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Issue 11

ECOLOGICAL ENGINEERING FOR SUSTAINABLE AGRICULTURE IN ARID AND SEMIARID WEST AFRICAN REGIONS

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French Scientific Committee on Desertification

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French Scientific Committee on Desertification

The creation in 1997 of the French Scientific Committee on Desertification (CSFD) has met two concerns of the Ministries in charge of the United Nations Convention to Combat Desertification. First, CSFD is striving to involve the French scientific community specialized on issues concerning desertification, land degradation, and development of arid, semiarid and subhumid areas, in generating knowledge as well as guiding and advising policymakers and stakeholders associated in this combat. Its other aim is to strengthen the position of this French community within the global context. In order to meet such expectations, CSFD aims to be a driving force regarding analysis and assessment, prediction and monitoring, information and promotion. Within French delegations, CSFD also takes part in the various statutory meetings of organs of the United Nations Convention to Combat Desertification: Conference of the Parties (CoP), Committee on Science and Technology (CST) and the Committee for the Review of the Implementation of the Convention. It also participates in meetings of European and international scope. It puts forward recommendations on the development of drylands in relation with civil society and the media, while cooperating with the DesertNet International (DNI) network.

CSFD includes a score of members and a President, who are appointed *intuitu personae* by the Ministry for Higher Education and Research, and come from various specialties of the main relevant institutions and universities. CSFD is managed and hosted by the Agropolis International Association that represents, in the French city of Montpellier and Languedoc-Roussillon area, a large scientific community specialised in agriculture, food and environment of tropical and Mediterranean countries. The Committee acts as an independent advisory organ with no decisionmaking powers or legal status. Its operating budget is financed by contributions from the French Ministry for Europe and Foreign Affairs and the Ministry for the Ecological and Inclusive Transition, as well as the French Development Agency. CSFD members participate voluntarily in its activities, as a contribution from the Ministry of Higher Education, Research and Innovation.

More about CSFD:
www.csf-desertification.eu

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une réalisation agropolis productions

Foreword

Mankind is now confronted with an issue of worldwide concern, i.e. desertification, which is both a natural phenomenon and a process induced by human activities. Our planet and natural ecosystems have never been so degraded by our presence. Long considered as a local problem, desertification is now a global issue of concern to all of us, including scientists, decision makers, citizens from both developed and developing countries. Within this setting, it is urgent to boost the awareness of civil society to convince it to get involved. People must first be given the elements necessary to better understand the desertification phenomenon and the concerns. Everyone should have access to relevant scientific knowledge in a readily understandable language and format.

Within this scope, the French Scientific Committee on Desertification (CSFD) has decided to launch a series entitled *Les dossiers thématiques du CSFD*, which is designed to provide sound scientific information on desertification, its implications and stakes. This series is intended for policy makers and advisers from developed and developing countries, in addition to the general public and scientific journalists involved in development and the environment. It also aims at providing teachers, trainers and trainees with additional information on various associated disciplinary fields. Lastly, it endeavors to help disseminate knowledge on the combat against desertification, land degradation, and poverty to stakeholders such as representatives of professional, nongovernmental, and international solidarity organisations.

These *Dossiers* are devoted to different themes such as global public goods, remote sensing, wind erosion, agroecology, pastoralism, etc., in order to take stock of current knowledge on these various subjects. The goal is also to outline debates around new ideas and concepts, including controversial issues; to expound widely used methodologies and results derived from a number of projects; and lastly to supply operational and academic references, addresses and useful websites.

These *Dossiers* are to be broadly circulated, especially within the countries most affected by desertification, by email, through our website, and in print. Your feedback and suggestions will be much appreciated! Editing, production and distribution of *Les dossiers thématiques du CSFD* are fully supported by this Committee thanks to the support of relevant French Ministries and AFD (French Development Agency). The opinions expressed in these reports are endorsed by the Committee.

