, etc.) show that laboratory-based medical responses focused solely on individuals are not adequate in themselves, but that it is urgent to adopt an ecosystem approach that incorporates the causal interactions between biodiversity and health. That recognition was the impetus for the creation of the 'One Health' concept, which offers an enhanced ability to detect and combat emerging pathogens at the animal-human-environment interface (Chap. 18).

However, the ecosystem approach is sometimes controversial because ecosystem services that regulate diseases, including zoonoses, and the ecological functions that support them have yet to be sufficiently described. First, the potential of biodiversity to 'provide' disease regulation services and so improve public health is perceived as a lever for development strategies, including in terms of climate change adaptation. Second, biodiversity also includes pathogen reservoirs. Within ecological host-reservoir-pathogen relationships, it may therefore lead to the emergence of diseases, *a fortiori* when vector habitat and wildlife reservoirs are profoundly modified by climate change and other anthropogenic pressures.

Some studies have shown that high species diversity is associated with a reduced prevalence of infection of several wildlife-related zoonotic diseases. Other studies, in contrast, suggest that biodiversity preservation can lead to health risks, as in the case of the fight against deforestation and increased malaria risk in Brazil (Valle and Clark 2013). That contradiction, between a biodiversity that moderates disease and one that may be a source of infectious disease, calls for a real research effort, taking the diversity of infectious diseases and their impact on epidemics and outbreaks into account, especially in the current global change setting. Development of the concept of a disease regulation service furnished by ecosystems would allow a better evaluation of the vulnerability and resilience capacity of socioecosystems under the stress of climate change. The results of such research could help establish an intersectoral approach that fully integrates health into spatial planning policies, thus reinforcing the essential recognition of the links between health, agriculture and the environment (Morand and Binot 2014).

Be that as it may, the ecosystem service concept has already been favourably received by numerous multilateral and bilateral donors, governments, researchers, conservation NGOs and private companies active in promoting and implementing mechanisms to limit degradation or increase the production of such services. These may be economic mechanisms, such as payments for services, or non-economic ones such as protected areas or watershed management programmes (Goldman and Tallis 2009). It remains to be seen whether they can stem the growing degradation of most of the planet's ecosystems, which are under serious threat, in particular from climate change. Conversely, one may question the adaptation potential of ecosystems in the face of climate change and whether they can continue to provide services that could indirectly help societies adapt to and mitigate climate change.

19.2 Value of Ecosystem Services in Reducing Socioecosystem Vulnerability

Numerous regulating and provisioning ecosystem services can help reduce societies' vulnerability to climatic variations—for example, products from natural ecosystems can act as a safety net for local communities whose crops are affected by drought. Another example would be watershed ecosystems that may reduce high water and flooding, an advantage for people living downstream (see also Fig. 19.1). Ecosystem services can thus help increase socioecosystem resilience at the local, national or regional level. This phenomenon is recognized in so-called 'ecosystem-based adaptation' approaches (Locatelli et al. 2008). Similarly, ecosystem management can contribute to climate change mitigation by reducing

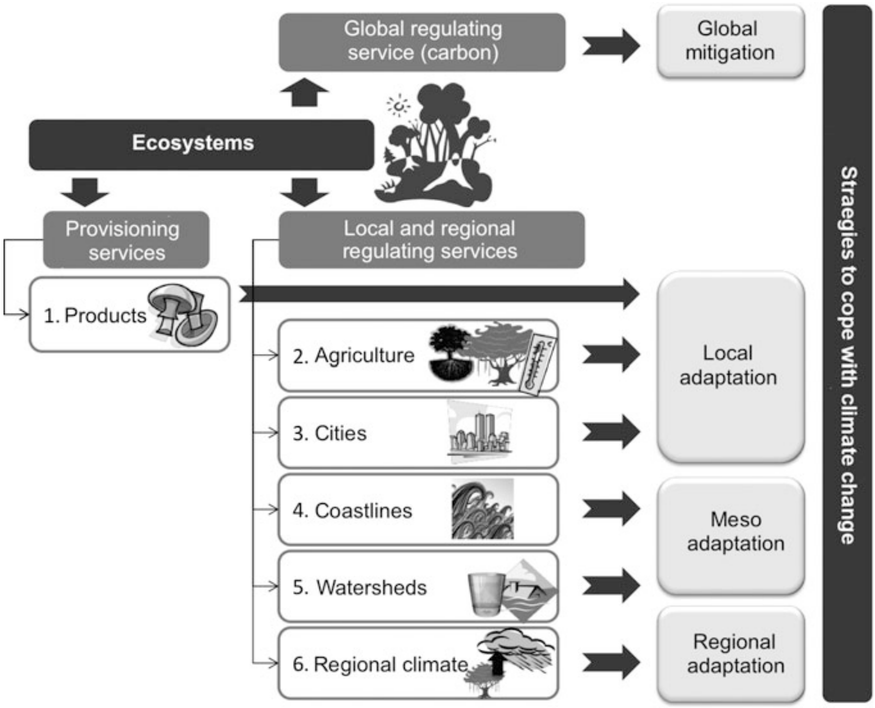

Fig. 19.1 Contribution of ecosystem services to strategies to combat climate change. From *top* to *bottom*, carbon sequestration contributes to mitigation; ecosystem products increase the resilience of rural economies by diversifying them (e.g. forest products serve as a safety net when climate changes affect agriculture); in agriculture, microclimate and soil regulation by trees (agroforestry) increases agricultural production's resilience to variations; regulating services provided by urban trees and forests reduce the effects of floods and heat waves in cities; mangroves and coastal forests protect against waves and storms; hydrological regulation services reduce the effects of climate fluctuations in watersheds; regional climate regulation can moderate the effects of climatic variations (according to Pramova et al. 2012)

greenhouse gas emissions from the degradation or loss of ecosystems and by enhancing carbon sequestration. While such ecosystem-based mitigation has been widely studied, there is still too little empirical data available on ecosystem-based adaptation for its value to be fully assessed. Priority needs to be given to identifying parameters that will make such adaptation more relevant or synergetic than technology- or infrastructure-based adaptation.

Moreover, if a decision is made to resort to adaptation based on ecosystems and ecosystem services, then such approaches must immediately be integrated into countries' regional and national development and adaptation strategies. Early political integration will increase efficiency and forestall the risk of contradictory development actions. For example, the construction of coastal infrastructure to mitigate the impact of rising sea levels can lead to the destruction of mangroves, which play a role in both carbon sequestration and the renewal of marine food resources for local populations, thereby increasing their vulnerability.

19.3 Impacts of Climate Change on Ecosystem Services

Species depend on ecological functions for their survival—such functions ensure the resilience of ecosystems in the form of dynamic equilibria and, in so doing, their ability to deliver ecosystem services. However, in the current context of climate change, new ecosystems and species communities are being created as the constituent animal and plant species respond differently to these rapid climate changes. The climate envelope or dispersal capacity of some species will allow them to adapt, but many species are liable to disappear (Malcolm et al. 2006) (Fig. 19.2). Thus, current changes in temperature and precipitation are disrupting the composition of biological communities and associated ecological functions, affecting ecosystem service production in multiple ways.

Marine ecosystems are particularly sensitive to this. The composition of marine biological communities can be quickly altered by increases in water temperature or acidity, which will impair the ecological functions of the marine ecosystem. The primary production rate and distribution are now greatly disrupted in all of the world's oceans (Harley et al. 2006). Unfortunately, marine primary production is essential to preserve biodiversity and fishing activities (Cury et al. 2008).

The main effects of climate change that have already been observed have major consequences on current ecosystem service sustainability (Table 19.2). At worst, the ecosystems may collapse, sometimes very quickly (Millennium Ecosystem Assessment, 2005). Moreover, history has shown how harmful these phenomena can be for societies, with several major social crises and severe depopulation (Zhang et al. 2011).

Fig. 19.2 The northern Queensland rainforest, Australia, is considered to be highly vulnerable to climate change. Characterized by Alexandra palms (*Archontophoenix alexandrae*), this unique ecosystem is home to a great diversity of endemic species with a narrow ecological range and limited distribution (© M. Pedrono/CIRAD)

Table 19.2 Major effects of climate change on biodiversity and ecosystem services already observed

Species extinction	Phenology, population abundance, population structure, mortality and spatial distribution are changed, which may lead to the extinction of plant and animal species. Factors of decline already present are aggravated
Ecosystem change	New species communities and ecosystems appear. It is uncertain how ecosystems will respond to climate change
Coastal flooding	There are changes in many countries' coastlines due to the rising sea level. Sea level areas are flooded. Small islands are most affected by this; some are disappearing
Increase in cyclonic events	Cyclones are more frequent and intense and have greater impacts on the environment and human populations. They also create severe flooding in their path
Reduction of freshwater resources	Inland areas already suffering significant water deficit are most affected. Groundwater can no longer be replenished; lakes dry up
Falling crop yields	While yields increase in some regions because of higher carbon dioxide concentrations, in most cases they collapse due to water stress or flooding
Disruption of human, animal and plant health	Tropical diseases and pests spread to temperate regions, with increased incidence of mortality. This is particularly the case of diseases carried by tropical insects and waterborne diseases

19.4 Preservation of Ecological Functions in the Climate Change Context

Although many species may perform a similar function within an ecosystem, they will respond differently to climate change—the most species-rich ecosystems are apt to be the least affected (Figs. 19.3 and 19.4). Hence, species diversity and ecological functions are interdependent, and an integrated approach is required to ensure their preservation. One way to support this is to promote the contiguity of natural habitats, for example via land corridors. Rather than focus on maintaining ecosystems in their present form, the adaptive strategies employed should recognize their dynamic nature and focus on protecting the functions and services they provide. The goal is to proactively define and optimize what is feasible in ecosystem adaptation (Nelson et al. 2013). Merely delaying the integration of climate change into ecosystem management plans would result in a significant financial cost to society—the cost of inaction—that is much higher than the cost of mitigation. In other words, the economic benefits to be derived from the fight against climate change far outweigh its costs (Stern 2007).

Fig. 19.3 More than half of the world's chameleon species are endemic to Madagascar. Here, a male Parson's chameleon (*Calumma parsonii)* in the rainforest corridor along the eastern coast of the island (© M. Pedrono/CIRAD)

Fig. 19.4 With nearly a hundred lemur species, Madagascar's primate diversity is second only to Brazil's. The Coquerel's sifaka (*Propithecus coquereli)* lives in the last stand of dry tropical forest in northwestern Madagascar (© M. Pedrono/CIRAD)

19.5 Conclusion and Outlook

The main value of the ecosystem services concept lies in its potential reciprocal benefits for biodiversity and human societies. In practice, however, policies for the preservation of such services are not necessarily those most relevant to biodiversity conservation. Only those that are relevant and thus create the conditions for a real synergy between the maintenance—or restoration—of biological diversity and societies' economic development should be encouraged. Extinction offers no second chances. It is crucial to invest wisely, especially in the current climate change setting. It is very difficult to forecast the impact of climate change on ecosystem services. The only certainty is that it will depend on the resilience of biodiversity and ecosystem dynamics. Research should be preferentially targeted toward gaining a better understanding of the likely impact of climate change on these ecosystems and the major ecological services they produce, in order to develop consistent and innovative adaptation strategies.

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Chapter 20
Life Cycle Assessment to Understand Agriculture-Climate Change Linkages

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Abstract As one of the most comprehensive environmental assessment methodologies, life cycle assessment enables evaluation of the environmental impacts of anthropogenic activities along a supply chain. Its implementation raises many scientific questions. In the case of tropical cropping systems, researchers are working to understand and model environmental emissions based on the diversity of environments and systems. They are also focusing on the relationship between emissions and impacts. Cropping system life cycle assessments show that the

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impact on climate change varies by crop, environment and type of practice. Life cycle assessment can help guide production methods so as to reduce their environmental impacts. But the choices are not always clearcut.

20.1 A Single International Standard to Quantify Agricultural Greenhouse Gases

Climate change is largely due to greenhouse gas (GHG) emissions related to agriculture and land use change (see Chap. 1). Why? Where exactly do the emissions come from? What mechanisms are involved?

The difficulties governments are having in agreeing on concrete measures to address the climate change challenge result from a twofold unresolved question: Who is to blame? Who will pay? To answer those questions, we must be able to identify and quantify GHG emission sources. If no measurements or indicators are available, it will be impossible to identify levers to improve system performance and reduce emissions.

Today there is a single standardized, internationally recognized methodology for estimating the environmental impact of human activities along a supply chain: life cycle assessment (LCA). After the first life cycle assessments of the early 1980s, LCA gained more traction in the 1990s with the development of bioenergy, leading to unprecedented international harmonization regarding environmental assessment, particularly through the structuring and formalization work led by SETAC.[1] Since the early 2000s, LCA has become a standardized conceptual and methodological framework under ISO series 14040 (2000–2006). It is based on two fundamental principles. First, environmental impacts are quantified throughout the supply chain or 'life cycle', from raw material extraction ('cradle') to end-of-life of the product or service ('grave'). Then, the impacts are quantified with respect to a functional unit, either a product quantity (one kilo, one car, etc.) or a usage or service (hours, kilometres, etc.).[2] In that way, the environmental impacts of systems producing a similar function can be compared. Thus, LCA has become the worldwide standard for implementing environmental product declarations (ISO 14025 Type III Environmental Declarations).

From the global change standpoint, the entire life cycle of a product has to be taken into account so that local environmental improvements at one production stage or in one place are not merely the result of problem-shifting to another stage or place (Jolliet et al. 2010). Similarly, comparison based on a common provided functional unit is paramount in order to avoid problem-shifting from one chain to

[1]SETAC: Society of Environmental Toxicology and Chemistry, one of the most important international scientific organizations dealing with structural issues of life cycle assessment (Jolliet et al. 2010).

[2]In the remainder of this chapter, references to 'product' alone will mean 'product or service'.

another to compensate for any functional shortcoming. Finally, LCA assesses environmental performance across multiple impacts, such as climate change, acidification, ozone layer destruction, etc. A priori, such a multicriterion approach does not emphasize any one impact but pinpoints the greatest impacts and their origins at certain production stages. The necessary tradeoffs and arbitrations can thus be documented.

While life cycle assessment is not familiar to everyone, GHG assessments are more widely used. The methods derived from them, such as the Carbon Footprint® of the French Environment and Energy Management Agency (ADEME), are partial LCAs focusing on the impact of climate change, with similar conceptual frameworks. There are also various international guidelines based on LCA that set out rules for calculating GHG assessments under certification schemes that may be voluntary (IPCC 2006; International Sustainability and Carbon Certification (ISCC) 2010) or mandatory (European Union 2009). GHG assessments are clearly essential given the climate emergency, but their popularity can be better understood if we analyse how well climate change modelling fits the LCA conceptual framework.

20.2 A Simple Conceptual and Methodological Framework for an Array of Scientific Challenges

Life cycle assessment is based on a conceptual framework that provides a simple expression of a product's environmental impacts as the linear resultant of the contribution to various impacts of the resources used and substances released throughout the supply chain. It employs a four-stage methodology: definition of the study objectives and boundaries of the system studied from the beginning to end of the chain; inventory of all resource flows used and substances released within the system; characterization or modelling of impacts based on the inventory; and interpretation of the results (ISO series 14040 2000-6).

Hence, the impact on climate change is calculated by taking an inventory of all GHG emissions per unit product into account. The emissions are then aggregated into a single impact indicator using IPCC's linear model, which characterizes what happens to GHGs in the atmosphere and their relative contributions to the global greenhouse effect. GHG assessments are LCA's flagship application because they perfectly fit its conceptual framework. GHGs are emitted anywhere but add up to a global impact on the atmosphere. They are marginal at the level of any given process because they are diluted at the global level. That limits the risk of exceeding thresholds or of feedback that might not be taken into account in the underlying linear model.

LCA implementation poses some problems because of insufficient data or scientific knowledge, which gives rise to a number of uncertainties. The main scientific challenges are, first, to define the representative system for the function studied, and second, to account for the variability of practices and of climatic and soil conditions.

Cropping systems for tropical crops are particularly diverse and many parameters are not systematically recorded. For instance, the median GHG emissions for cassava production in Thailand are 80 kg CO_2-eq/t of roots[3] but range from 30 to 210 kg CO_2-eq/t of roots depending on fertilizer management (Tran et al. 2014). Hence, different types of farms must be distinguished rather than try to define one (necessarily unrepresentative) median system. The analysis of the many and highly diverse agroforestry systems in the tropics is a particularly complex task. They provide many products and services, so the way emissions are allocated between products must be carefully defined. Finally, the boundaries of the system to be studied are often difficult to define in the case of family farms in developing countries, where flows between plots and farms are numerous and spatiotemporally varied.

Moreover, cropping systems play host to many biogeochemical processes at soil-plant-atmosphere interfaces that generate emissions into the environment. Such emission processes, often complex, are controlled by numerous soil, climatic and biological factors, which in turn are influenced by agricultural practices. Various models may be used to estimate emissions in the field, but many uncertainties remain because the mechanisms involved are only partially understood and modelled. One example is the discrepancy between the estimates of nitrous oxide (N_2O) emissions from agriculture achieved by top-down approaches (e.g. the bioclimatic model sets the amount of nitrogen emitted as N_2O worldwide at around 4 % of the nitrogen in fertilizers; Crutzen et al. 2008) and by bottom-up approaches (e.g. the statistical model based on measurements in the field worldwide indicates an average coefficient of around 1 % of the nitrogen in fertilizers emitted as N_2O; IPCC 2006, based on the study of Bouwman et al. 2002a). That discrepancy reveals the existence of unexplained mechanisms and illustrates one of the most common uncertainties in the modelling of emissions in the field. As with these emission factors, which are directly proportional to total nitrogen supplied, the extent to which the influence of practices on emissions is taken into account is quite limited. In the case of tropical crops, the uncertainty is even greater, because the models commonly used (e.g. IPCC 2006) are based on datasets in which tropical conditions and farming practices are underrepresented (Bouwman et al. 2002a, b). Mechanistic models can better assess the influence of practices in estimates for many crops, but the large number of parameters to be calibrated is often prohibitive in the case of tropical systems, which diverge too widely from the models' original validity ranges. Whatever the conditions and models used, many scientific challenges remain to be addressed before all processes linking environment, practices and emissions can be properly understood and factored into estimates. These challenges

[3] CO_2-eq means CO_2 equivalent, i.e. in this case the sum of all GHG emissions weighted by the global warming potential of the various GHGs. Those potentials are the characterization factors in the IPCC linear model; they reflect, in particular, the fact that not all GHGs last the same length of time in the atmosphere, nor do they all react the same with other atmospheric components. Their contributions to the global greenhouse effect are, accordingly, also variable; for example, 1 kg of N_2O is roughly equivalent to 298 kg of CO_2.

at the cropping system level (Bessou et al. 2013b) are also found at larger scales, such as a whole farm or territory, where connectivity and compensation phenomena, etc., must also be taken into account (Bellon-Maurel et al. 2013).

There are other challenges relating to impact modelling. The limits of the linear model may be overcome by developing regional characterization factors that can be used to adapt the model to the sensitivity of the local host environment. Such factors are particularly critical in the case of localized impacts that are more sensitive to changes in the immediate environment, such as eutrophication, or resources unequally distributed on the global scale, such as water in dryland areas. Finally, researchers are working to improve the modelling of impact chains by including new design parameters such as the consideration of soil carbon and albedo in climate change impact assessments. They also propose to introduce new impact chains, such as the salinization of environments (Payen et al. 2014), the impact of practices on functional soil biodiversity, etc.

20.3 What Does Life Cycle Assessment Tell Us About the Impact of Crops on Climate Change?

Since the 2000s, many studies have been published on the life cycle assessment of various agricultural products intended for food or energy. LCA is regularly used to provide an environmental viewpoint on major issues raised by our consumption patterns. The environmental benefits of organic over conventional farming are one such issue and has been evaluated in many available studies dealing with many different crops. Tuomisto et al. (2012) conducted a meta-analysis of published results for Europe to highlight the observable trends. They showed that there is currently no statistical difference in GHG assessments between organic and conventional farming when all product groups are considered. Where organic practices are used, however, the soil organic matter content is statistically higher than with conventional practices. Organic farming could benefit if that parameter were included in evaluations. Other reviews also tell us about the main recurring sources of environmental impact for various cropping systems. A review of LCAs carried out on perennial crops (Bessou et al. 2013a) compared 70 LCAs[4] for raw or processed agricultural products, particularly in the case of bioenergy supply chains. In most chains, the cropping system seems to be the main contributor to global warming, eutrophication and toxicity impacts. The main sources of emissions contributing thereto are the production and application of nitrogen fertilizers, in particular in the case of global warming and eutrophication, and pesticide and fertilizer use, as regards toxicity. Those main emission sources are critical for

[4]The LCAs reviewed covered 14 products: peaches, apples, bananas, oranges, citrus, cocoa, coconuts, kiwis, coffee, grapes, olive oil, jatropha oil, palm oil and sugar cane. Of the 70 LCAs reviewed, 60 % were partial and only addressed global warming or the energy balance.

cropping systems, even those less mechanized or where the cropping system only serves to produce the raw material for a processed product (bioenergy, ground and packed coffee, etc.).

Since 2009, CIRAD has been developing the LCA-CIRAD© database on developing countries' produce: citrus, cotton, tomatoes, palm oil, coffee, rice, cassava, jatropha, beef, etc. The following case studies are taken from that database and afford a detailed analysis of some systems, to clarify the practices and conditions that cause GHG emissions.

In Mali and Burkina Faso, CIRAD researchers quickly built on their research on the development of *Jatropha curcas* as an energy crop to launch an environmental assessment approach based on life cycle assessment (Benoist et al. 2011; Chapuis 2014). Regarding climate change, these studies indicate that in the West African context, the yield response of *Jatropha curcas* to fertilizers would be quite low, so additional GHG emissions due to fertilizer inputs would not be offset by improved yield. However, more surveys and experiments are needed to settle the point.

For palm oil, Asian and Brazilian supply chains were compared using a GHG calculator, PalmGHG, developed for RSPO[5] (Bessou et al. 2014). The software accounts for production stages from raw material extraction to the production of crude palm oil at mill gate (Fig. 20.1). The average GHG assessment was 1.67 kg CO_2-eq/kg of crude oil,[6] but a wide disparity was found between chains: from −0.02 to 8.32 kg of CO_2-eq/kg of crude oil. A comparison of various scenarios from a theoretical reference case illustrates the various sources' relative importance (Fig. 20.2). The main sources of GHG emissions are peat oxidation, land use change, methane effluent from oil mills (Fig. 20.3), and fertilizers. A negligible amount of fossil fuel was burnt for field mechanization, transport and the oil mill. When a palm plantation is established on peat soil, annual GHG emissions due to oxidation dominate the overall emissions. This study, based on LCA principles, clearly shows the virtually prohibitive risk of planting on peat in terms of GHG. On the other hand, it appears that GHG can be markedly reduced by planting on degraded land or savanna, by capturing methane emitted during effluent treatment and converting it into electricity, or by optimizing fertilizer inputs.

An LCA study of Thai rice pointed out the very high GHG emissions in flooded rice fields (3–5 kg CO_2-eq/kg of rice produced), and elucidated the effect of tillage practices on methane emissions. Note that at the global level, flooded rice cultivation[7] (Fig. 20.4) accounts for 13 % of all anthropogenic methane emissions. In northeastern Thailand, the way flooded paddy irrigation is managed is decisive for methane emissions. Thus, it is recommended that temporary drying periods be

[5]Roundtable on Sustainable Palm Oil.

[6]1.67 kg CO_2-eq is equal to the emissions of a car carrying a person for about 11.5 km (Ecoinvent v2.2: 01945 XML).

[7]In 2012, flooded rice accounted for some 3 % of the world's usable arable land http://faostat.fao.org.

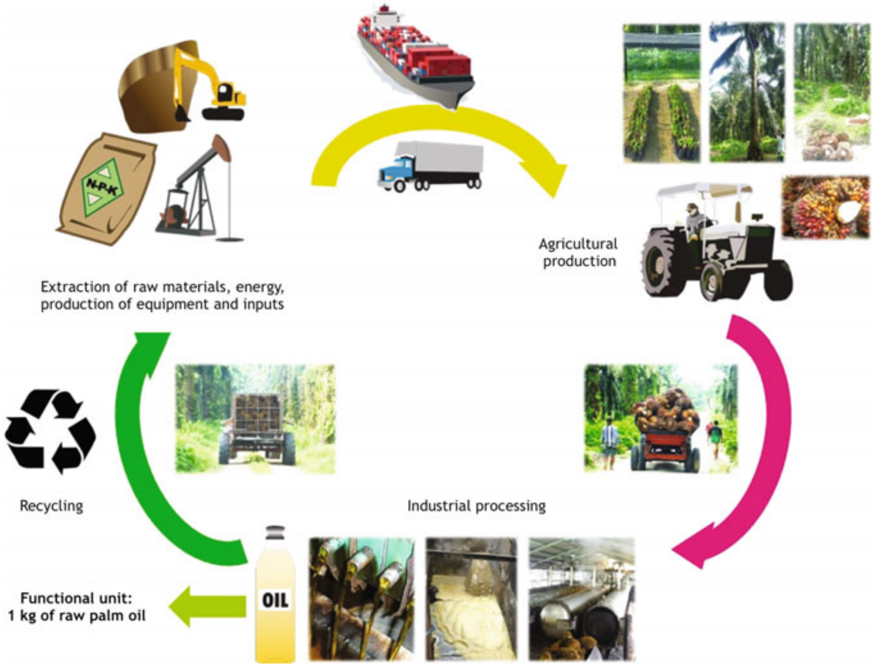

Fig. 20.1 A palm oil production system studied using life cycle assessment

introduced into the system. It is also important, in the light of the results, to carefully limit urea inputs, which are another source of environmental impact: fractionation, coarser fertilizer and burial are also recommended to limit volatilization in the form of greenhouse gases (Thanawong et al. 2014).

Life cycle assessment can also supply data for comparison of the impacts of agricultural products by origin. In the winter, for example, is it better to eat tomatoes grown in France or imported from Morocco, where the climate is more suitable? A comparison of the environmental impacts of French table tomatoes (Boulard et al. 2011) and of Moroccan ones (Payen et al. 2015) shows that there is no clearcut answer. Importing tomatoes from Morocco minimizes the impact on global warming but maximizes the impact on water resources (Fig. 20.5). Hence, all impact categories must be considered to take all pollution transfers into account. Some choices may be very difficult.

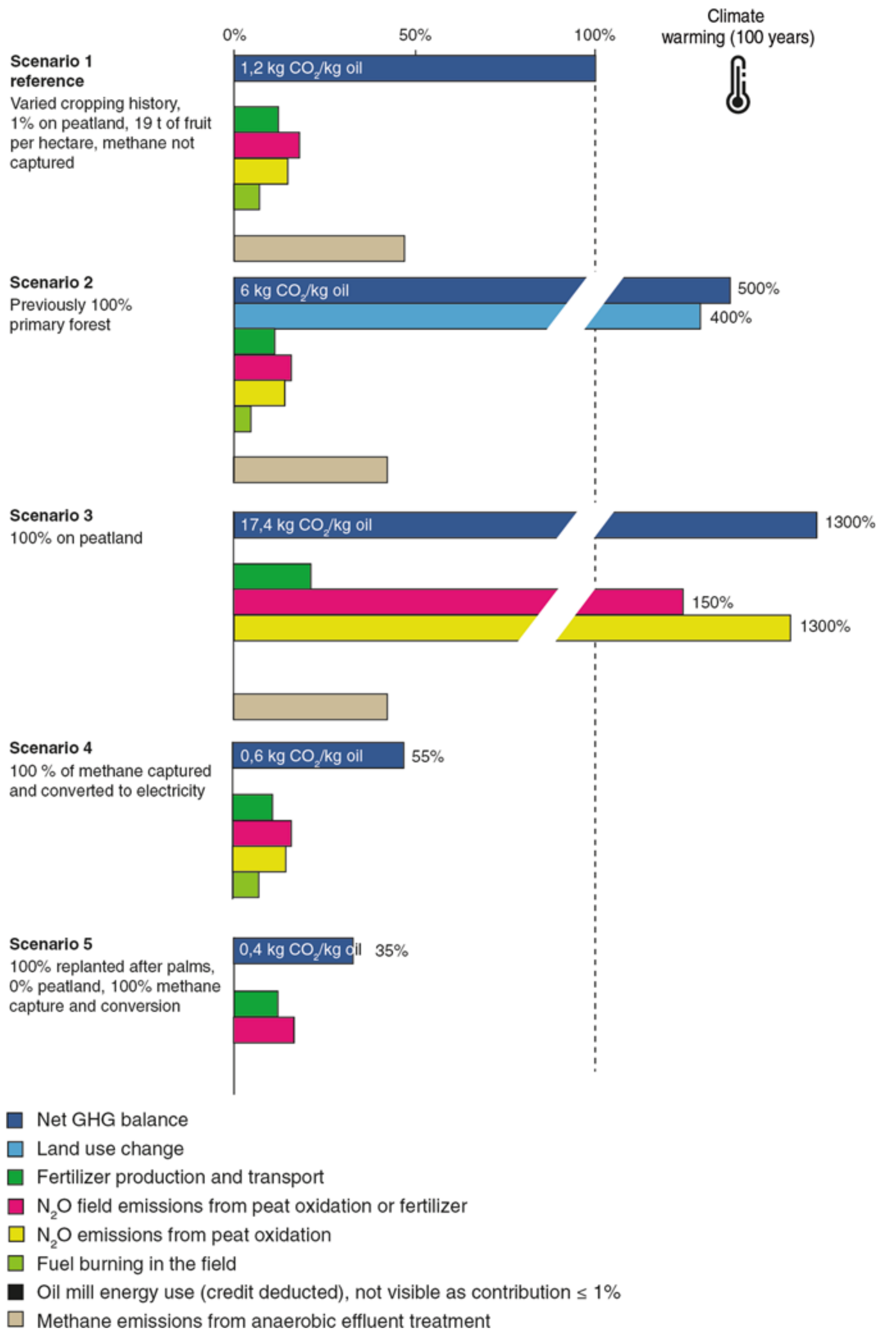

Fig. 20.2 Preserve the forest, do not plant on peat and capture methane from slurry treatment. The figure shows GHG emissions per kilogram of crude palm oil calculated with PalmGHG for various planting scenarios. Contributions ≤ 1 % are not visible

Fig. 20.3 Effluent application on a stand of oil palms in Asia (© C. Bessou/CIRAD)

20.4 What Does Life Cycle Assessment not Tell Us?

In the first part, we spoke of a twofold unresolved issue for action against climate change: Who is to blame? Who will pay? Life cycle assessment can provide a partial answer, but not the whole answer.

For one thing, as with any modelling study, the impacts quantified are only potential impacts, more or less uncertain depending on the impact category. The many uncertainties all give rise to scientific issues, including those mentioned above. LCA makes use of state-of-the-art characterization of production systems and environmental impact mechanisms. The more research advances, the more reliably the impacts can be quantified. But what if a decision has to be made? There is still a margin for error. In addition, LCA gives results for several environmental impacts, not all of which necessarily trend the same way. Which to choose?

Again, though economists have developed a methodology based on life cycle costing throughout a supply chain (Adnot et al. 2012), LCA does not yet integrate the strictly social dimension of sustainability. Research work is under way,

Fig. 20.4 Flooded rice paddies in Indonesia (© C. Bessou/CIRAD)

especially at CIRAD/IRSTEA/ELSA,[8] to develop an evaluation of the social impacts of a product's life cycle by integrating mechanisms into the methodological framework that can characterize social impacts throughout a given supply chain. The challenge is to successfully integrate new indicators, relating for instance to the status and wellbeing of individuals involved in the production process (workers, local population, economic partners, etc.) (Feschet 2014; Macombe et al. 2013). Consideration of a supply chain's social and economic impacts is also essential in guiding development choices. LCA can tell us, for example, what the main sources of GHG emissions are in the production of palm oil. What it cannot tell us is who should pay for the preservation of a tropical forest on peatlands—the oil producer or the end user? The cosmetics distributor, downstream, or the logger of the forest stand that existed before the palm plantation, upstream? As a proportion of the quantity

[8]Irstea: National Research Institute of Science and Technology for Environment and Agriculture; ELSA (Environmental and Sustainability Life Cycle Assessment) is a research group dedicated to life cycle assessment and industrial ecology as they apply to agrobiological processes www1.montpellier.inra.fr/elsa/.

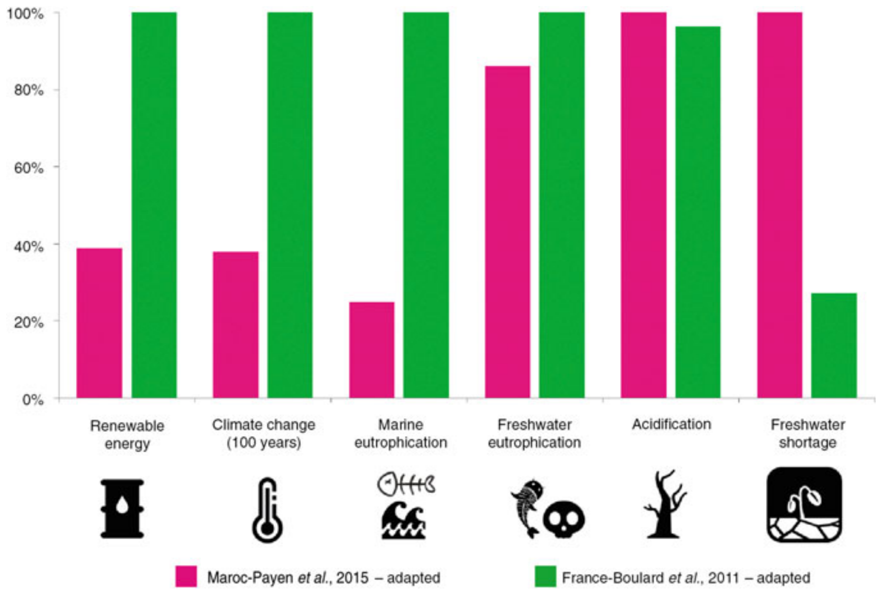

Fig. 20.5 Pollution transfer between impact categories (GHG assessment and water use) in the case of fresh tomatoes sold in France. The figure shows the environmental impacts calculated using a RECIPE H LCA (2008) and comparing two systems for the production and supply of fresh tomatoes to the French market. *Green* produce of France; *pink* produce of Morocco imported into France

shipped, or of the gross domestic product? What are the models for sustainable development?

In conclusion, LCA can first clarify where the main impact sources are, then target, test and prioritize improved practices. It also highlights risks that can never be offset, such as irreversible peat oxidation or pollution transfers, for example between impact categories. LCA researchers work to improve and pool knowledge to better characterize systems and better model emission and transfer mechanisms in the environment. They also spur scientific advances to develop or improve impact chains in LCA. Researchers can still only partially answer the questions raised by the improvement of the method. At its current stage of development, LCA is nevertheless one of the most complete and consistent methods of estimating the impacts of human activities on the environment, including climate change.

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Chapter 21
Payment for Environmental Services in Climate Change Policies

Driss Ezzine-de-Blas, Marie Hrabanski and Jean-François Le Coq

Abstract Payment for environmental services is intended to ensure better management of natural resources while contributing to economic development and ecosystem protection. This policy instrument is based on economic incentives to offset the opportunity costs of environmental service providers. Hence, it links providers and users of environmental services and acts as a powerful catalyst for collective action. In this chapter, we discuss the economic principles underlying the instrument and its modes of governance, and we present some innovative examples. We show that by maintaining ecosystems and associated ecosystem services, the practices favoured by these payments contribute directly and indirectly to climate change adaptation or mitigation policies.

21.1 Background

The challenges of climate change demand social, technological and institutional innovations. Payment for environmental services (PES) serves conservation purposes in all three dimensions, in particular by maintaining and improving natural and anthropogenic ecosystems. Unlike conventional approaches to nature conservation and integrated conservation and development projects, PES offers economic incentives in exchange for compliance with one or more clauses, spelled out in a contract aimed at maintaining or restoring one or more given environmental ser-

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Fig. 21.1 An example of payment for environmental services (here, hydrological regulation in a watershed) that impacts other services—in this case, the beauty of the landscape. Valley of the Annapurna Circuit, Nepal (© D. Ezzine-de-Blas/CIRAD)

vices. The main innovation of PES with respect to conventional conservation strategies lies in its contractualization and cross-compliance principles: both parties must comply with the terms of their agreement, and the economic incentive must confer a positive net benefit, that is, deter deforestation where that is a threat, restore forest where it has disappeared, or encourage adoption of agroecological practices on farms that had not previously adopted them (Fig. 21.1). In practice, environmental additionality—changes in management practices such as a ban on forest destruction, the burning of farmland or woodland, or the abandonment of farming and grazing in environmentally sensitive areas, etc. due to the implementation of the scheme—is not always respected. Changes in practices can, however, be encouraged by incentives of many different kinds, in cash or in kind (hives, fences, agricultural inputs), agricultural and forestry investment plans (silvopastoral enrichment, shade-grown coffee, low-input farming systems, forestry plantations), labour or social aid (scholarships, school construction, trail maintenance, wells and water purification).

By maintaining ecosystems and associated ecosystem services, practices favoured by PES contribute directly and indirectly to climate change adaptation or mitigation policies. PES contributes to mitigation by reducing greenhouse gas (GHG) concentration and protecting existing forests and the soil carbon stock. It also encourages practices aimed at capturing atmospheric carbon dioxide in plantations and contributes to better carbon management. The climate regulation potential of PES explains why the international initiative on reducing greenhouse gas emissions from deforestation and forest degradation, known by the acronym REDD+,[1] makes frequent use of PES-type instruments. Indirectly, PES also contributes to climate change adaptation policies by protecting ecosystem services that reduce vulnerability, such as hydrological regulation, biodiversity, or services related to multifunctional agriculture (traditional knowledge, pollination, soil conservation, etc.).

This chapter analyses PES and its role in strategies to counter climate change. After a brief look at the theoretical characteristics of its socioeconomic model, we present several examples of PES and discuss the role it can play in global climate change adaptation and mitigation policies.

21.2 Economic Theory and Payment for Environmental Services

A PES scheme is a contract between at least one environmental service provider and at least one user of that service, provided that the service is in fact delivered (Engel et al. 2008). Figure 21.2 illustrates that definition by showing the prerequisite economic conditions for a PES-type agreement.