RICHARD ESCADAFAL

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Preamble

Over the past 10 years, the French Scientific Committee on Desertification has conducted a series of reviews and published many reports on topics that have seldom been investigated but are essential for the development of dryland areas—the contribution of direct-seeding mulch-based cropping systems, why we should invest in arid areas, restoring natural capital, pastoralism in dryland areas, and carbon in dryland soils. The Committee has played a pioneering role in these initiatives by dealing with cross-cutting issues focused on combating desertification and soil degradation, in addition to biodiversity preservation and the adaptation of farming systems to climate change.

This *Dossier* looks at potential contributions of ecological engineering to the management of agrosilvopastoral systems in sub-Saharan dryland areas, while helping to describe and define appropriate agroecological practices. Based on the authors' and contributors' experience, West Africa is focused on to illustrate the ecological intensification approach to agricultural production in the broad sense, which also takes livestock and forest production into account. Examples from non-African tropical dryland areas worldwide are also discussed to illustrate the potential of agroecological engineering in this climate setting.

The aim here is not to discuss all agricultural development related issues but rather to focus specifically on different examples we think are relevant to this ecological engineering approach. After reviewing a few key features of agriculture in dryland, arid and semiarid areas, examples of biological or ecological processes that could be adjusted to the benefit of agrosilvopastoral systems are covered. These examples address different key factors with regard to ecosystem functioning, including biodiversity, material and energy flows, and landscape ecology. The *Dossier* ends with a review of these so-called agroecological practices in the agricultural development socioeconomic context of arid and semiarid regions of West Africa. It was, of course, not possible to thoroughly assess all of the parameters. Essential issues such as land security with regard to restored plots, agricultural price stability and learning and support problems are thus not covered. It is essential that these ecological engineering techniques benefit family farms, which predominate in dryland regions.

This *Dossier* is being published at a time when international bodies are strongly encouraged to focus on halting biodiversity loss, storing more carbon and restoring land to hamper its degradation. The authors warrant praise for so clearly presenting sometimes complex, but inherently sustainable techniques.

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Dryland agriculture in West Africa – multiple functions and high environmental constraints

Arid and semiarid regions of West Africa are marked by severe environmental constraints that have shaped natural ecosystems and human activities.

WATER SHORTAGES— A DRYLAND FEATURE

Arid and semiarid areas—otherwise jointly referred to as 'drylands'—are primarily defined by the climatic conditions to which they are subjected, including low, infrequent, irregular and unpredictable rainfall concentrated within a period of a few months, along with temperature, solar radiation, high evaporation and low air humidity. The arid or semiarid conditions are dictated by the extent of total annual rainfall deficiency and the short rainy season, thus reducing the vegetation growth period to less than 4 months, and by the rainfall irregularity during the rainy season. Fauna, flora and natural ecosystems, as well as human activities such as farming, are thus forged in this insecurity or climate risk setting.

▼ **A Malian landscape**
Semi-wooded grassland with *Acacia raddiana* near the Hombori mountains..
V. Robert © IRD

→ FOCUS | What future climatic conditions will prevail in West Africa?

Forecasting models indicate that future climatic conditions in Africa will be characterised by an increase in extreme events—drought periods, heat waves and floods following heavy rainfall. Projections for the mid-21st century indicate that the Sahel belt will be highly exposed to these events. The scenarios highlight an increase in the number of hot days to over 100/year (heat waves presently last 26-76 days/year).

Various rainfall patterns are foreseen in the different subregions—simulations show a rise in annual rainfall with an increased risk of flooding in Central and East Africa and a decrease in rainfall in West Africa, especially at the beginning of the rainy season, which is a critical period for annual crop germination and growth.

This difference in rainfall patterns between western and eastern Sahel regions is out of line with expected temperature patterns. Forecasts indicate a warming trend over a latitudinal gradient, with northern Sahel regions warming more than southern regions. In the mid-21st century, temperatures in Africa are expected to rise to higher levels than ever before in recent history (by over 3°C in some places).