The economic underpinning of PES stems from the principle of internalization of externalities. For a PES to be economically viable, the environmental service must be known and the economic losses sustained by users owing to its degradation must be greater than the opportunity costs (lost profits) for its providers. The principle relies on the fact that society derives benefits from the functioning of protected ecosystems, whereas that protection has a cost that is generally not borne by service recipients (the people who benefit from water quality, etc.). What a PES does is compensate those who, through their practices, contribute to that protection. When the difference is positive, the user of the environmental service will in theory be willing to compensate the service provider. At the same time, service providers must receive a payment that covers their opportunity costs, namely the shortfall in profits caused by the cessation of one activity to undertake another. Service provision contracts fall into two main categories: either the service user derives a direct —i.e. physical—benefit from the services, e.g. improved water quality, regulation of hydrological flows, pollination, or multiple services of multifunctional agriculture; or the user benefits through the purchase of an offset right that does not involve a direct biophysical link with the source of the environmental service.

[1]Reducing Emissions from Deforestation and Forest Degradation.

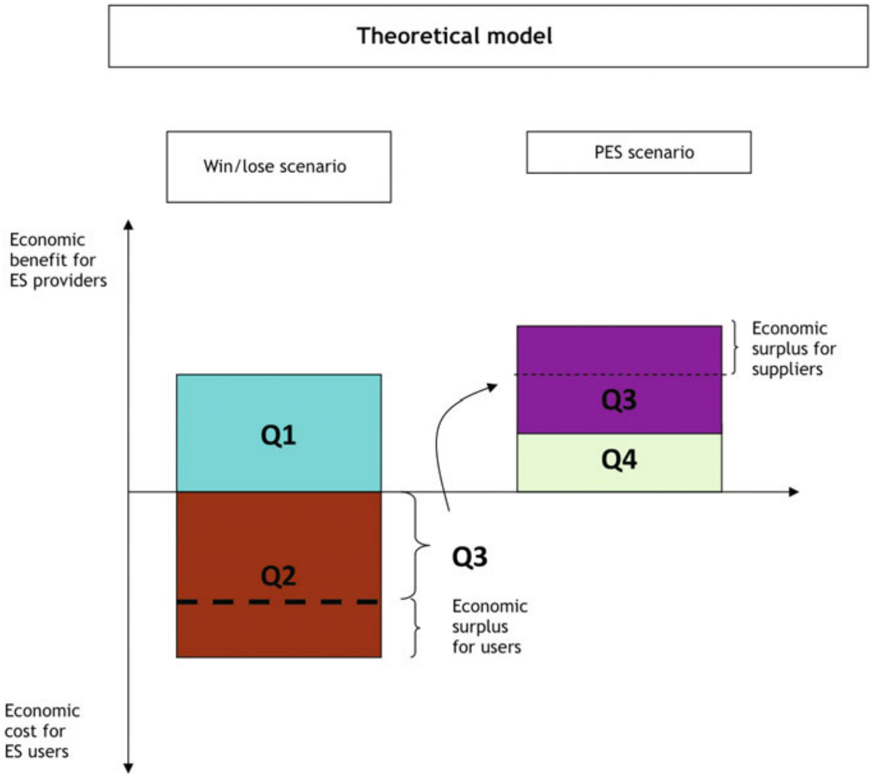

Fig. 21.2 Economic model: how a payment for environmental services works. *Q1* most profitable land use; *Q2* externalities derived from *Q1*; *Q3* compensation paid by users to environmental service providers; *Q4* land use income compatible with the provision of the environmental service; *PES* payment for environmental services; *ES* environmental service (cf. Pagiola and Platais 2007)

21.3 A Variety of Arrangements

In the field, payment for environmental services takes a wide variety of forms. Worldwide, such payments can be classified according to the type of environmental service provided, their geographic scale, the economic sector or sectors involved (private, public, civil society) and whether or not they involve market-oriented governance (Ezzine-de-Blas et al. 2014). The PES examples presented below highlight their diversity but also their innovativeness and efficiency.

21.3.1 Inclusion in Government Policies and Projects

National programmes may focus on agricultural and forest ecosystems. They more or less explicitly include the climate dimension and put more or less emphasis on efficiency. A first example of a national PES can be found in the USA, which in 1985 became the first country to implement a national PES policy (Claassen et al. 2008), with the aim of fallowing certain grain-growing areas (wheat, sorghum, maize) on marginal yet ecologically valuable land. To allocate the payments, the Natural Resources Conservation Service used a geographic information system in which cultivated areas were classified by ecological importance and agricultural yield. Farmers wishing to enter the programme were ranked by efficiency based on the areas they had submitted to the project. Contracts were awarded in descending order of efficiency while funds were available. A follow-up and inspection system involving 5 % of the farms each year verified contract performance and identified violations. Existing evaluations of the impact of the Conservation Reserve Programme show that it effectively conferred conservation status on large areas of marginal land, which therefore had a low opportunity cost.

Another often cited example of a national PES concerns Costa Rica. In 1996, Costa Rica pioneered the environmental service concept in its fourth Forest Act, which laid the foundations for a national programme of payment for environmental services (PPES) (Le Coq et al. 2012). Costa Rica's forest regulations mention four environmental services provided by forest ecosystems that need to be sustainably used: carbon capture for climate regulation, biodiversity conservation, watershed protection and landscape preservation. To that end, the PPES has since 1997 been making compensatory payments to farmers and forest owners to promote protection, reforestation and sustainable forest management. The eligible areas were defined by the National Forestry Financing Fund (FONAFIFO) and the office in charge of Costa Rica's conservation areas based on environmental (importance for biodiversity and water resources) and social criteria (human development indices). The fact that the demarcation process ignored the risk of deforestation and the opportunity cost for farmers of not clearing land goes some way to explain the debate over the programme's environmental effectiveness (Arriagada et al. 2012). Social aspects took precedence in the programme, in particular the goal of wealth redistribution from the cities to the rural poor. In part for that reason, PES achieved great legitimacy and hence became sustainable (Legrand et al. 2013).

On the project scale, PES involves local government, non-governmental organizations and businesses to varying degrees. For example, in the Los Negros River micro-watershed in the department of Santa Cruz, bordering Amboró National Park in Bolivia, the municipality of Los Negros has partnered with USAID to protect forests that play a key role in water quality and the protection of endangered bird populations (Asquith et al. 2008). Payments are made by downstream water users with support from USAID's Biodiversity Conservation Programme. The municipality monitors water flow and quality and makes regular inspections of the forests enrolled in the programme, and has found that the contract forests are intact.

Fig. 21.3 Payment for environmental services can help conserve forest lands that compete with agricultural uses. Biological Corridor of Huila, Colombia (© D. Ezzine-de-Blas/CIRAD)

Given the low payment, however—€3/ha/year—there are doubts as to whether the programme can cover all affected forests and keep farmers in the project over the long term (Asquith et al. 2008). In order to foster the long term permanence of conservation, some PES schemes seek to influence farmland practices (Fig. 21.3). An example is the support of the City of Munich and European agricultural subsidies for farmers in Mangfall Valley to transform their intensive cropping into organic farming (Grolleau and McCann 2012). To solve the problems posed by the high nitrate and pesticide concentration in urban water, the City of Munich negotiated a series of economic incentives with farmers and offered technical support for them to convert their farming systems.

21.3.2 Involvement in Market-Oriented Institutional Arrangements

While the vast majority of national PES experiments or projects are funded out of national or local government budgets, specific taxes or funds from donors, PES can also be implemented through funding from market-based economic governance. Market-based institutional architecture and PES are nevertheless two different things (Fig. 21.4) (Karsenty and Ezzine-de-Blas 2014). That type of governance is mainly found in three cases: PES related to income from tourism, in the case of the voluntary carbon credit market, and PES funded through mitigation banks concerned with the issue of biodiversity conservation.

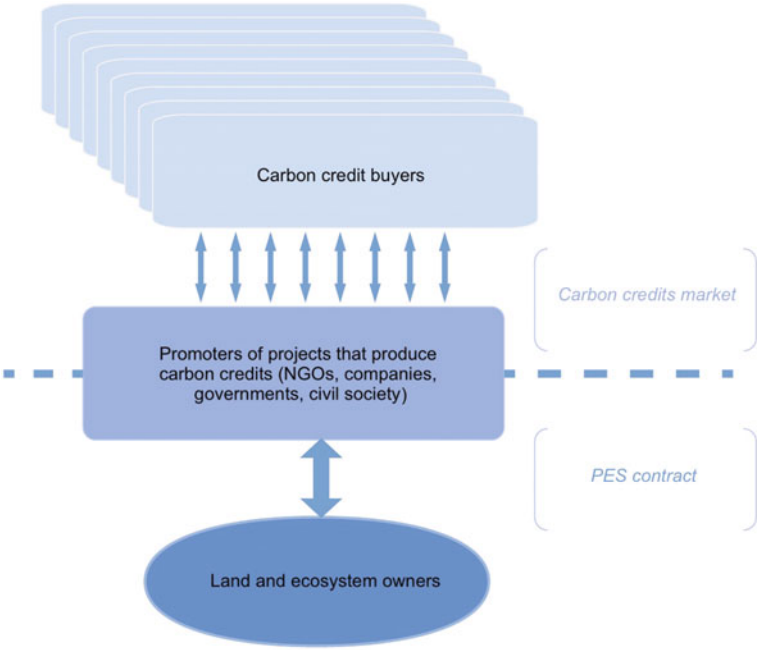

Fig. 21.4 Links and breakpoints between payments for environmental services and the institutional architecture for accessing offset rights, taking the example of carbon credits (adapted from Karsenty et al. 2014)

In the case of a PES scheme linked to tourism, like Zimbabwe's Campfire programme (Frost and Bond 2008), payments are made under an agreement between the village and a tour operator, who obtains the wherewithal for the PES through travel packages. Package costs may be a function of the number of animals seen, so there is competition to attract more tourists between the villages with the greatest biodiversity and the best marketers among the tour operators. Studies analysing the impact of these PES schemes show that while their environmental effectiveness is high, their replicablility is low, given the limited number of tourists in such a market and their unequal socioeconomic impact, which is a consequence of the uneven geographical distribution of wildlife.

The case of the carbon credit market is more complex. It should first be pointed out that many carbon capture policies are applied at the national level and do not involve REDD+. Such is the case of the Costa Rican example already cited and the Chinese Slope Land Conversion Programme (Xu et al. 2010). The REDD+ mechanism has its roots in the Kyoto Protocol, which, after 1997, introduced new market strategies to stop global warming, allowing exchange transactions in the area of emission reduction that involve the signatory States and the private sector. To achieve those goals, two so-called 'flexibility' mechanisms were instituted. One refers to 'joint implementation'. The so-called Annex I (developed and transitional) countries and the private sector engage in investment activities to reduce GHG emissions in the territory of other Annex I countries, and receive carbon credits in exchange. Through such projects, the transitional countries gain financial resources and access to environmentally friendly technologies. Another mechanism, known as the 'clean development mechanism', differs from the previous one in that it relates to investments made by developed countries in developing countries.

Both tools, which were supplemented as of 2007 by the REDD+ mechanism, still under discussion, are based on the crucial idea of carbon offsets, which assumes, among other things, sophisticated carbon accounting and an equally complex evaluation of 'carbon sinks'. The underlying principle of carbon offsets is that a given amount of GHG emitted in one place can be 'offset' by the reduction or sequestration of an equivalent amount of GHG in another. That principle of 'geographic neutrality' is at the heart of the mechanisms established by the Kyoto Protocol. It implies setting a price on carbon and putting pressure on the major greenhouse gas emitters so that eventually it becomes more cost-effective to reduce their own emissions than to buy carbon credits.

In addition to these mechanisms, 'voluntary offsets' are available to stakeholders not subject to the obligations of the Kyoto Protocol, such as communities, individuals or companies not subject to quotas. The offsets have been gradually developed by applying rules similar to those governing the Clean Development Mechanism. Voluntary offset certificates have been developed to attest to the compliance of such projects and ensure the reliability and credibility of the system and the carbon credits issued: the Verified Carbon Standard (VCS), Gold Standard, Climate, Community and Biodiversity Standard (CCBS) and Plan Vivo, among others. The principle of geographic neutrality affords a logical basis for a quantitatively measured voluntary offset system aimed at reducing, or at least not adding to, the amount of atmospheric carbon. In so doing, new markets and derived products can notionally be created to meet international commitments.

In the biodiversity sector too, offset schemes have been developed that are inspired by carbon offset mechanisms. However, biodiversity is more complex to measure than a tonne of carbon. Until the 1990s, environmental offsets consisted exclusively of compensation in kind—or custom, case-by-case compensation—in the form of restoration, rehabilitation, creation or preservation of damaged sites, for example through reforestation. The emergence of the biodiversity offset concept in political arenas marks a shift from regulatory offset mechanisms to two other offset schemes presented as market instruments (Hrabanski 2014). Financial compensation is one aspect of the offset schemes, whereby monies are paid to a third-party organization that will provide compensation in kind; the other aspect is the mitigation banks. The latter are a recent development whose purpose is to collect biodiversity units within an entity called a bank, thus acting as an intermediary between buyers and sellers of offset units (Lapeyre et al. 2014).

Such a scheme exists in Germany, where the mitigation banks are overwhelmingly (80 %) administered by the public sector. Their purpose is almost exclusively to offset damage caused by the implementation of municipalities' town planning. In contrast, when France created its first mitigation bank in 2008, the plan was for

CDC Biodiversité (a subsidiary of the *Caisse des Dépôts et Consignations*, created for the purpose) to acquire land or use public land for the optimum use of existing biodiversity (Froger et al. 2015). Hence, an offset proposition would be created whereby the project authorities could undertake a no-net-loss project. In that way, environmental policies would act to preserve what exists—flora, fauna and ecosystem services—but above all (and this is the chief innovation) to replace what would disappear as a result of actions considered to have priority for environmental protection. The scheme was put in place to cope with the potential demand for offsets in areas where pressure on biodiversity was expected to be high. Alongside these public mitigation banks there are private ones, as in the United States. Similarly, 'biobanking', established in 2007 in Australia, is a market system wherein owners wishing to generate biodiversity units (species and ecosystems) use a site called a 'biobank' that connects them to potential buyers of biodiversity units.

21.4 A Contribution to Climate Change Adaptation and Mitigation Policies

Payment for environmental services is an instrument whose primary purpose is to channel multiple stakeholders' efforts into financing and implementing an ecosystem protection scheme. That power of coordination and collective learning is emphasized by many authors and shows how PES can make users and suppliers of environmental services aware of the importance of optimal management of the natural resources they depend on (Muradian 2013). In that way, PES helps to enhance various stakeholders' adaptability by building their capacity for socioenvironmental action and innovation (van de Sand 2012). In addition, their environmental objectives relate to services that either directly promote climate change mitigation through the capture and reduction of carbon emissions, or have an indirect impact in that they improve the adaptability of ecological and human systems. It is clear that they foster adaptability, given the number of PES programmes that protect hydrological regulation and multifunctional agriculture, thus enhancing the resilience of those socioecosystems. This multiservice aspect of payments for environmental services makes them a central tool in climate change adaptation strategies.

However, PES has a number of economic and social drawbacks. At the economic level, its efficiency compared with other conservation and development instruments has yet to be demonstrated given the projects' very high start-up costs. There is also the problem of willingness to pay. For example, while the REDD+ initiative is being promoted by the programmes of several international institutions and tropical countries, China's Slope Land Conversion Programme alone (a reforestation programme) was able to mobilize more financial resources and restore more forest area than all REDD+ projects in the voluntary carbon credits market:

14 million hectares have been reforested[2] by the Chinese government, as against 3 million ha by REDD+ (Simonet and Seyller 2013).

As regards implementation, the environmental effectiveness of many PES schemes is impaired by lack of knowledge of the baseline or *status quo ante* of the service, of differentiated payments, and of whether cross-compliance principles (conditionality) have been respected (Ezzine-de-Blas et al. 2014). Similarly, significant problems of equity and environmental justice are emerging—several case studies have shown the difficulty of reconciling environmental efficiency with the fight against poverty (Narloch et al. 2011). Moreover, access to PES requires clear property rights, thus excluding resource-dependent people who lack such rights. Again, the use of economic incentives can lead to a rise in utilitarian values as opposed to altruistic values in the sphere of environmental protection (García et al. 2013). Finally, the question of the true opportunity costs arises when economic offsets only succeed in keeping rural populations in poverty (Ezzine-de-Blas et al. 2011). Opportunity costs to fight against vectors of ecosystem degradation can be much higher than project assessment costs (Gregersen et al. 2010).

21.5 Conclusion

Payment for environmental services is a new conservation tool that contributes to climate change mitigation and adaptation. Its implementation has shown that it can be adapted to various social contexts and promote new forms of coordination and collective action among stakeholders. The mainly public funding of PES schemes and their implementation contrast with the neoliberal discourse usually associated with them. By linking to existing (tourism) or emerging (carbon, biodiversity) governance institutions, such schemes can help give rural communities access to useful financing, to maintain or adopt legitimate practices and combat or adapt to climate change. Nevertheless, the problem of access to funds, as illustrated by REDD+ financing, confirms the limits of private funding in addressing environmental problems. PES schemes are useful and necessary adjuncts to climate change adaptation and mitigation strategies because of their positive socioenvironmental impact and the large geographic scope of their application. Finally, PES has a number of limitations inherent in its principles, for instance in terms of efficiency and—especially—equity, which would justify caution. However, its potential synergy with other policies—environmental, economic and social—to form a policy mix that can meet the challenges of climate change has yet to be explored.

[2]With a seedling survival rate ranging from 20 to 90 % (Xu et al. 2010).

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Chapter 22
Tackling the Climate Change Challenge: What Roles for Certification and Ecolabels?

Sylvaine Lemeilleur and Gaëlle Balineau

Abstract Certification and ecolabelling are forms of private governance meant to reflect sustainable development issues. These instruments encourage 'good' environmental and social practices, many of which are akin to climate change mitigation and adaptation approaches. To make it clear how effective they can be in that role, we present them here, recalling that they are at once standards for best practices, by definition supposed to inform and guide stakeholders' choices, and market incentives (bonuses, minimum prices, etc.) to change production practices. Despite their advantages, voluntary sustainability standards are proving to be ambiguous tools for meeting the challenges of climate change.

22.1 Background

Two types of actions are under way to manage risks associated with climate change: mitigation processes such as attempts to reduce world greenhouse gas (GHG) emissions, and adaptation processes to reduce the consequences of such changes and societies' vulnerability to them.

There are, however, many obstacles to the inclusion of market tools and binding legislation in the formulation of public climate change policies. The difficulty the international community is having in trying to reduce GHG emissions is a sign of the difficulty of taking effective, coordinated action in that area. GHG emissions, a major source of anthropogenic climate change, are considered by most economists

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to be negative externalities of human activity (Stern 2008),[1] whether in production, consumption or trade. On the assumption that markets can function perfectly, the tools available to internalize these externalities include the ‘polluter pays’ principle, i.e. taxing GHG emitters, creating a market for the right to pollute and hence setting a price for such rights, or, finally, regulation (via binding legislation). But those solutions are hard to implement, given that the problem is collective, i.e. subject to certain participants’ opportunism (free riding), and global, while jurisdictions remain national. Other difficulties arise from lingering uncertainties and information asymmetries, plus the fact that countries’ interests diverge according to their level of wealth and the structure of their economies (cf. the failure of negotiations on trade in environmental goods; Balineau and de Melo 2013).

In that context, ecolabelling and the associated certification processes emerge both as forms of private governance (standards, cognitive resources, information vectors, etc.) and as new types of market tool (premiums, minimum prices, long-term contracts, etc.) to address sustainable development and global environmental change issues. The main purpose of those instruments, which in this chapter we shall refer to as ‘voluntary sustainability standards’, is to promote ‘good’ environmental and social practices, without however diminishing yields or product quality, in order to spur sustainable development (Lemeilleur et al. 2014). A certain number of them are akin to climate change mitigation or adaptation approaches (soil cover, carbon sequestration, agroforestry, agroecology, etc.). Despite the extensive, mainly economic, literature on ecolabelling and certification aspects, few studies clearly raise the question of these tools’ ability to meet the specific challenges of climate change.[2]

This chapter contributes answers to that question by focusing on the essential points to be considered in discussing the importance of ecolabelling and environmental certification, and by presenting some recent research findings on those points. The first part shows how the practices required by voluntary sustainability standards may be akin to climate change mitigation or adaptation processes, by giving examples of the specifications of the main ecolabels available for two iconic production chains: cocoa and timber. The second part looks at how voluntary sustainability standards function and discusses how their criteria can meet the challenges of climate change. The conclusion provides some perspectives on broadening the scope of the standards towards the climate change challenge, and suggests avenues for future research.

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[1]“Greenhouse gas (GHG) emissions are externalities and represent the biggest market failure the world has seen” (Stern 2008).

[2]FAO’s reference book on climate-smart agriculture (FAO 2013), for example, contains only a few anecdotal references to voluntary sustainability standards.

22.2 Mitigation, Adaptation and Voluntary Sustainability Standards

The Standards Map database of the International Trade Centre (ITC, Geneva) lists over 130 voluntary sustainability standards, while the Ecolabel Index database lists more than 450 such approaches. In the agrifood sector, those standards, with which compliance is voluntary, often cover tropical products and have long been associated with a niche market of a few kilotonnes (e.g. organic farming). At the end of the 2000s, faced with recurrent criticism by environmental lobbies and the media, who accused them of destroying tropical forests and biodiversity and contributing to climate change, agrifood manufacturers gradually undertook sustainable production endeavours through certification and ecolabelling, which enabled them to display, literally as well as figuratively, their commitment to more sustainable development. Ecolabelling then underwent a shift towards 'mass certification' and involved many hundreds of kilotonnes of products on world markets (Daviron and Vagneron 2011).

These standards were promoted by agribusiness in partnership with international non-governmental organizations (NGOs), the goal being to promote sustainable development by implementing appropriate practices, some of which appear to be similar to those of climate change mitigation or adaptation.

We illustrate our point through a detailed analysis of the specifications of voluntary sustainability standards for timber (Fig. 22.1; Table 22.1) and cocoa (Fig. 22.2; Table 22.2). The choice of these two sectors is justified by the very important role of forests and agroforestry in terms of carbon sequestration, and hence reduction of global warming (forest management and soil cover), but also by the large number of ecolabels issued for their products, which allows comparisons to be made. Moreover, these ecolabels are often the business-to-consumer type, so they are visible to the consumer, the key player in that regard.[3] In the tables below, we list the names of the different ecolabels designed for each product and indicate whether mitigation or adaptation approaches are taken through a number of criteria, which are more fully elaborated in the text that follows.

An analysis of the specifications shows that, despite the many uncertainties that remain as to the dangers of any particular agricultural practice in terms of GHG emissions (Chap. 20), the standards for cocoa growing and forest management and harvesting do include criteria identified as mitigation criteria by research findings and IPCC. Those criteria are fourfold:

- With respect to the reduction of carbon emissions, IPCC recommends that deforestation be controlled, while preserving forest reserves and reforesting treeless farmland, as the conservation of carbon storage environments is a factor

[3]We chose not to include the major round tables on soybean (RTRS ecolabel) and palm oil (RSPO), because these, even though they explicitly reference climate requirements, remain chiefly at the business-to-business level. Furthermore, there are fewer ecolabels for such products.

Fig. 22.1 Forest prospectors at the foot of a rainforest giant (*Entandrophragma angolense*), Cameroon (© C. Doumenge/CIRAD)

Table 22.1 Timber ecolabels

Name	Dominant characteristic	Mitigation criteria?	Adaptation criteria?
Verified carbon standard	Environmental only, carbon offset	Yes	No
Climate, community and biodiversity standards	Environmental, carbon offset	Yes	Yes
PEFC international	Environmental	Yes	Yes
Forest stewardship council (FSC)	Environmental	Yes	Yes
Naturland	Environmental (organic)	Yes	Yes
Fair trade International—Hired Labour	Social, fair trade	Yes	Yes

Source L. Joanny, based on the Standards Map database (ITC)

in climate change mitigation. Several standards seek to achieve that result by specifying criteria such as ‘a minimum number of shade trees’ for cocoa, ‘a ban on logging in virgin forests’, ‘limited timbering’, and by encouraging ‘reforestation’;

Fig. 22.2 Cocoa pods after harvest and clubs to break the pods, Ecuador (© E. Cros/CIRAD)

Table 22.2 Cocoa ecolabels

Name	Dominant characteristic	Mitigation criteria?	Adaptation criteria?
GlobalGAP crops	Environmental	Yes	No
Unilever sustainable agriculture code	Environmental	Yes	Yes
SAI platform—farm sustainability assessment	Environmental	Yes	Yes
LEAF marque	Environmental	Yes	No
IFOAM standard	Environmental (organic)	Yes	Yes
Naturland	Environmental (organic)	Yes	Yes
Sustainable agriculture network—rainforest alliance	Socio environmental	Yes	Yes
Sustainably grown	Socio environmental	Yes	Yes
Bio équitable	Social, fair trade, organic	Yes	Yes
UTZ certified	Social	Yes	Yes
HAND in HAND fair trade Rapunzel	Social, fair trade, organic	Yes	Yes
Small producers symbol	Environmental, fair trade types	Yes	Yes
Fair trade	Social, fair trade	Yes	Yes
Fair trade International—Hired Labour	Social, fair trade	Yes	Yes

Source L. Joanny, based on the Standards Map database (ITC)

- With respect to chemical fertilizers, decreasing use will reduce indirect emissions caused by their manufacture and application, in particular through nitrous oxide emission from nitrogen fertilizers (Chap. 20). Almost all cocoa standards 'restrict the use of fertilizers and chemicals' or encourage their 'moderate' use;
- Regarding soil use and management, the standards' criteria call for 'erosion prevention', 'crop diversification', 'improvement of soil fertility', 'crop rotation', 'soil structure maintenance', 'prevention of soil compaction', 'reduced tillage' and 'soil cover'. Improvement of soil carbon storage is indeed a factor in climate change mitigation, which is achieved, among other things, through reduced tillage, maintenance of soil structure and aeration, and erosion reduction (Jastrow et al. 2007). IPCC also recommends crop rotation, agroforestry systems and the use of cover crops to reduce carbon dioxide emissions;
- As regards energy, the standards' criteria encourage 'control of energy consumption', 'energy efficiency' and 'renewable energy use' to reduce the use of fossil fuels, which are strong GHG emitters.

Hence, almost all sustainability standards contain measures for climate change mitigation or, more generally, limitation of the negative externalities of agricultural and forestry production. However, criteria that are akin to climate change adaptation, for example by addressing risk reduction or the vulnerability of exposed populations, are not included in all standards: while rare in predominantly environmental standards, particularly in terms of tolerable levels, they are recurrent in standards that mainly reflect social or fair trade concerns (Fairtrade, for example). Some examples of such criteria would be: 'guaranteed access to clean water, food and housing for resident employees' or measures such as 'social safety nets' for farm workers (minimum wage, access to health services, etc.), 'a long-term business relationship with producers', 'price commitment by both parties at the beginning of the season', 'a higher than market price', 'on-demand training', 'diversification of production and income sources', 'a fund supporting social and environmental projects in developing countries'.

Of course, the distinction between adaptation and mitigation criteria is not always meaningful or relevant. Thus, soil and forest protection will also reduce people's vulnerability to climatic events, which are increasing in frequency and intensity. In storms, for example, forests moderate the strength of winds and waves in coastal areas, soil protection limits the probability of landslides, etc. (Locatelli 2010). Conversely, voluntary sustainability standards that include training programmes or economic criteria like minimum prices, premiums for collective investments, long-term contracts, etc., thus improving producers' skills and economic situation, can enable those producers to make less environmentally harmful choices—for example, when they can afford to renew part of an ageing cocoa plantation instead of clearing new forest land.

In summary, the objectives of voluntary sustainability standards are fairly similar to those of climate change mitigation and adaptation. In the next section, in order to isolate three different ways in which the standards could help achieve those objectives, we present some recent findings about their effectiveness.

22.3 How Useful are Voluntary Sustainability Standards in the Context of Climate Change?

22.3.1 Ecolabels, Certification and Information Asymmetry

Certification and ecolabelling are primarily a means of correcting the information asymmetry between buyers and producers as regards the environmental quality of goods and services. Whether voluntary sustainability standards are able to effect changes in consumption and production behaviours by displaying the relevant information (e.g. a product's carbon footprint) will depend on their ability to produce and transmit information that buyers find credible on the way in which goods are produced and traded.

Balineau and Dufeu (2010) hold that there are two prerequisites for a label to succeed in gaining consumers' trust, and hence bring them to alter their consumption patterns: first, the standard behind the label must be trustworthy, i.e. must contain criteria of proven effectiveness in attaining the stated goal; second, the warranty system must be such that the label's presence on a product means the specifications have in fact been met. Only when both conditions are met can consumers have confidence in the ecolabelled products.

As regards the first prerequisite, Balineau and Dufeu (2010) point out that for certified goods whose production and trade standard is only a means of achieving a final objective, as in the case of 'best practices', consumer confidence depends on the existence of experts who can certify that the recommended practices are effective. The problem with climate change, as is pointed out by Bessou et al. (Chap. 20), is that experts sometimes cannot determine whether a particular practice is better or worse than another. In other words, the situation is one not of information asymmetry between consumers and producers, but of shared uncertainty, which no standard can by itself dispel—except by creating the conditions for shared reflection and creation of knowledge (see below, "Labels as non-market tools").

With respect to the second prerequisite, labels generally implement one of the following two warranty systems (Steinrucken and Jaenichen 2007): either a first- or second-party certification system (also called 'self-declaration' or 'peer control'), whose credibility depends on the parties' individual (first case) or collective (second case) reputation; or a system of certification by a third party, i.e. an independent, accredited certifying organization. The theoretical literature (Engel 2006; Strausz 2005) holds that such mechanisms' reliability depends on several parameters: in the first case, the risk of detection in the event of fraud (by consumers' associations or the press, for example); in the second, the credibility of the accreditation agency (often guaranteed by government).

22.3.2 *Standards as Market Instruments: Can Production Activity Externalities Be Internalized Through Labelling?*

The current exponential growth of ecolabelling attests to a degree of consumer willingness to pay for goods that contribute to sustainable development. That willingness encourages producers to consider the environmental objectives mediated by the ecolabels (better income, guaranteed market access, training, premiums, etc.) and change their production practices accordingly (Balineau 2013; Weber 2012). However, doubts remain as to whether this buy-in will last (Lemeilleur et al. 2013): if the market for the ecolabel in question were to disappear, would producers continue to implement more environmentally friendly practices? That is an important question, for two reasons: First, the economic model underlying some ecolabels is based on the assumption that the adoption of best practices mainly depends on a learning curve and start-up costs, which a temporary certification can finance (such was the foundational idea of fair trade, cf. Daviron and Vagneron 2011). Second, worldwide competition between labels and designations of origin implies that producers may cease to benefit from label incentives after a few years, so it is crucial that the learning effects remain.

Again, voluntary sustainability standards may have many adverse effects—from an environmental point of view, but also as regards inequalities. We shall cite two examples. First, unlike payments for environmental services, where the payment is independent of the quantity produced, since the environmental service is the focus of the contract, the financial incentive received by a certified producer applies per unit sold. That mode of payment may automatically encourage certified producers to produce more (Lemeilleur and Carimentrand 2014) or to specialize. There is a high risk that producers will be nudged into single crop specialization since sustainability standards often focus on a single farm product. That production channel is of course regulated by the specifications for a given farm, but standards provide no regulation at a more global scale, and lack any concept of equilibrium or of a systemic approach across an entire territory, watershed or ecosystem.

Second, the cost of certification is significant, as many employees are needed to handle all the information. Hence, producers unable to pay the cost are shut out (Vorley and Fox 2004) and, therefore, the absence of ecolabelling on a given product does not mean it has not also been produced using sustainable practices (Lemeilleur and Allaire 2014). Unequal access to quality marking through certification casts serious doubt on the arguments for certification's effectiveness that cite its ability to correct information asymmetry and thus promote good environmental practices.

22.3.3 Non-market Aspects of Standards

The processes of developing and implementing voluntary sustainability standards also have non-market aspects that are also intended to promote and encourage sustainable development.

Indeed, one of the first prerequisites for the success of ecolabelling is for consumers to be aware of the issues related to climate change and actually realize the benefits of forest conservation, for example, and so be willing to pay a higher price (Podhorsky 2008). In that sense, labels, taken as a whole, help fulfil this first prerequisite. Most organizations that issue labels do indeed conduct communications campaigns to increase consumer awareness of the challenges of responsible consumption. Of course, the risk is that this dual role of judge and jury—as some NGOs are paid based on product sales made under their seal—will discredit the process (Balineau and Dufeu 2010). In any event, standards primarily govern good production practices and, as indicated above, can really only guarantee what methods are used, not whether a good result can be achieved, nor of course the result itself. The objectives of the standard and the methods formalized in the specifications are linked by a subjective belief, supported by a representation or doctrine of what constitutes ‘quality’ (Lemeilleur and Allaire 2014). For example, a standard indicating a certain maximum level of nitrogen fertilizer implies that a causal link has been established between that threshold of nitrogen fertilizer application, air quality (via nitrous oxide emissions) and global warming, all of which is debatable.

In that context, the government (or any other public stakeholder, including researchers) may have a role to play in providing a public good such as information about the various voluntary certification processes, climate change issues, and the ability or inability of such processes to meet the challenges (or the state of research findings).

A final note, nevertheless: by their nature, the application of sustainability standards can have a paralysing effect on agricultural practices. Standards are monolithic, excluding everything that deviates from their standardization and pre-sets (Citton 2013), so they run counter to farmers’ capacity for innovation and may thwart or even eliminate that family farming feature (Lemeilleur et al. 2014), all the more so when smallholders who do not comply with the protocol are also excluded from the overall market (Carimentrand 2009; Lemeilleur 2013). And yet the spirit of innovation shown by family farms is essential in dealing with the consequences of climate change. By limiting it, sustainable label specifications may simply be damping down family farms’ resilience in the face of climate change. In the long run, it is hard to imagine how the universalizing, homogenizing tenor of such systems, which overlook the diverse range of contexts, can help meet the challenges of global environmental change, which is spatiotemporally complex and variable.

22.4 Conclusion and Outlook

Climate change mitigation and adaptation practices are intrinsically linked to sustainable development practices: for example, the ability for people to have long-term, diversified livelihoods and natural resources seems indispensable if they are also to cope with the challenges of climate change. Voluntary sustainability standards, whose primary purpose is to support sustainable development endeavours, may therefore have a role in such global environmental change.

Nevertheless, these tools have a number of operational limitations that may cast doubt on their ability to meet the challenges of climate change. In the first place, both labels and environmental agreements are only tools, and cannot resolve the fundamental uncertainties as to the best practices to be adopted to mitigate climate change and adapt to its effects—their role in consumer awareness is therefore limited. Secondly, the compensation mode, based on a premium per unit sold, may automatically encourage certified producers to produce greater quantities or to specialize at their own farm level. Such an incentive to intensify production, even in an environmentally friendly way, ignores any effects at the level of ecosystems or entire territories and so may—paradoxically—defeat the purpose, whether that be sustainable development, mitigation or adaptation to climate change. Finally, the lack of flexibility and adaptability of these transnational standards is a serious impediment to any effort to cope with the rapid shifts in climate change patterns.

Beyond the research on best practices, which offers immense promise, new questions are appearing:

- How much demand is there among consumers in developing countries for endeavours such as these, and what warranty systems would they find trustworthy? Could we conceive of more localized standards, suited to different contexts, more scalable, and less monolithic?
- Some voluntary sustainability standards are evolving towards the adoption of a territorial approach or, more generally, a more integrated one. These trends offer some interesting pointers toward better mitigation (avoiding pollution transfer) and greater reduction of populations' vulnerability. But will consumers be willing to pay for that kind of approach (e.g. a producers' insurance fund or initiatives to enhance a whole territory, not just a product)?
- What role would development assistance stakeholders then play in taking advantage of this willingness to pay?

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Chapter 23
Climate Policy Assessment on Global and National Scales

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Abstract The term 'climate policy' covers both policies to reduce greenhouse gas emissions (called mitigation) and policies to adapt to climate change (adaptation). Current literature on climate policy assessment essentially consists of ex ante assessments of mitigation policies, using more or less sophisticated economic models. Adaptation studies, while still very much in the minority, are becoming more frequent. The growing number of climate policies being implemented in different countries throughout the world should lead to a proliferation of ex post assessments in the coming years.

23.1 From Climate Policy to Integration of Climate Issues into 'Non-climate' Policies

The term 'climate policy' refers to all public policies designed to limit the effects of global warming. A distinction is drawn between mitigation policies, aimed at reducing greenhouse gas (GHG) emissions, and adaptation policies, which seek to limit the negative impacts of climate change on human societies (or even, in some cases, to take advantage of possible beneficial effects), whether the impacts are already present or, more often, only anticipated.

Because GHGs are generated in virtually all areas of activity, mitigation covers a wide variety of actions, ranging for instance from fossil fuel taxation, to reduction of fugitive emissions of natural gas or methane capture from landfills, to the fight against deforestation.

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Similarly, adaptation covers a broad range of actions: for instance from the abandonment of spruce—which is heat-intolerant—in lowland areas of Western Europe, to infrastructure upgrades in areas likely to be affected by major floods or the development of climate insurance mechanisms, to dyke-building to protect coastal areas threatened by rising sea levels.[1]

Whether they focus on mitigation or adaptation, climate policies typically have other consequences than just control of the greenhouse effect. For example, replacement of coal-fired electric plants with gas-fired plants or with renewable energy generation will limit GHG emissions, but will also tend to reduce fine-particle emissions, benefiting health. Similarly, a policy favouring urban public transit at the expense of cars is likely to reduce GHG emissions (if emissions from public transit are less per passenger-kilometre) while potentially helping to reduce traffic congestion. These non-climatic effects of climate policies are referred to in the literature as 'co-benefits', when they benefit human societies, and as 'adverse side-effects' when they are detrimental.[2] As will be seen, integrating co-benefits and adverse effects into climate policy assessment is a major challenge.

Climate policies, however, are only part of the toolbox available to governments to combat climate change, for they are defined as policies intended—by implication, primarily—to combat climate change. Speaking of *co*-benefits clearly emphasizes that implicit hierarchy of objectives.