Future climate projections are variable and uncertain. It is not easy to predict the impacts of climate change on agricultural activities in West Africa, so climate models must be developed at spatiotemporal scales suitable for addressing agricultural issues. Very few meteorological forecasting based tools are currently being used by farmers to improve their management of climate hazards and enable them to adapt their practices to these forecasts. The lack of accessibility to meteorological data and forecasts, as well as the fact that these forecasts are not tailored to farmers' needs (spatiotemporal scale, forecast time, degree of confidence), are the main obstacles to their development in sub-Saharan regions.

SOIL—A NATURALLY LIMITED RESOURCE

Soils in arid and semiarid West African regions can be highly mature (e.g. ferruginous leached soils) or immature (e.g. dune or alluvial soils). They nevertheless generally all have a rough texture at the surface, with relatively low organic matter and plant nutrient contents. Some soils also have quite high organic matter and plant nutrient contents, especially in lower parts of catchments or on large floodplains.

In addition to the organic matter and nutrient contents, two other indicators could be considered to assess the agronomic potential or primary production capacity of soils. The first indicator is the soil depth, which determines the volume that roots can readily utilise, while the second is the state of the thin topsoil horizon, i.e. crusting can physically limit water infiltration or even modify the root structure of plants growing in the soil. These different parameters highlight soil degradation processes, in addition to erosion and soil loss phenomena, which are sometimes serious and usually attributed to a reduction in plant cover protecting the soil. This cover can decline as a result of overgrazing, intense fuelwood harvesting, increased bushfire frequency and cropland encroachment. The soil then becomes vulnerable to very heavy rainfall. Landscapes in all of these regions often have sparse vegetation, completely crusted soils aggravated by intensified degradation processes, sometimes leading to an almost desertified state.

Other types of soil degradation also occur in these regions, such as salinization. This is sometimes naturally associated with the presence of a body of salt water. The emergence of salty soils in dryland areas can also be the result of poorly managed irrigation and drainage practices.

ECOSYSTEMS SHAPED BY WATER AND SOIL CONSTRAINTS

High climate risks and ancient soils have shaped ecosystems in arid and semiarid regions. Organisms living in these regions, particularly plants, are totally adapted to these harsh environmental conditions: drought-resistant trees, very fast growing annual herbaceous plants able to complete their growth cycle in a few weeks, perennial herbaceous plants that are highly efficient in terms of nutrient use (e.g. *Andropogon gayanus; see next page*).

Interactions between these organisms are hinged on these constraints. The structure of natural ecosystems is thus adapted to these more or less prolonged arid conditions, as is the case of savanna plant stands, combining trees and herbaceous strata, or striped bush characterized by alternate strips with and without vegetation (*see page 7*). Moreover, resource sharing between individuals is the *leitmotif* of these ecosystems, e.g. trees take up water and nutrients from deep soil horizons via their root system and redistribute part of this to the herbaceous surface layer.

▲ Salt bloom (aluminium and/or iron sulphate) formed at the soil surface in crusty patches. Senegal.
J.-P Montoroi © IRD

→ FOCUS | *Andropogon gayanus*, a perennial grass growing in a closed circuit?

Andropogon gayanus is a grass that is widespread on West African savannas. This species emerges after a few fallow years (about 6) and farmers consider its presence to be a sign of soil fertility. In addition to being palatable to livestock, *A. gayanus* generates straw that is conventionally used in making various items, while also serving as a building material.