However, there are many examples of public policies whose primary purpose is clearly not to combat climate change but which nevertheless have significant effects on emissions and/or on adaptive capacity. Town planning is a good example. Because they structure urban space, town planning policies play a key role in determining transport needs for households and businesses, and hence GHG emissions, and yet economic (property tax, construction financing, etc.) and social considerations (access to housing, risks of segregation, etc.) are most often their priority.

The distinction between climate policies and those whose main objective is not to combat climate change (referred to herein, for want of a better name, as non-climate policies) may appear purely rhetorical, but the distinction is an important one in the public climate change debate. Focusing the debate on climate policies alone tends to put the spotlight on very specific forms of public action, such as carbon taxes, markets for tradable emission permits, or the creation of dedicated

[1]In the recent IPCC assessment report the reader will find a detailed discussion, sector by sector and region by region, of the various options available for adaptation and mitigation (Field et al. 2014, for adaptation, Edenhofer et al. 2014 for mitigation).

[2]This terminology, taken from the last IPCC report (Edenhofer et al. 2014) is far from definitive. The terms 'ancillary benefits' or 'indirect benefits' (among others) are also used. Ürge-Vorsatz et al. (2014) contains a rundown of the various terms.

Fig. 23.1 Diversification of rural families' activities: community bread production in Kisalaya, Nicaragua (© S. Fréguin, CIRAD)

funds (for adaptation or mitigation), etc. Conversely, anything that makes for better integration of the climate issue into 'non-climate' policies is overshadowed.

Yet non-climate policies have a decisive effect on a large share of all GHG emissions and the ability to adapt to them. Hence, for ambitious anti-climate-change objectives to be attained, such policies must take account of the climate issue (Hourcade and Shukla 2013). For example, adapting a country highly dependent on agriculture to climate change may involve diversification of activities in rural areas to non-agriculture sectors (Fig. 23.1) or population migration away from the areas potentially most affected. Adaptation in that case goes well beyond climate policy at the margin (such as installing air conditioners) and necessitates a review of development strategies. The same reasoning applies to mitigation.

In what follows, we shall begin by discussing climate policy assessment, then focus on the specific problems posed by the integration of climate issues into policies whose primary objectives lie elsewhere.

23.2 Assessing the Value of Climate Policies: The ‘Cost-Benefit’ Approach

In evaluating climate policies, the first question is, “are they worth the effort?” In other words, are the constraints the policies impose (e.g. rising energy prices, in the case of a carbon tax) offset by the benefits they confer: less climate change, so less impact to be mitigated and fewer negative consequences for human societies to adapt to?[3]

That is a very tough question, as the constraints imposed and benefits conferred by climate policies must be simultaneously and consistently evaluated, but responsibility for the evaluation of each lies with different disciplines and bodies of knowledge (roughly, IPCC groups III and II, respectively; Edenhofer et al. 2014; Field et al. 2014), which are not easily reconciled. The benefit aspect, in particular, is still particularly hard to grasp.[4] Of course, information on the impacts—and therefore on those that may be avoided under a given climate policy—can always be supplied, but incorporating that information into a cost-benefit assessment on climate policy will require significant investment.

The first cost-benefit analyses to emerge circumvented the difficulty by using very compact models (see the seminal paper by Nordhaus 1992) that represented the impacts in simple functional forms with few parameters. A wide range of possible visions of impacts can be easily explored using such models. A second series of studies, such as Stern’s (Stern 2007), depend instead on detailed models of the Earth system, in which the impacts are better represented than in aggregated models (i.e. more processes are captured), but not well enough as to dispel all uncertainty.

The cost-benefit studies available to date lead to very different recommendations. Some take a ‘wait-and-see’ approach, advocating that GHG emission limits be phased in, while others call for an immediate, all-out attack. The differences are of course due to different visions of climate change impacts,[5] but also varying degrees of optimism regarding technological progress or societies’ capacity to change their lifestyles and consumption patterns.[6]

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[3]When the difference between benefits and costs can be measured, a subsidiary issue is the search for the ‘best’ climate policy options, that is, those that maximize that difference.

[4]The way in which the climate will change in a given emissions scenario remains uncertain—the more so the lower we go in the geographic scale. Also, the way the major biogeophysical cycles (the water cycle, for example) and ecosystems respond to climate change is still poorly known. And lastly, the impact the changes will have on societies will depend on their lifestyles, their wealth, their knowledge, etc. All of these parameters are difficult to predict in the long term.

[5]In particular the presence or absence of non-linearities (Ambrosi et al. 2003).

[6]Part of the debate centres on the relative weight to be assigned, in economic calculations, to future cash flows relative to present cash flows, a parameter called the ‘discount rate’ (see e.g. Heal 2009).

As all of the parameters are so uncertain, it is an illusion to suppose that cost-benefit analyses can help to identify 'the' right policy. Crucially, however, they already inform the debate by elucidating the conditions under which a given climate policy can actually be 'worth it' (Perrissin-Fabert et al. 2012).

23.3 Assessing Climate Policy Effectiveness: The 'Cost-Effectiveness' Approach

The difficulty of simultaneously evaluating the constraints and benefits associated with a given policy is so great that much of the literature on climate policy assessment focuses on a simpler question. Given a certain mitigation or adaptation objective, expressed in physical units—for example, to reduce GHG emissions by a million tonnes, or to guarantee a coastal town's inhabitants a constant risk of flooding despite the foreseeable rise in sea level—what is the least constraining policy to achieve it?

The cost-effectiveness approach is less demanding than the cost-benefit approach, since benefits (in other words, the climate change impacts obviated by the policy) need no longer be evaluated. Conversely, it tells us nothing whatsoever about the policy's social value. For instance, a cost-effectiveness analysis can reveal the least expensive way to reduce a country's emissions by 50 % by 2050, but it cannot tell us whether 50 % is too ambitious or too timid.

That is not to say a cost-effectiveness evaluation is easy; quite the reverse. The consequences of climate policies for the economy and society are inherently difficult to assess. A carbon tax, for example, will tend to drive up the price of energy and energy-intensive goods. Companies will respond by adapting their production processes to give more weight to other factors (e.g. labour), and households will shift, at least in part, to goods and services with lower carbon content. Imports and exports will be affected, more so if the tax is not simultaneously levied by the country's trading partners. Domestic firms may become less competitive as a result. And so on. Anticipating the final result of these interactions requires sophisticated tools that are still far from being scientifically stabilized (Box 23.1).

Cost-effectiveness evaluations for mitigation policies may, as a first approximation, be sorted into two broad categories. The first chiefly seeks to cost out mitigation objectives at the global level, and in particular—in recent times—to determine how to keep the average temperature at the Earth's surface from increasing by more than 2 °C relative to preindustrial times, at the lowest possible cost. Mitigation policies are represented in a fairly crude way, such as a carbon tax differentiated by major region of the world, possibly combined with different measures of support for clean technologies. That kind of study, summarized in Chap. 6 of Edenhofer et al. (2014), concludes in particular that the +2 °C goal is still achievable, and relatively affordable, always provided there are very large tracts of land available to sequester carbon in biomass or to generate carbon-negative

Fig. 23.2 Okoume logging in a natural rainforest in Gabon. What climate policies can move forestry toward mitigation? (© D. Louppe/CIRAD)

bioenergy,[7] and subject to far-reaching assumptions on the functioning of the economic system.

A second strand of the literature evaluates the cost of emission reduction sector by sector, based mainly on sectoral techno-economic models. That work can of course not be reviewed here, but summaries can be found in Chaps. 7–12 of Edenhofer et al. (2014). As regards only agriculture, forestry and other types of land use, IPCC summarizes the literature by pointing out that the least costly mitigation options, on average, at the global level, are: in forestry, reduced deforestation and forest management (Fig. 23.2); and in agriculture, crop and grazing management and soil restoration (with higher avoided emissions costs). The report also notes that changes in diet and lower losses in the food production chain may have great potential, but little investigation has been done in that area.

[7]I.e., first- or second-generation fuels coupled with sequestration of CO_2 emissions from combustion.

Box 23.1. On the cost of emission reduction, mitigation policies' main indicator for cost-effectiveness evaluations.

Cost-effectiveness evaluations of mitigation policies generally result in a mitigation cost, expressed as so many monetary units per tonne of avoided carbon dioxide (CO_2) emissions (e.g. €/t CO_2). That unit cost is calculated as the ratio between the total cost produced by the policy—with respect to a so-called 'baseline' situation wherein the policy would not have been adopted, all else being equal—and the volume of emissions not emitted because of the policy.[8]

It is therefore an average. In one sense, it is averaged over time, since the calculation shows the costs (numerator) and the emission reductions (denominator) throughout the public policy's validity period. In other words, two policies with the same emission reduction cost can actually have very different temporal profiles. In another sense, it is a spatial average. For instance, a grant for the installation of small run-of-river turbines may be expected to spawn many projects, whose costs (relative to avoided emissions) are by no means necessarily equal (the watercourses being more or less suitable, the flow more or less regular, etc.). Such differences are glossed over by the average cost. In particular, it is often useful to know the marginal cost as well, that is, the cost of the most expensive installed turbine.

The exact meaning of the numerator in the ratio also needs to be clarified. In some analyses, it is the engineering cost associated with the policy, in others a sectoral cost, and in still others a so-called 'macroeconomic' cost—all of which differ in scope and in the way they are calculated.

Engineering costs are direct costs associated with the emission reduction operations triggered by the policy. Take, for example, a policy that promotes renewable energy and entails the construction of new wind farms in a country that generates its electricity from coal. The associated 'engineering cost' is the difference between a wind farm's total cost (investment, operation and maintenance) and the total cost of a coal-fired plant with equivalent characteristics (capacity, service life, etc.).

Sectoral costs comprise, in addition to the direct costs, the costs (or profits) for the various stakeholders in the economic sector concerned. Thus, paying forest owners for the carbon sequestered by their trees is likely to result in longer rotations, with a direct cost to the owners that can be estimated. But, by reducing the timber supply, this policy will impact prices, and hence the different stakeholders in the supply chain (traders, primary and secondary processing) and the end consumer. The sum of the costs for each stakeholder constitutes the sectoral cost.

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[8]If the policy reduces emissions of gases other than CO_2, a conventional 'exchange rate' is used (the global warming potential of the gas over 100 years according to the United Nations Framework Convention on Climate Change) to express the reduction as tonnes CO_2 equivalent (denoted t CO_2-eq). For example, emission of 1 t of methane 'equals' 23 t of CO_2.

The macroeconomic cost, meanwhile, covers the impact of the policy at the macroeconomic level (change in GDP, unemployment rate, etc.). It is estimated using dedicated models, which present the savings in a highly aggregated manner. The value of that level of analysis is that it seeks to capture economic feedback that may be very important to the evaluation—for example, the effect of a carbon tax on income or on the balance of trade—but which a sectoral analysis (and a fortiori an engineering analysis) will miss.

The three levels are not equivalent, even when expressed in the same currency. Great care is needed, then, in comparing emission reduction costs one to one. Neither is there any clear hierarchy between studies at each level. Macroeconomic assessments may appear more complete at first glance, since they summarize the impact of public policy on the overall economy (not just one sector). However, they reflect a very coarse view of the technology and the associated constraints—an area where techno-economic and sectoral models are much more useful. Further, the available macroeconomic models often assume that the economic system runs very smoothly (agents make correct predictions, markets work properly, prices adjust quickly, etc.), so comparisons between these tools are misleading to say the least.[9]

23.4 Evaluation of Co-benefits and Adverse Side-Effects

One of the major innovations in the literature over the last 10 years has been a much more detailed examination of climate policies' co-benefits and adverse side-effects. A detailed summary will be found in each sectoral chapter of Edenhofer et al. (2014).

However, integrating co-benefits into climate policy assessment raises difficult problems, the most serious one, in practice, being the lack of measurements. In most studies, climate policies' consequences in dimensions other than the purely climatic are ignored. To gauge those consequences would require specific studies, costly to undertake and therefore generally omitted. For example, few evaluations of biomass energy deployment policies seriously assess their implications for biodiversity.

In the recent literature, however, climate policies are more and more frequently assessed in several dimensions, either through a combination of separate studies, or

[9]Techno-economic models have often been termed more 'optimistic' in that they produce emission reduction costs that are lower than in macroeconomic models. Ongoing research is trying to reduce the disparity between the two families of models, in particular by producing so-called 'hybrid' models that contain a general representation of the economy, but retain a somewhat detailed representation of the technical system and less-than-totally-smooth functioning of the economy (Hourcade et al. 2006).

because some of the assessment models mentioned above integrate modules on, for example, local pollution or inequalities. The implications of policy choices for climate and any co-benefits or adverse side-effects are typically evaluated separately, in physical terms. For example, an epidemiological model is used to estimate the number of days of sick leave that are likely to be gained if coal-fired power plants are replaced with renewable-energy power plants. Thus, the evaluation uses a number of criteria.

The next step is to determine the total net cost of the policy by integrating direct costs, co-benefits and adverse side-effects into a common metric. For example, can a local pollution reduction achieved by a breakthrough in renewable energy at the expense of coal offset the policy's economic cost, perhaps in terms of higher energy prices, producing an economic downturn?

That stage is conceptually more difficult. On the one hand, a physical reduction, e.g. of local pollution, does not necessarily correspond to an economic benefit. If pollution is already very low, the cost of additional pollution reduction for companies and households may be incommensurate with the public health benefits. On the other hand, the fact that a given climate policy produces a co-benefit does not mean that a different climate policy, with a specific policy on that co-benefit, would not be more effective.

23.5 Outlook

In general, when we speak of assessment of public policies, we mean ex post assessment. In the case of climate change, as we saw above, the assessment exercises have mostly been conducted ex ante, for the simple reason that few climate policies have so far been implemented in the world, or in any case not long enough for an ex post assessment to be relevant. That situation should gradually change as public policies to limit the impacts of climate change become more common.

Then, too, most studies focus on evaluating mitigation policies; those that deal with adaptation are very much in the minority. That imbalance is due to a much better developed base of tools and models for mitigation than for adaptation (climate policy assessment in particular being based on all the tools developed to assess energy policies since the first oil shock), but also to the greater attention paid to mitigation by the international community during the 1990s and much of the early 2000s. In that area too the balance is being redressed—because tools to evaluate impacts and adaptation are rapidly being developed, but also because of a realization that even if mitigation policies are a success, the scale of climate change will be so great that significant adaptation action will be required.[10]

[10]Moreover, mitigation and adaptation are often linked, for example in the field of agriculture and forestry.

Climate policies are only one aspect of the tools available to governments to combat climate change. The challenge is also (or mainly?) to take the climate issue into account in integrated policies whose goals are (primarily) of a different order. In that case, assessment becomes more delicate, since what it really amounts to is comparing a number of development trajectories of a whole system (a city, a national economy, etc.) using a multicriterion analysis—one of the criteria being GHG emissions or climate change vulnerability. Comparing widely varying future states presents economic analysis with methodological problems that have as yet no solution. There are, however, attempts at integrated analyses, for instance at the city level (see in particular Chap. 12 of Edenhofer et al. 2014).

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Part IV
Looking Ahead

Chapter 24
What About Climate-Smart Agriculture?

José Tissier and Jean-Yves Grosclaude

Abstract Climate-smart agriculture seeks to simultaneously address the three major challenges of food security, adaptation to climate change and climate change mitigation. The authors question the usefulness of this new concept, which FAO and other institutions have been championing since 2009. Its main value does not lie so much in its originality or theoretical relevance as in the fact that, since it has enjoyed a certain vogue on the international stage, it offers a locus for discussion of global public policies, taking in not just the food security and climate challenges, but also those of employment and biodiversity. There are a number of points—importance of family agriculture, role of professional agricultural organizations, relevance of agroecology, integration of biodiversity, funding arrangements, etc.—that still need to be discussed in order to enrich the climate-smart agriculture concept. The recently established international alliance for climate-smart agriculture may also present an opportunity to facilitate consideration of issues relating to agriculture in the broader sense in international climate negotiations. A concrete proposal for development of a mechanism to achieve 'resilience and reduced emissions in rural areas' is put forward at the end of the article. It could help support the ecological transition of family farming to climate-smart agriculture in pilot rural areas.

24.1 Background

The international community has progressively adopted numerous institutions to help meet the major challenges facing world agriculture. In addition to FAO, which maintains a careful daily watch on agricultural issues, including food security, the

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Committee on World Food Security has since 2009 been reporting directly to the United Nations General Assembly. Among its members is a panel of high-level experts, set up on the Intergovernmental Panel on Climate Change (IPCC) model, which examines all major issues connected with agriculture, such as access to land and other natural resources (water, biodiversity, etc.), maintenance of a sustainably healthy environment for humans, climate change and its interactions with agriculture, world poverty, and wealth and job creation.

24.2 What Does the Climate-Smart Agriculture Concept Contribute?

Climate-smart agriculture (CSA) combines two key concerns of the international community as the century begins, namely food security and climate. But is this just the latest pointless gesture of the aid for development community, so quick to create new fashions to justify their existence and land on their feet? Or could it be a major conceptual shift in the theory of development? That will be the focus of our discussion here, based on the following FAO definition: climate-smart agriculture comprises three pillars: food security (production), adaptation to climate change (or the resilience of agriculture to climate disruption) and climate change mitigation (emission reduction or carbon storage).

The initial goal appears laudable, as the issue of food security and agricultural productivity needs to be integrated into public climate policies from the outset, while recognizing the need for tradeoffs between the various objectives in some situations. Climate-smart agriculture is designed as a flexible, iterative process, to be implemented in an uncertain environment. Its goal is to precisely identify, then mobilize, the various stakeholders (farmers, scientists, policymakers, etc.), to decide on the actions to be taken, define public support policies and provide the necessary funding, in line with research results, but also with the knowledge of practitioners.

Climate-smart agriculture emphasizes context and the need to find solutions that consider both the multiplicity of objectives (in terms of production, social well-being, environmental quality, and climate change adaptation and mitigation) and ecosystem diversity in a given territory.

Finally, climate-smart agriculture highlights the multifunctionality of agriculture. Such things as employment or the provision of environmental services—carbon sequestration in soil, improving groundwater quality, etc.—are analysed rather as expected products of farming activity than as constraints.

The focus on a systemic approach is not innovative, but is a positive development. The integration of production systems—agriculture and livestock, agroforestry, fish and rice, for example—makes it possible to take advantage of the different functionalities of agroecosystems and uncover valuable synergies.

Climate-smart agriculture is implemented within a defined territory, with well-defined public support policies. Interestingly, the 'landscape approach' presented in the FAO CSA Sourcebook (FAO 2013) goes beyond the classical landscape approach, which focuses exclusively on biophysical factors (climate/soil/plant communities), becoming more akin to the territorial approach (Caron 2005), which includes issues of governance, regulation and the actions of stakeholders and institutions.

In climate-smart agriculture, farmers are an integral part of the private sector. Moreover, the reference to the Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests (FAO 2013) is reassuring insofar as it points up the need for securing farmers' access to land lest it be massively bought up by national and international investors, with the attendant risk of social exclusion.

Advocates of climate-smart agriculture consider trade a key factor in food system resilience, as it will offset any shortfalls in physical production caused by the effects of climate change in a given part of the world. However, they do recognize that international trade may also be a risk factor. They do not directly incriminate the increasing liberalization of international agricultural trade, which foments direct competition between agricultural economies very unequally endowed with production factors. They do however observe that a country's excessive dependence on the international foodstuffs market can lead to major food crises, with a particularly severe impact on the poorest.

Climate-smart agriculture is relevant to all of the world's countries, but they are not all on the same page with respect to the challenges to be met—a country's developmental level necessarily affects its approach. Climate-smart agriculture's designers realize that developing countries do not always have the requisite financial or human resources to devise integrated public policies that are developed and implemented in cooperation with all stakeholders. Threatened as they generally are by climate change, and concerned with food security and development, developing countries are the primary focus of climate-smart agriculture, which seeks to build their capacities and in particular those of their agriculture ministries, to enable them to engage in ongoing negotiations under the United Nations Framework Convention on Climate Change.

Thus, while not conceptually innovative, the climate-smart agriculture concept does shed light on a number of important development principles and may help elucidate the complex interactions between agriculture, food, markets and climate. But its greatest merit lies elsewhere. The international community has embraced the concept, particularly in African countries (*Alliance pour la coordination et la convergence des interventions de l'agriculture climato-intelligente en Afrique de l'Ouest*) and in Asia (Climate Smart Agriculture Learning Platform for South Asia), and a very broad alliance[1] has been formed to promote it. These developments afford an opportunity to go beyond the initial objectives and provide a forum for

[1]Global Alliance for Climate Smart Agriculture (GACSA).

debate, not so much on agricultural policies in the narrow sense as on global public policy (Box 24.1), which must meet not just the food security and climate challenges, but also those of employment and biodiversity.

Box 24.1. Initial feedback and advocacy in West Africa.
FAO's Economics and Policy Innovations for Climate-Smart Agriculture (EPIC) programme's endeavours in Malawi, Vietnam and Zambia have shown that some farmers are struggling to adopt the technical proposals of climate-smart agriculture. To cope with those challenges, FAO has identified five stages in the development of a climate-smart agricultural strategy:

- assess the situation and identify climatically appropriate agricultural practices;
- understand the obstacles hampering the adoption of climate-smart agricultural practices;
- establish coherent policies through a process of consultation with stakeholders and rigorous analysis;
- manage climate-related risks;
- direct investments based on the results of the previous stages.

Although Africa contributes only 4 % of the world's GHG emissions, the New Partnership for Africa's Development (NEPAD) has begun adopting the climate-smart agriculture concept. In the Economic Community of West African States (ECOWAS), for example, political leaders are concerned with deforestation, degradation and land-use changes. Though it has some questions about the content of climate-smart agriculture, ECOWAS wants to do more than apply adaptation techniques at the plot level; it would like to see more comprehensive adaptation approaches with defined deadlines. At the country level, implementation of climate-smart agriculture presupposes firmer links between research, producer organizations, decentralized State services and local communities. The latter, in particular, must be strongly mobilized in a decentralization context.

Similarly, ECOWAS considers that climate change adaptation is impossible without the effective involvement of non-State stakeholders (professional organizations, civil society organizations, private sector, etc.), and has decided, accordingly, to integrate climate-smart agriculture into its common agricultural policy, the regional expression of NEPAD's Comprehensive Africa Agriculture Development Programme (CAADP). That policy is based on national and regional agricultural investment programmes and, because of the interdependence of sectoral policies, is complementary to and coordinated with the National Adaptation Programmes of Action (NAPAs).

ECOWAS has appealed to regional and international organizations working in the region to take part in an alliance for the coordination and convergence of climate-smart agriculture actions in West Africa.

24.3 More Work Needed on Certain Important Issues

Some proposals in the FAO publication, however, seem inadequate or even questionable, if the goal is to specify the economic stakeholders to be relied upon and the agricultural production modes to be promoted.

In the 'land sharing' versus 'land sparing' debate (Figs. 24.1 and 24.2), the FAO document seems to clearly favour the latter approach.

That debate essentially relates to the issue of biodiversity rather than climate. Land sharing refers to extensive agriculture, richer in biodiversity but occupying more space, and land sparing to a more intensive approach, leaving more room for natural areas. In climate terms, the land sparing approach means reducing GHG emissions per unit produced, implying more intense cultivation of a given area, and hence the need for a high volume of external inputs. At the whole territory level, this approach would keep a larger area free of all agricultural activity and, because biodiversity-rich natural areas would be preserved, would tend to maximize ecosystem services within the territory. Conversely, the land sharing approach tends to reduce overall GHG emissions by increasing ecosystem service production on all lands (agricultural and other), even if reduced input use on intensively cultivated

Fig. 24.1 An agrarian landscape in a hilly region of Vietnam: tea, rice fields, eucalyptus trees and areas of natural vegetation, illustrating the land sharing approach. Phu Tho Province, North Vietnam (© V. Porphyre/CIRAD)

Fig. 24.2 Field cropping of rice and spray boom, illustrating the land sparing approach, Brazil (© B. Courtois/CIRAD)

land leads to less gross yield per unit area and ultimately to more farmland in the territory.

While in some situations the land sparing approach can save natural areas—if not taken over by other activities (mining, etc.)—and so afford environmental co-benefits, that is not universally true. Each country's developmental level must be considered—particularly as regards land use—as well as its place in international trade. In a country where most natural arable land is in use, reducing GHG emissions from farmland makes good sense. Conversely, in countries where there is still undeveloped agricultural land, more intense cultivation could slow deforestation. But even that point is in dispute—if intensified cultivation boosts the land's productivity, the deforestation process may accelerate! In any event, the analysis needs to be complete, looking not just at the way the issue is affected by agricultural markets but also at the externalities generated by agricultural activity, whether positive or negative, local or global.

Finally, considering that most of the mitigation potential of agriculture and livestock farming is based on better management of the stock of soil organic matter, it is essential to change farming practices and hence production systems on all agricultural land, which after all amounts to 40–50 % of the Earth's surface. The justification often invoked for use of the most intensive production methods is their supposed ability to mitigate climate change at the global level, but that reasoning is incomplete, being based on a single indicator, i.e. the annual physical output per unit area of the main crop. It ignores other goods or services provided over time by the cultivated ecosystem, thus penalizing diverse and multifunctional agricultural systems. What it generally amounts to, then, is a fig leaf for business as usual (no mitigation of GHG emissions).

The promoters of climate-smart agriculture make no distinction between agriculture making moderate use of external inputs, agriculture based on sustainable intensification of crop production, conservation agriculture, integration of agriculture and livestock farming, and organic farming, all of which may be diametrically opposed on some issues (e.g. the role of genetically modified organisms). Since we are speaking of an alliance, the hesitation to ostracize any particular school is understandable—to the extent that the school in question helps to meet the food, climate and biodiversity challenges—but climate-smart agriculture could advocate more assertively for agricultural production methods that seek to make intensive use of ecosystem services such as photosynthesis, through intercropping and agroforestry, or biological atmospheric nitrogen fixation. It could set specific goals, such as reduced reliance on imported chemical inputs, in line with the efforts of the proponents of agroecology, in its broadest sense of ecologically intensive agriculture (Griffon 2013). And it could make recommendations for action and call for an increase in research activity in the agroecological science field and activities in support of alternative agricultural modes hitherto neglected by agricultural research institutions (as advocated in 2009 by the international collective study "International Assessment of Agricultural Knowledge, Science and Technology for Development" [IAASTD] 2009).

Similarly, diversification of agricultural production systems is little more than one option among others for improving climate risk management in agriculture. The designers of climate-smart agriculture seem unwilling to harshly criticize specialized farming systems, even though some of the latter's characteristics (overuse of inputs, simplification of crop management practices, specialization of production areas, disconnect between mixed farming and livestock farming systems, heavy mechanization) are cited as having a direct impact on the landscape.

In general, even though ecosystem services and biodiversity are repeatedly mentioned, they are not among the main priorities of climate-smart agriculture, which are limited to the 'triple win': food security, adaptation and mitigation. Agriculture that was simply smart might seek to add a fourth win in the form of biodiversity conservation.

Climate-smart agriculture is relevant to all of the world's farmers, but not all are equally ready to meet the challenges mentioned above. Although many studies exist, particularly in the context of the Observatory of World Agriculture, the FAO publication offers no socioeconomic analysis of the diverse types of agriculture in today's world: family farming, more or less well endowed, landowner farming, and corporate agriculture. And yet the underlying rationales of these types of agriculture, and the human, technical and financial resources available to them, are very different, as are the behaviours and practices they are led to adopt on the big issues. In particular, the absence of any reference to family farming—which is not offset by the too frequent name-checking of rural communities—must in any event be corrected if we are to identify potential barriers to innovation and debate the terms of agricultural transformation.

Finally, the FAO book gives exceedingly short shrift to farmers' organizations, which could nevertheless be important stakeholders in the Alliance. There are scattered references to the value of collective action in generating economies of scale in supply, storage and collection functions. Fortunately, structuring of the agricultural sector and professional collective action are issues that climate-smart agriculture is gradually beginning to integrate into its thinking.

24.4 Public Policies Are Indispensable

In the 21st century, agriculture urgently requires consistent, comprehensive policies that reflect rural communities' interests—the vast majority being family smallholders, among whom women hold a decisive place—and reconcile them with the collective interests championed by nation-states, regional groupings and international institutions that seek a new world governance model, such as the United Nations.

For such policies to be designed and put in practice, and not just as they affect agriculture and food, they must be based on sound scientific knowledge that takes particular cases as well as general principles into account. In so doing, agricultural sciences must be called upon, but also ecological and social sciences. That will mean going beyond academic approaches to take into account local vernacular knowledge acquired over time and through local experimentation by stakeholders in their various areas (Caron et al. 2014).

Another requirement for the design and practical implementation of such public policies and actions is the mobilization of private economic stakeholders (agricultural professionals, upstream industries and agrobusiness, traders, etc.), consumers and citizens, as well as public representatives.

The climate-smart agriculture concept fully embodies the principles mentioned above and appears flexible enough for many countries and institutions to adopt it. Based initially on international agricultural research and development institutions, it highlights the need to mobilize all stakeholders at the national and local level to design and implement appropriate public policies, but also to promote territorial approaches.

The French party has finally decided, not without some reservations and questions (Girardin 2014), to join the Alliance, which took shape on 24 September 2014. French aid for development policy must take an interest in the new initiative, whose stated objectives (the quest for the production-adaptation-mitigation triptych) and proposed approach (to build upon scientific research, mobilize all stakeholders and promote territory-based public policies) appear broadly consistent with France's strategic orientations.

'Taking an interest', however, necessarily means helping to define the doctrine that goes with the concept, which even according to its promoters is still evolving.

The concept seems solid. The incompleteness of certain parts is not so much a risk as an opportunity to bring together the many programmes and initiatives and foster a broad international debate on how to link the agricultural issue—in all its dimensions—to the climate issue. But both should be debated in international climate forums. In the name of effectiveness, however, and to avoid remaining stuck with a list of agricultural best practices to be promoted regardless of context (provided they contribute to climate change mitigation), the 'soft consensus' will one day need to be transcended and a number of points clarified. In the course of that process, the progress made by the international community must be kept in mind, particularly with regard to the need for equitable access to land and natural resources, the concept of responsible investment in agriculture, in both social and environmental terms, the international recognition in 2014 of the importance of family farming, and lastly the many achievements in the field of agroecology.

Though the task is not always easy, and involves substantial tradeoffs, coherent policies need to be developed and implemented in which biodiversity is not sacrificed to economic development and the millions of family smallholdings are not left to their fate just to enhance carbon sequestration in the soil of big agribusiness farms.

In the end, humanity needs smart agriculture not only to cope with climate change, but also to cope with issues relating to economy (wealth creation), society (job creation), and the environment (sustainable management of natural resources and biodiversity), etc. In short, the world needs a new agricultural revolution—one whose emergence can be favoured by the current climate-smart agriculture approach if it maintains a broad, shared vision.

24.5 Public Aid for Development Can Play a Decisive Role

Public aid for development should always be thought of as public support for sustainable development. Constantly seeking to move forward simultaneously and in the same way on each of the four criteria—food security, adaptation, mitigation, biodiversity—is clearly unrealistic. But we need to ask ourselves what the effect will be of financing water management in agriculture, establishing an agricultural financing mechanism or creating a training centre? Will it, in the end, merely promote the techniques of the first green revolution, with increasing use of external inputs (synthetic pesticides and herbicides, mineral fertilizers), with all that implies in the way of negative externalities for the environment (groundwater quality, GHG emissions, biodiversity reduction, landscape simplification, etc.)? Or, conversely, will stakeholders be given the opportunity to shift to another mode of production to meet current challenges?

In that way, Africa's commitment to the climate-smart agriculture concept will be its chance to entertain a greater ambition than merely extending the Green Revolution techniques of the 1960s to the whole continent (to which some add a fillip of 'modernity' in the form of genetically modified seeds). Just as Africa was able to bypass any investment in landline telephony by adopting mobile phones directly, why should it not directly adopt modern agroecological techniques, which many African farmers have already greatly helped to enrich?

Funding arrangements for climate-smart agriculture are as yet very vague, and are indeed one of the issues of forthcoming international negotiations. In any event, funding of agricultural development will in future tend to be increasingly synonymous with funding for the fight against climate change in rural areas. Many funding sources already exist, especially multi-donor climate funds, which predominantly or exclusively target adaptation actions. But the transaction costs necessary to back up farmers' efforts to cope with climate change by the use of carbon credits still seem very high and unsuited to family farming. However, the REDD+ mechanism[2] constitutes a valuable baseline from which to plan for the financing of sustainable intensification of agricultural production systems, and a possible inspiration for the creation of similar mechanisms. It could also be very helpful to give further thought to payment for environmental services.

In spite of the progress made in recent years, the integration of agriculture is still a stumbling block for international climate negotiations. An international initiative such as the Global Alliance for Climate-Smart Agriculture could facilitate the inclusion of issues related to agriculture in the broadest sense—which IPCC has summed up as "land use, land use change and forestry", with the acronym LULUCF—in discussions in preparation for COP 21 (the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change, Paris, December 2015).

As the 'landscape' approach constitutes one of the preferred climate-smart agriculture implementation pathways, there could be value for developing countries, especially in Africa, in developing and promoting a mechanism to achieve 'resilience and reduced net emissions in rural areas'. This could be part of the Positive Agenda for 2015. The areas selected should be large enough that management of production systems, natural resources and land can generate various vital ecosystem services and small enough that the actions contemplated will allow the populations concerned to take an active part.

The proposed approach would ensure consistency between practices developed at plot, farm and landscape levels to meet the challenges of production, climate change (adaptation and mitigation), but also employment and biodiversity. In defining the pilot areas, the goal should be the adoption of development dynamics that will benefit their inhabitants while improving their resilience to climate change by reducing emissions, sequestering carbon and stopping biodiversity erosion. The approach developed first in pilot areas selected by the countries concerned may be gradually extended if it proves successful.

[2]REDD+ is a mechanism that emerged from international negotiations on climate change. It seeks to encourage developing countries to 'reduce emissions from deforestation and forest degradation' (REDD) and to protect and restore their forest carbon stocks (+).

Climate change adaptation and mitigation require significant changes in development dynamics and growth at the territorial level (rural as well as urban). Where measures are coordinated across various areas of activity (agriculture, forestry, biodiversity, water, energy, transport, processing industry, waste management, etc.), territorial policies will need to be implemented, policies that rural local authorities will enforce and be accountable for.

In that context, it would be appropriate, for example, to supplement REDD+, which mainly relates to forests, with a mechanism seeking to make rural areas resilient and low GHG emissive. Such a mechanism would encourage and support local authorities in taking measures such as intensification of agroecological pathways from plot to landscape, in both crop and livestock farming; reforestation, hedging and protection of sensitive areas, including wetlands; energy efficiency and sustainable renewable energy generation, not excluding biomass use; spatial planning; land connectivity; etc. Such a mechanism could eventually be universally adopted, as each rural local authority can set its own course to achieve progress on climate change and deforestation and land degradation dynamics. It would complement a supply chain and sector wide approach (agriculture, energy), which is also necessary, in particular to address the employment challenge, and would enable local governments to mobilize specific additional resources.

One condition for the mobilization of those resources could be the formulation of 'rural climate plans' defined and implemented in the various rural areas of concern by all stakeholders, and particularly family farmers. Local authorities would manage funding and act as guarantors of progress. The plans would of course form part of the country's national strategy and contribute to its implementation.

Funding from the international community would promote the ecological transition of pilot rural areas by financing:

- capacity building in these areas for local stakeholders (local authorities, local development associations and professional organizations) but also regional governments;
- a research component in the areas of agroecological engineering, green technologies, remote sensing and information technology, including the development of measurement, reporting and verification methods;
- the activities included in the plans.

Ultimately, these climate-smart areas would form a mosaic (Scherr et al. 2012) of fields, grazing lands, natural areas, wetlands or woodlands, with a greater or lesser degree of protection—units linked together in a network of biotic and abiotic interactions that would be favoured by the maintenance or development of green infrastructure such as hedgerows, drainage streams, riparian buffer forests or grassy strips along the edge of cultivated fields. Each unit could host a variety of species and, in the case of agricultural land, a variety of crops and crop management systems.

In many countries, National Adaptation Programmes of Action (NAPAs) and Nationally Appropriate Mitigation Actions (NAMAs), which present the various measures chosen in each country, may be complete enough for the national strategy on resilient, positive-energy rural territories to be clear.

In any case, a preparedness fund should be provided upstream of these activities to support local authorities in designing rural climate plans and, where NAPAs and NAMAs prove non-existent or incomplete, to support governments in designing a national strategy on resilient, positive-energy rural areas.

Such an approach could be very useful in countries where a non-collective approach is precluded by the large number of stakeholders, developing countries in particular. Financing of such plans would help to support the ecological transition of family farming in pilot rural areas that could eventually be identified as climate smart territories.

The funding source remains unclear. It could be carbon credits, but also existing climate funds or the multilateral Green Climate Fund established by the Copenhagen and Cancún agreements, which was capitalized and launched in late 2014.

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Chapter 25
Climate-Smart Agriculture and International Climate Change Negotiation Forums

Patrick Caron and Sebastien Treyer

Abstract We offer some perspective on the climate-smart agriculture movement, which arose from a proposal by world agriculture stakeholders in the international climate negotiation process. As early as 1992, agricultural production was seen as a central issue in the negotiations, but one that was too politically charged for international coordination to make progress in that area. The climate-smart agriculture concept has more recently been based on the wager of 'triple win' solutions in agricultural productivity, climate change adaptation and greenhouse gas emission reduction. Each of these three dimensions corresponds to an issue within the negotiations (fight against poverty, food security, climate change mitigation) that has its own playing field and players, both nationally and internationally. The climate-smart agriculture concept cannot hide the fact that individual actions can never address all of the issues and that some crucial ones will inevitably be subject to political arbitration in situations where the stakeholders have unequal resources. We thus advocate that climate-smart agriculture initiatives explicitly clarify their political agenda and their underlying agricultural sector transformation pathways. That appears essential both at the national level and to facilitate international dialogue on climate strategies in agriculture, in line with the climate agreement expected in Paris in 2015. In conclusion, we give some thought to the crucial role of science, which should not seek to depoliticize but rather to help structure the political debate and effective international coordination.

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25.1 Climate-Smart Agriculture, A Proposal from the Agricultural Community

Originally, the climate-smart agriculture (CSA) movement emerged to question the inclusion of climate change concerns in agricultural sector development, in particular to ensure a foothold for that sector on the international agenda of climate change negotiations. The movement reflects a concern on the part of agriculture and agricultural institutions. The agricultural sector has been singled out for criticism on the score of deforestation and encroachment on great forests in the name of increased production, on the score of livestock farming, in the report *Livestock's Long Shadow* (FAO 2006), or following the appeal for a vegetarian diet launched in 2008 by Rajendra Pachauri (IPCC[1] Chairman and, in that capacity, Nobel Peace Prize laureate for 2007; statement of 8 September 2008 to *The Observer*). Hence the issue of land use, exacerbated by large-scale expropriations following the so-called hunger riots, finds itself at the heart of the debate and the land sparing vs land sharing dichotomy (Chaps. 24 and 26), which is emblematic of the development models to be rethought: should natural areas be protected and the rest cultivated without environmental constraints, or should production and protection be attempted in the same areas? These questionings in the agricultural sector come after a long period of neglect by public officials and drastically reduced public support for the sector, while the task of food production has been left to private stakeholders—as was pointed out in the World Bank's *World Development Report 2008*, which focused on agriculture (Banque mondiale 2008). The end of the first decade of this century thus marks an inflection point. At the same time, whether on environmental or social issues, the multifunctionality of agriculture is being asserted in public policies (IAASTD report, McIntyre et al. 2009), albeit to a limited extent as it was tabooed by FAO in the early 2000s and deliberately avoided on the grounds that it distorted the organization of trade (Caron et al. 2008). Agricultural multifunctionality is nevertheless in line with the Millennium Ecosystem Assessment, which opens the door to recognition of the services rendered by agricultural ecosystems.

25.1.1 Agriculture: Central to Climate Talks but Too Politically Charged

Within the United Nations Framework Convention on Climate Change, agriculture has enjoyed a paradoxical position for 20 years. In 1992 it was made one of the priority issues in Article 2, which sets out the ultimate objective of the Convention: "to achieve stabilization of greenhouse gas (GHG) concentrations in the atmosphere

[1]Intergovernmental Panel on Climate Change.

at a level that would prevent dangerous anthropogenic interference with the climate system", quickly enough to avoid overly abrupt changes, "to allow ecosystems to adapt naturally to climate change and ensure that food production is not threatened". Since then, however, the agricultural issue has remained a politically sensitive issue in climate negotiations for at least three reasons, the upshot of which was that intergovernmental discussions on the issue were stalemated until 2013.

The first reason was that developing countries invoked Article 2 to insist that discussions on agriculture address only adaptation issues, to the exclusion of GHG emission reduction issues: these countries rightly emphasize their vulnerability to the impacts of climate change on food security, which must be an absolute priority in demographic transition situations. They also saw mitigation measures in agriculture as a way for developed countries to slough off responsibility for action to developing countries. So much is evident in the controversial study by McKinsey ("marginal emissions abatement cost curves", Enkvist et al. 2007), which presented agricultural mitigation measures in developing countries as more cost-effective than other mitigation measures in developed countries. Countries' strategic positions, however, are far more diverse than this simple developing/developed country divide. They depend on agriculture's importance in each country's total emissions, its vulnerability to climate change impacts, how food security issues are framed domestically, and whether the country is a big importer or exporter.

The second reason for agriculture's becoming a politically sensitive issue in climate negotiations was that agricultural discussions quickly changed shape, as highly conflictual discussions on trade negotiations in agriculture were imported wholesale into the UNFCCC[2] discussions. The third and final reason, probably, was that negotiators shrank from the highly polemical debate on the direct and indirect effects of climate change on food security, price volatility, the local environment, or land-use changes for purposes of biomass energy generation in agriculture.

As a result, the only discussions on 'agricultural issues' related for years to the mere possibility of their being placed on the agenda of the Convention's Subsidiary Body for Scientific and Technological Advice (SBSTA). A number of stakeholders did attempt to make technical and scientific progress while the Convention's formal bodies were embroiled in political discussions. The OECD countries, however—especially those such as New Zealand or France for whom agriculture is a significant part of their total GHG emissions—have sought to advance scientific and technical understanding of the issues and the leeway through international initiatives. For example, the Global Research Alliance on Agricultural Greenhouse Gases launched in 2009 has made an essential contribution to the improved measurement, inventory and allocation of GHG emissions in an area where their diffuse nature and the complexity of the ecological cycles make them much less easy to pin down than in other domains. Another example is the joint effort between the livestock farming industries of France and New Zealand to identify areas for improvement in the various livestock sectors. Another part of the same dynamic, undertaken at the

[2]United Nations Framework Convention on Climate Change.

behest of the Netherlands, World Bank and FAO, has been the series of global scientific conferences on climate-smart agriculture begun in 2011 at Wageningen in the Netherlands, and continued in 2013 at Davis, California. These advances in scientific expertise are contributing to the preparation of key elements of a possible agreement that will include mitigation commitments in agriculture (e.g. measurement and verification of emission reductions) but omit consideration of the political issues that would help decide the content of an agreement.

Even though intergovernmental discussions have bogged down, it may also be noted, as FAO did as early as 2009 in Copenhagen, that many developing countries have already included non-binding agricultural mitigation measures in their Nationally Appropriate Mitigation Actions (NAMAs). The REDD+ endeavour on deforestation, which is the subject of specific negotiations, has also led a number of concerned developing countries to discuss agricultural measures to reduce deforestation.

For the different communities involved in the agricultural sector, the gradual recognition of the importance of agriculture in addressing climate issues at the UN climate talks in Warsaw in 2013 (COP 19), as previously the forestry issue at the Durban negotiations in 2011 (COP 17), is being hailed as a success. The trend continued in Lima in late 2014 (Fig. 25.1). Corresponding changes have been observed in the discourse between the main representatives of the agricultural sector

Fig. 25.1 The site of the United Nations climate talks in Lima, Peru, in December 2014 (© B. Martimort-Asso/IRD)

and environmental NGOs, moving away from the head-on clashes of the 1990s on the biodiversity and pollution issues to a measure of reconciliation in the late 2000s, then after 2010 to a vision of agriculture as 'part of the solution' to environmental challenges.

25.1.2 Climate-Smart Agriculture: Triple Win or Necessary Policy Tradeoffs?

The climate-smart agriculture conceptual proposal, building on the triple win of a sustainable increase in yields, adaptation and climate change mitigation (FAO 2013),[3] appears to be an opportunity to harmonize, or failing that to identify areas of convergence between, three major programmes of the Millennium Global Assessment and of international negotiations, which are otherwise oblivious of one another:

– food security, reaffirmed as a major issue following the hunger riots, and the goal of producing 70 % more food (according to FAO's 2009 estimates, echoed by the great majority of stakeholders and experts), even though some voices make it clear that the way the issue is being handled today does not make it primarily a production issue;
– the fight against poverty and the modalities and channels of bilateral and multilateral public development assistance (G8, G20, UN), reaffirmed at L'Aquila in 2009 and complicated by security issues following 9/11, in the clear understanding that climate change will affect primarily poor and vulnerable rural populations and that adaptation is one of the essential conditions for their resilience; and
– climate change mitigation, which is emphasized by IPCC, UNFCCC and the Kyoto Protocol as a forum unto itself and which has already made room for the land use and forestry issue (REDD), revisiting issues raised long ago (1972) by the Club of Rome, by opening debate on consumption patterns, industrial models, wealth sharing and certain countries' responsibilities in the treatment of global issues (history of industrial nations, extraordinary growth in emerging countries). The recent emphasis on pathways to deep decarbonization (IDDRI-SDSN 2014) once again highlights the profound uncertainty surrounding development models that arises from the climate issue.

Experts who support this conceptual proposal mainly give examples of changes in farming practices rather than the adoption of radically innovative technologies, for example landscape-scale soil conservation and land management techniques

[3]Reflecting different expectations, the programmes are sometimes defined in such a way as to highlight food security instead of sustainable increases in yield and productivity, or other development goals altogether.

Fig. 25.2 Terrace cropping, northern Cameroon. Climate-smart agriculture does not mean only technological shifts (© P. Dugué/CIRAD)

(Fig. 25.2), which can bring simultaneous improvements in yield, resilience, and the carbon footprint of agricultural systems in developing countries (FAO 2013).

However, each of the three sets of negotiations that embody the concept draws—and is crossed by—its own fault lines, pitting the stakeholders, their strategies and worldviews against each other. Although some agricultural activities can in fact meet the expectations all three sets of negotiations agree on, it would be doubly illusory to suppose that that means a triple win (food security, adaptation, mitigation). The first illusion is that the needed arbitrations in each of these sets, and *a fortiori* where they intersect, will be readily achieved—they will be difficult in the extreme. In that game there will be winners and losers. Asymmetries in power and resources between the stakeholders (between movements representing farmers, between farmers and other commodity chain stakeholders, particularly upstream, but also between countries) mean that a balance of power can be achieved only through political arbitration based on an agenda and the existence of legitimate forums. The second illusion is that one action, however beneficial, will by itself enable the issue as a whole to be addressed.

25.2 Clarifying the Political Agenda Underpinning the Inevitable Arbitrations

More generally, discussion of the climate-smart agriculture concept paves the way for the establishment of a new negotiating arena, which will be valuable insofar as it really helps to address crosscutting issues worldwide. No such arena can be created, however, without reference to existing forums in the various specialized fields: public development assistance, food security and climate change, as we have seen; but also, since many positions depend on them, the World Trade Organization, emerging energy market regulation, and property rights in living organisms.

If the discussion becomes a true intergovernmental forum, it is very likely that national positions will be set each time through a specific round of internal negotiations in which one aspect will take precedence over the others (development aid, food security, climate change, trade, etc.). Outcomes will depend on the way stakeholders' interests play out in each nation and on the connections between State machinery, private interest groups and civil society as well as on constraints that will be specific to each nation (employment, energy, budget, etc.), rather than the agricultural sector's objective characteristics. Indeed, positions are being redrawn and new coalitions are emerging that mark a change from the debates of the last 20 years and 'traditional divisions'. Unexpectedly, opposing views are being expressed by countries whose agricultural sectors have similar characteristics (export, supply, sectoral structure, organizational schemes, prominence of environmental issues). Thus, increasingly profound differences are found between India, which emphasizes agricultural support policies to ensure adequate internal production, and China, which defines itself as both a major exporter and importer. Similarly, European countries and New Zealand are coming closer given the importance of agriculture in their total emissions, and that in turn creates a split in the Cairns Group.[4]

What is at stake in national as well as international arbitration is the ability to institute and maintain a political programme for the agricultural sector that will meet the expectations of society as a whole, rather than letting the agenda of a particular sector prevail (i.e. agricultural, industrial, financial, etc.). By that is meant the ability to explain the choice of a socioeconomic development model, usually a novel one, in which the agricultural sector's role constitutes a contribution to the societal project, and to recognize and reward accordingly the many functions fulfilled by the agricultural sector. Beyond local practices and expressions, then, and in line with the Earth Summits, development patterns and the role played therein by the agricultural sector are the focus of the climate-smart agriculture debate, both nationally and internationally. Hence, it is important for each country to set out a clear forward-looking vision of the transformation of its agricultural sector, on the basis of which an explicit discussion can be engaged on the place the sector has and

[4]A group of countries that export agricultural products, which was formed in 1986 in Cairns, Australia, to promote trade liberalization in that sector.

will have in the country's economic and employment situation. In that vision, there must also be room for questioning and clarifying the impacts of the sector's restructuring owing to a given climate-smart modernization project, thus permitting the indispensable political debate to take place (Treyer et al. 2014).

25.3 Fostering a Policy Dialogue on National Transformation Pathways

The reconfiguration of discussions within the Climate Convention since the Copenhagen shock in 2009 (failure to negotiate an agreement to replace the Kyoto Protocol) is actually very consistent with the above analysis, as we have relinquished the illusion of burden sharing, whereby, by international fiat, each country would have been assigned its share of the burden, moving instead to the gradual rebuilding of trust among an increasingly numerous group of countries that are instituting mitigation policies and measures. It is now important to convince those countries of the benefits of, and the imperative need for, international cooperation to make their national efforts effective, coherent and ambitious. In contrast with the deep pessimism that followed Copenhagen, it is clear that more and more initiatives are under way to reduce GHG emissions, whether undertaken by national governments, local authorities or specific sectors of the economy. How can we build on that wealth of initiatives, even if they do not yet appear equal to the magnitude of the climate challenge?

Under this new realpolitik, it is undeniable that the best deal achievable at the 2015 United Nations climate talks in Paris (COP 21) will be an agreement whereby the aggregate of countries' 'contributions' (reductions in medium-term emissions) announced in March 2015 will most likely be quite insufficient to ensure that the global average temperature increase does not exceed 2 °C by 2100. What kind of agreement would really place that long-term goal within reach? How can an agreement be designed that confirms the efforts already made, but which above all engenders a dynamic of gradual improvement in countries' ambition (through a 5-yearly review), so there is the least possible deviation from the 2 °C pathway?

First of all, the only way to reconcile such an agreement with the achievement of the long-term objective will be for mitigation initiatives, whether governmental or put forward by other stakeholders or partnerships, such as the Global Alliance for Climate-Smart Agriculture, to be subject to accountability processes and a common, rigorous reporting framework that will not only ensure accurate measurement and reduction of emissions but also clearly show to what extent the desired results have been achieved.

Then, to turn international cooperation into a real mechanism for collective learning and action, aimed at making a country's or sector's individual efforts more ambitious, it is imperative for every country and every stakeholder to accompany its reasonable short- to medium-term emission reduction commitment with an explicit, and more fundamental, long-term transformation pathway. That pathway would not be a legal commitment but would afford a basis, within each country and between countries, for a discussion of the necessary conditions for the transformation of development models from a political, economic, commercial, technological, etc., point of view, even while everyone sees the changes as too radical to be implemented as things now stand.

Whether we are speaking of countries' climate or agricultural development policies, or of multiplayer partnerships such as the Global Alliance for Climate-Smart Agriculture, their contribution to the collective international dynamic that may be produced by the Paris agreement of late 2015 will be credible only if it meets two conditions: first, agricultural transformation actions and projects must be undertaken in the spirit of climate-smart agriculture, while, second, the performance to be achieved, the redistributional impacts and the incentives offered are also integrated into a clear accountability framework.

Both conditions (an accountability framework for measurement and audit, explicit discussion of transformational pathways) are also those that govern discussion of the REDD mechanism on deforestation and forest degradation, which also tends to hover at the level of national policies. It would seem logical, therefore, for agricultural and forestry approaches to be coordinated, so that the transformation of rural territories, the policies that influence them, and the effects of interaction between their constituent areas can be viewed as a whole.

25.4 Outlook for Research

And what of science in the grand scheme of things? It is faced with a huge paradox! Political players ask science for 'evidence', answers to their questions and solutions to their problems, even though the scope of the innovations and transformations being studied is still largely unknown, whether in its biological or political dimension, and the processes involved are as yet far from well known. The real question is how to escape the positivism of triumphalist science, to build a programme that can both govern our actions right now, in an uncertain world, and deal with issues that are likely to arise 10 or 30 years hence, but which as yet exceed our grasp. Scientific communities should therefore be involved in learning processes that will proceed by combining heterogeneous sources of knowledge and by evaluating and sharing experiences.

Science will also be essential to give credibility to the agreement that seemingly will emerge in 2015, and to midwife the evaluation that will be essential for a real learning process that can inspire the various stakeholders to step up—quickly enough—their ambitions and efforts. The challenge for science then will be to ensure the rigour of methods and metrics for emission reduction monitoring, which is of particular importance to the agricultural sector; and to participate in the construction, evaluation and critical discussion of the long-term transformational pathways that will necessarily be at the heart of the collective dynamic engendered by the agreement.

The priority areas for scientific investment will also need to be identified. Even now—though this will require further study and debate—a number of scientific challenges can be identified:

- the need to rethink the concept of the performance of agricultural practices insofar as it is politically determined, taking into account functions other than food production, in particular those relating to climate change, while also taking into account temporal and spatial scales that may be different from those for implementing the action. The means of measuring performance and the long-term development of databases (metrics) are also a challenge in that context; for while an agroforestry coffee plantation in Costa Rica may seem to be a carbon emitter if we consider only the IPCC standard output applicable to forests (considering that only trees accumulate carbon, ignoring the fact that the coffee plant is itself a small tree and not an ordinary crop that performs no sequestration in biomass or soil), such a plantation actually becomes a very clearly sequestering entity at plot level (Roupsard 2014) when the real carbon dioxide exchanges are accounted for using the latest methods of continuous eddy covariance recording above the canopy. Similarly, carbon dioxide sequestration by the plots of a 700 ha farm would largely offset GHG emissions (carbon dioxide, nitrous oxide, methane) from the factory's processing activities and fertilizer application, which, under the C-Neutral coffee growing certification (NAMA-Café, Costa Rica), would enable many farms to shed their net GHG emitter status and become carbon credit vendors. The challenge is national and international:
- understanding the synergies and antagonisms linked to the achievement of the three pillars of climate-smart agriculture;
- modelling interactions between climate change impacts and the reorganization of production and processing chains and food habits. That modelling must take into account the processes' biological, ecological, economic and social dimensions, the disruptive effects of uncertain, extreme processes, and the consequences for populations' resilience;
- the impact of investments and actions taken in the agricultural sector or in the climate field in relation to the challenges posed by climate-smart agriculture and the planned transformational pathways;
- the engineering methods employed in undertaking actions, supporting decisions and assessing their impact, with input from various disciplines;
- a better understanding of the linkages between policy orientations and priorities at different scales and of the processes whereby policies affecting agriculture are developed (sectoral and crosscutting policies), which could influence or support climate-smart agriculture initiatives as well as the governance of such multiplayer mechanisms.

Addressing these challenges identified by agricultural research will necessarily mean mobilizing communities working in the field of climate, whereas the two communities have so far not worked together sufficiently.

In conclusion, discussions surrounding the climate-smart agriculture concept are highly political. The fact that some NGOs refused to take part in the Global Alliance for Climate-Smart Agriculture when it was launched, in September 2014 at the Summit of Heads of State on climate convened by the United Nations Secretary-General, is sufficient evidence of that political tension. The NGOs in question challenge the Alliance's governance mechanism, transparency and accountability. It is true that many stakeholders rather rushed into it, induced by enthusiasm and the bonanza effect, that is, the opportunity to cash in on the funding on offer to fight against climate disruption. The political dimension was not always considered, while some affected ignorance of the issues at stake in the search for alternative development models.

Such a multiplayer initiative could however constitute an important source of support for the 2015 Paris agreement on climate, insofar as it will give substance, in a major sector, to a dynamic of collective learning and dialogue on agricultural policies, both at the country level and worldwide. The goal would be to make explicit the strategies pursued to seek food security, poverty reduction and the fight against climate change through action in the agricultural sector. The challenge is also to move beyond the fault lines that are now deepening between proponents and opponents of a Green-Revolution-style model, as also observed in agroecology. That will be possible only under certain conditions, particularly in terms of accountability and proper coordination, or real consistency, with such other mechanisms as REDD+. In addition to the political difficulty of negotiating such a mechanism, the outlook for research and the challenges to the role of science are key if the initiative is to become an instrument for concerted action.

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Chapter 26
New Research Perspectives to Address Climate Challenges Facing Agriculture Worldwide

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Abstract A broad span of knowledge is needed to analyse the relationship between agriculture and climate change, from international or local governance, to stakeholders' practices, to biology and genomics. The uncertainty related to climate hazards complicates adaptation and mitigation strategies. It is essential for adaptation and mitigation not to be separated in practice, even where analysis does deal with them separately. Climate-smart innovations can be stimulated by analyses and participatory learning approaches, which are all the more necessary in that the scientific standards are very incomplete. To meet the challenges, innovative solutions as well as those already available will also require political, institutional and financial backing. Future research must come up with new climate-smart options to strengthen stakeholders' and systems' resilience and to create an environment conducive to change. Work on improving agricultural production alone will not be sufficient—the whole food system must be considered.

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26.1 Context

In the face of uncertainty, scientific research needs to take risks, to dispel doubts as far as possible. As regards climate change in developing countries, farmers are faced with dire uncertainty. For West Africa alone, to take only one example, there are as many models predicting a decrease in rainfall as an increase (Druyan 2011). While 'action in an uncertain world' (Callon and Barthe 2005) should be the hallmark of all our research and its applications, implementing that approach when it comes to meeting poverty-stricken farmers' expectations is far from simple. Negotiation processes between stakeholders and other 'hybrid forums', while essential, must be grounded in scientific evidence or nearly proven assumptions. In order to join with farmers in devising innovative practices involving both climate change adaptation and mitigation while ensuring food security, researchers must have a broad knowledge base incorporating international or local governance, stakeholders' practices, and biology and genomics, to name only a few key areas.

The tangle of climate change mechanisms makes the equation 'mitigation + adaptation + food security' a thorny one to solve, while the socioeconomic characteristics of developing countries' societies make the issue a formidable and particularly intricate one. Issues such as access to climate information, availability of skills and training for farmers, perception of change, access to credit and opportunity to invest are more difficult to deal with when one does not know what tomorrow will bring or when an innovation may have abrupt and immediate consequences. And yet, as all farmers know, and as their farming strategy reflects, climate hazards are a reality they dealt with long before IPCC brought to light the disruptions we are now witnessing. Since time immemorial, a great many have diversified crops and varieties, moved herds from pasture to pasture, staggered planting dates, rotated fields, and plied all kinds of trades, all for the very purpose of minimizing risk.

Similarly, the array of options we now call 'sustainable agriculture' is geared towards taking various hazards into account. One need only think of soil and water conservation, efforts to increase the level of soil organic matter, preservation of natural resources in cultivated areas, crop associations, multipurpose trees, the use of local or lesser-known species, selection of varieties suited to a specific practice or resistant to a particular stress, or a governance rule which, it is thought, will encourage long-term forecasts or concerted territorial management. Of course, climate change is a physical and biological phenomenon whose global scope is unknown, but for the farmer it is not totally foreign to his practice and experience, so traditional knowledge and expertise can be linked to new solutions. Let us keep in mind, however, that the looming issue of greenhouse gas emissions will cause a real disconnect—taking the far future into account obliges us to rethink our way of conceiving innovation. To create conditions for the development of climate-smart agriculture will hence require establishing an environment conducive to changes in practice (Lipper et al. 2014). Based on the above, it is possible to offer some general avenues for research to address climate constraints on agriculture in developing countries and planet-wide.

26.2 Avoid Separating Adaptation and Mitigation

Adapting to climate change is usually the first concern of officials in charge of developing countries' agricultural sectors. The Kyoto Protocol, in which the obligation to reduce greenhouse gas emissions applied only to industrialized countries, has reinforced that polarity. While the disparity was once justified, it appears less so today, for two reasons. First, IPCC analyses have shown that the land sector accounts for some 24 % of all greenhouse gas emissions, and every country in the world contributes thereto. Africa, for example, with less than 15 % of the world population, accounts for 11 % and 18 %, of global anthropogenic emissions of methane (CH_4) and nitrous oxide (N_2O) respectively (Hickman et al. 2014). The second reason for not separating adaptation and mitigation arises from the fact that crop and livestock farmers' decisions and agricultural practices do not distinguish between the two processes; accordingly, innovation can simultaneously improve yield, resilience and the carbon footprint. In any event, the issue is a crucial one. But in fact things do not always work that way. A supposedly adapted crop that is planted on soil with a low organic matter content will not be viable without a massive supply of inputs, making for a highly negative mitigation footprint. Energy biomass production in plantations bolstered by great quantities of fertilizer will certainly reduce emissions, but cannot be considered adapted. In terms of performance, then, adaptation and mitigation may in some cases not have opposite effects. But we still need to be able to evaluate that performance! Conversely, while the two processes have been, and sometimes still are, treated separately in initiatives to combat climate change, the reasons for that are institutional and political, related to the implementation of specific frameworks and tools, especially in the field of climate finance—they are not agricultural reasons or part of an attempt at innovation!

One might conclude that climate-smart agriculture's triad of 'productivity, adaptation and mitigation' should not be considered an innovation, still less a slogan, but only a useful framework for the design and implementation of practices suited to the challenges. In thinking that, however, we run the risk of forgetting that industrial agriculture has depleted the range of practices available by focusing exclusively on hazard control, creating artificial production conditions, and paying insufficient attention to the optimum use of the biological and ecological functionalities of ecosystems (Griffon 2013). The same is true, though less so, of agriculture in developing countries. Promoting climate-smart agriculture presupposes a paradigm reversal in the area of food production and supply systems; the consideration of multiple scales, especially landscape or region; and the issues of institutions and public policy, so that genuine transformative change can be sustained (Steenwerth et al. 2014). Therefore, any research efforts undertaken to combine adaptation and mitigation, while relying on the design and evaluation of context-specific, flexible solutions, must from the outset link innovation to public policy and financing (Lipper et al. 2014). The practices to be promoted will need to be undertaken at a higher level than the plot or the farm and will require collective action by many stakeholders at landscape, territory or country scales (Harvey et al. 2014; ICRAF 2014). Business as usual (meaning no mitigation of GHG emissions) is not an option! As we have seen, innovation will also need to address the ways in which technologies relate to social relationships and policy, so as to ensure the wished-for transformation and modernization of the agricultural sector.

26.3 Innovate by Generating Knowledge and Facilitating Learning

Our understanding of the physical mechanisms of climate change and its impact on biological and food systems is imperfect, and more so in the tropics than elsewhere (Thornton et al. 2014), even though some 134 countries are in the tropics, with 80 % of the planet's biodiversity and 40 % of its surface area and its population—very often living in poverty (Hallé 2010). IPCC also notes that the risks to agricultural productivity and food security are higher there than in the temperate zone. Given the complexity of the processes and the uncertainty surrounding them, it may be considered that a conventional diagnosis plus prescription approach is inadequate and that for appropriate innovations and changes to take place, any research undertaken should aim to produce both knowledge and inventions, taking care at the same time to elucidate the changes under way and to get involved in learning systems.

People living in the tropics are particularly vulnerable to climate variability and extreme events, but little is known about how to forecast the occurrence of a given stress and, most importantly, about whether different stresses, combined, can produce new effects. Such is the case, for example, of the association between increased concentrations of carbon dioxide, causing higher temperatures, and increasingly haphazard water availability. While it is possible, in the temperate zone (or in mountainous tropical areas), to find approximate analogues for the future hotter state of a given area by looking at lower latitudes or elevations, Corlett (State of the Tropics 2014) shows that such analogues are difficult to establish in lowland tropical areas. No one knows what a wet equatorial zone (with rainfall all year) will be like in a warmer climate, since no such case now exists anywhere (State of the Tropics 2014). Similarly, asking farmers to move crops to higher elevations (or latitudes) in anticipation of higher temperatures is a coarse-grained solution that fails to account for the likelihood that the various climatic parameters will, in the future, combine in novel ways. Climate change is expected to be more variable and hit harder in the intertropical zone; profound land use changes are under way there, particularly on the margins of forest watersheds; and research systems are on the whole less active in this zone. For all those reasons, an unprecedented worldwide research effort is needed. Specialized climatology studies will also be required to further analyse the impact of change and provide data for modelling efforts. In-depth research reveals unexpected links, for example, between climate change and yield parameters (Box 26.1).

Box 26.1. Impact of climate change on yield factors in oil palms.
Alain Rival, James Tregear and Estelle Jaligot

In oil palms, the sex ratio (the ratio between the number of female inflorescences and the total number of inflorescences) is an important factor in determining the number of bunches, which is one of the main yield factors. Male and female inflorescences are produced alternately on the same plant—as flowers of both sexes are produced by the same plant, the oil palm is considered monoecious. However, since male and female inflorescences are produced at different times, it is also called ‘functionally’ or ‘temporally’ dioecious. Sex determination is influenced by genotypic factors, because recurring plant breeding cycles have led to an ongoing feminization of progeny. Sex ratio regulation is also affected by environmental effects—different types of stress, such as a water deficit or severe pruning, can cause a failover to a male flowering cycle. Many observations tend to confirm the hypothesis of a sex ratio that varies with the ratio between carbon assimilation and mineral absorption. An effect of water stress on the sex ratio is not inconsistent with the ‘nutritional’ hypothesis: reduced photosynthetic activity caused by water stress will reduce the plant’s carbohydrate content. While there may be no genuine ‘climate change’ effect on the sex ratio, there is certainly an environmental impact that urgently needs to be studied so that possible future climate effects can be anticipated.

From now on, research will have to rely not just on recent sex determinism results in model plant and animal species, but also on innovative genomic and epigenetic approaches, to identify relevant candidate genes and the systems that regulate them. Experimental schemes and original physiological models are in place to enable phentotyping and transcriptome analysis of palms subjected to water testing. The approaches developed for the study of the oil palm floral anomaly known as mantling were used to develop an epigenetic approach to study the molecular determinism of floral structure. It is essential to combine several different approaches in order to gain further insight into the role of epigenetic changes in sex determination.

The long-term goal is, by selective breeding, to create dioecious oil palms whose pollination could be more readily controlled. That is also the best strategy for regions where an absence of water stress generates uninterrupted cycles of female flowers, and hence pollination problems. The provision of dioecious plant material would be particularly useful under marginal growing conditions, especially in areas that have a dry season (Africa, Latin America). Marker-assisted selection (MAS), which relies on newly acquired knowledge of the genes controlling sex determination, should help achieve that goal.

To design and evaluate context-specific solutions, the necessary diagnosis cannot be limited to the parameters and impact of climate change, it of course extends to the analysis of the environment and the societies concerned. There are many examples of agricultural innovations that have gone unheeded, especially in developing countries where 'good ideas' regarding technical and institutional change do not spontaneously map to reality on the ground. Perhaps to a greater extent than in other places where increased production has been synonymous with economic and social progress, the difficulty in implementing good ideas in developing countries is exacerbated by socioeconomic factors that rule out the conventional approaches and options of industrial agriculture. Could climate change at last be the opportunity to turn things around? And ensure that diagnosis and action go hand in hand, marking a break from the practice of transferring wholesale solutions designed and evaluated according to criteria that do not necessarily reflect all of the issues to be addressed? And ensure that better use will be made in developing countries of rural societies' knowledge and that those societies will, through participatory approaches (Fig. 26.1), be truly involved in the design, evaluation and dissemination of innovations, whether the latter relate to selection, crop management systems or public policy? Success stories do exist and ought to be emulated, like the assisted natural regeneration of trees in agroforestry fields in Niger, a traditional practice encouraged by an amendment to the Land Act in line with research results (Sendzimir et al. 2011), village agroforests in Sumatra, Indonesia, and elsewhere (Fig. 26.2), or the empirical selection by African farmers of photoperiodic sorghum varieties adapted to irregular rainfall (Traoré et al. 2001).

Fig. 26.1 Consultation with local stakeholders is essential. A participatory research session in a village in Madagascar (© G. Serpantié/CIRAD)

Fig. 26.2 Agroforestry is one response to climate change challenges. Canopy of a village damar agroforest (*Shorea javanica*) for resin production in Krui, Sumatra, Indonesia (© E. Torquebiau/CIRAD)

Research methods need consequently to be rethought owing to the integration of climate issues. The knowledge acquired so that new agricultural strategies and practices may emerge (Lipper et al. 2014) must reach different levels of national and local decision-making on production practices or other factors such as access to information, credit, insurance or investment.

26.4 Devise New Climate-Smart and Resilient Options and Create an Environment Conducive to Change

'Option' should not be understood here merely as a new cropping system or a new practice: a climate-smart option consists of a *complete set* of measures, an *approach* whereby policies, funding if possible, and practices combine to orient change toward simultaneous consideration of food security and climatic disruptions. Given the issues at the international level, research on this topic lends itself better than in some other cases to interdisciplinarity and integration of the various stakeholders in a discussion involving science, action and governance (Steenwerth et al. 2014). That in turn should lead to the formulation of public policies which, from the outset, incorporate the three pillars of climate-smart agriculture and stimulate resilience in systems and stakeholders.

In a context of uncertainty and an ongoing need for adaptation, resilience, in the sense of building capacity for transformative change to achieve sustainability, deserves special attention. The term 'resilience' does appear repeatedly in the founding documents of the climate-smart agriculture concept (FAO 2013; Lipper et al. 2014). The challenge of controlling and supporting change pathways is a fundamental one. To that end, some propose new agricultural options, based on the principles of agroecology and ecological intensification (Griffon 2013), that aim to strengthen the ecological mechanisms involved in biological and ecosystemic cycles. The challenge is to boost productive capacity and renew natural resources without depleting them, preserving organic matter and storing carbon. These options arise from the now well-known limitations of the Green Revolution approach based on chemical forcing of biological cycles and high fossil energy consumption to intensify agricultural production on certain lands in order to save others or limit the cost of their development. Conversely, other channels have been opened up by the successes in payment for ecosystem services in Latin America (Vignola et al. 2009) and ecosystem-based adaptation (Munang et al. 2014). 'Agroecological' agriculture can claim to be climate-smart on account of its ability to boost resilience. On another scale, factoring in issues related to climate disruptions also raises the issue of land use. That can be seen in the concept of integrating agricultural production and nature conservation objectives on the same unit of land ('land sharing'; Fig. 26.3), which is opposed to 'land sparing', where agricultural production and nature conservation take place in different areas (Grau et al. 2013). When it comes to evaluating the impact on mitigation at higher spatial levels, however, and factoring in side-effects, the issue is still open.

Others see use of the climate-smart agriculture concept as mere greenwashing and sloganeering. Some civil society organizations have deemed it a Trojan horse for agrifood and multinational seed and pesticide firms. And indeed, nothing in the definition of climate-smart agriculture requires it to abandon an industrial vision of agriculture based on economies of scale and denaturalization of the environment.

Devising new climate-smart options, as we see, stirs up opposition and creates tension with various certainties and ideologies regarding the status of technology and development models, and not only in terms of the agricultural sector. Any endeavour to generate such options is also caught up in complex power relationships, which cannot be ignored by those advocating climate-smart agriculture.

Science is far from having conclusive answers to all of these questions, so the field is open to the expression of the most virulent rhetoric. There is an urgent need therefore to cast an analytical eye on the agricultural transitions now under way, to adduce evidence whereby different systems and pathways can be compared with regard to the current issues of social and environmental footprint (Caron et al. 2014) and, especially, climate change.

But as we have said, it is not enough to come up with new production options. They must still be suited to a variety of specific contexts, generate appropriate transition conditions, and allow for the necessary learning. Public policies, including funding policies, are an integral part of the array of climate-smart options. However, the picture is quite fuzzy as yet. How can one avoid falling into clichés

Fig. 26.3 A multifunctional landscape illustrating land sharing between different uses: protected or forest areas in the background, fields, grazing land and dwellings in the middle distance, and a biodiversity corridor in the foreground where bundles of straw are collected. Ndumu, KwaZulu-Natal, South Africa (© E. Torquebiau/CIRAD)

about the need for long-term financing, long-term public policy, or governance rules negotiated and accepted by all? How can one avoid the tired rhetoric about stakeholder participation or sharing the wealth of nations? In that connection, it is safe to assume that climate-smart options are likely to emerge when collective solutions based on trust (Ostrom 2008) have made it possible to enhance resilience, rethink government action and define new regulatory mechanisms—especially in a context of pressure resulting from population growth or resource depletion (Boserup 2005).

How can research contribute to an 'environment conducive to change'? In that regard, a number of research themes or approaches, some of which have been mentioned in this book, seem particularly important:

- characterization of the multifunctionality of agriculture (Caron et al. 2008) and the way it contributes to stakeholders' and systems' resilience;
- landscape- and territory-scale approaches (Harvey et al. 2014; Scherr et al. 2012; Torquebiau 2015; Caron 2011), which are essential, both in assessing the footprints of modes of production at that scale and in making collective action the starting point for the (indispensable) makeover of government action. Beyond the establishment of institutions working at that scale that will cover a

wide variety of activities (including livestock farming, forestry and off-farm activities), novel governance mechanisms can be tested, as the most innovative opportunities to combine adaptation and mitigation are no doubt to be found at the landscape and territory scale;

- modelling applied to the links between climate change and tropical farming systems (Affholder et al. 2012);
- breeding for resilience—which will require enormous international research efforts in genomics and the collection, conservation and exchange of germplasm, as well as phenotyping and genotyping (Lybbert et al. 2013);
- studies on the relationship between climate change, pests and diseases (including vector diseases) that affect ecosystems and agroecosystems, since there seem to be more and more outbreaks and upsurges (Alitzer et al. 2013);
- water management, in a context of scarcity and tension between irrigation water users and other consumers, which requires a sustained innovation effort (Grafton et al. 2013);
- analysis of the food system as a whole—not just the agricultural system—which means conducting studies looking both at the demand for foodstuffs and production conditions as well as other factors linked to food—such as consumption patterns, health, losses in the field or in supply chains, and recycling of by-products, all of which are connected to, and impinge on, climate change (Godfray et al. 2010);
- research on alternative crops such as perennial grains, roots and tubers, and certain underused species, which have great potential from a perspective of resilience and adaptation to climate change, although they are now little studied (FAO 2014).

26.5 Conclusion

Agriculture is without doubt at a crossroads, whether due to criticism from civil society for its environmental footprint or because of persistent food insecurity. It also indisputably represents, for the same reasons, a crucial focus for the resolution of pressing issues for all of humanity, insofar as its activity affects other sectors, in particular in the context of climate disruptions. Does climate change complicate the situation or, conversely, does it offer the opportunity to build on and apply the innovative practices that have been tested in recent years? The fact that the word agroecology is now heard in agricultural circles is not trivial. Let us hypothesize that climate change constraints will lead to the invention of a new agricultural future.

What, then, of research? More than ever, it must strive to devise, test and evaluate new technologies, to spur innovation, but also to shed light on, participate in, assess and document the changes under way. In that regard, the question of models, knowledge, information and data, and of the information systems that are needed now and will be needed to work out and negotiate the future, is essential. Here, however, research is facing a new situation. It is not just a question of identifying the 'finds' available or addressing topical issues; today, given the coming acceleration of climate change, what we need to be thinking of are the issues to be addressed in 10 or 20 years; and at the same time caution is essential, since we know so little, in supporting the learning processes now under way. We have a big job on our hands—conducting research at the local and international level while undertaking innovative endeavours and exercising scientific diplomacy!

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