▲ *Andropogon gayanus* fallows after recultivation, Burkina Faso.
Dry stems from the previous season are clearly visible at the onset of the rainy season, along with regrowth at the beginning of the new crop year (young green leaves).
S. Dugast © IRD

A. gayanus is a perennial grass with a highly developed deep root system. A few years after its emergence—like perennial grasses that grow in Sudano-Sahelian savanna regions—it develops a closed nutrient cycle (i.e. with minimal nutrient loss). This cycle is based on rapid mineralization of the root or litter residues it produces and by immediate root uptake of nutrients resulting from this decomposition. These mineral resource concentration and conservation processes enable the plant to grow in nutrient-poor soils, with intense primary production achieved a number years after cropping abandonment.

Shortening of the fallow period, sometimes combined with an increase in the frequency of bush fires and/or grazing, often results in the disappearance of *A. gayanus* due to the lack of sufficient time for it to regenerate. The introduction of this species in short-term fallows was nevertheless found to result in the generation of as much as 25 t/ha of dry matter after 2 years in Burkina Faso (Serpantié & Ouattara, 2001).

AGRICULTURAL AND PASTORAL PRACTICES TAILORED TO THESE ENVIRONMENTAL CONSTRAINTS

Agricultural and pastoral activities that prevail in dryland regions may also adapt to these constraints over time through timber-crop-livestock integration. This may occur on farms, in villages—where herders and crop farmers coexist and where trees and crops are associated—but also on a broader territorial scale via nomadic herding and transhumance practices.

Vast areas in the driest regions (such as the Sahel) are generally devoted to pastoral livestock farming. Crop farming is more clearly established in areas that benefit from a little more rain (more than 400 mm/year), sometimes far from areas that have natural water supplies, e.g. river valleys. Historically, irrigation techniques are less developed in savanna crop areas south of the Sahara, while so-called rainfed agriculture clearly prevails (Pélissier, 1966). Besides agricultural activities per-se, other resources such as timber trees are exploited and generally managed by local communities. This concerns both savannas and forest trees, as well as trees outside forests*, in crop fields or villages.

▲ A West African locust bean tree stand with a small granary in the vicinity of Kobané village, Guinea.
E. Bernus © IRD

* Terms defined in the glossary (*page 60*) are highlighted in blue and underlined in the text.

→ FOCUS | Plant stands adapted to prolonged arid conditions – savannas and tiger bush

Grasslands – an emblematic ecosystem in West Africa

Grasslands represent a major ecological formation in West Africa. They are characterized by close tree-grass cover associations whose respective compositions and structures vary according to the temperature and soil moisture (soil climate) conditions. Environmental conditions—especially including an annual drought period—dictate the vegetation composition. Fire also affects this composition, in addition to the structure of the different layers.

The tree and grass communities have a close relationship, especially in terms of competition for light, water and soil nutrients. These resources are nevertheless often shared—trees tap nutrients in deep soil horizons and restore part of them at the surface in litter produced by the trees. Some trees even draw from these horizons to the benefit of grasses in contact with trees. Grasslands are also impacted by the wildlife and livestock they host. It has thus been shown that grassland productivity is to a certain extent increased by wildlife grazing.

Despite major environmental constraints, primary production in grasslands is often very high under some conditions. This paradox could be explained by the grassland structures, which combine different complementary plant forms (trees, annual and perennial herbaceous species), microbial organisms, i.e. rhizobia, mycorrhiza and other microorganisms that promote plant growth, (*see p. 13*), and they are adapted to the presence of large mammals. Grassland plants have specific soil exploration strategies via their root systems, promoted by mycorrhizal fungi, atmospheric nitrogen capture by microorganisms (especially species with a symbiotic relationship with legumes), nutrient transfers between different organisms and enhanced nutrient usage efficiency.

Knowledge on the functioning of these grasslands—an exemplary natural ecosystem in arid and semiarid West African regions—thus provides elements for ecological engineering regarding the use of these environments.

Tiger bush – more sustainable production in a smaller spatial area

The landscape in Sahelian regions of Niger often has a unique pattern of alternating strips of vegetation separated by bare ground. These strips are oriented perpendicularly to runoff flow. This spatial organization resembles tiger skin on aerial images, thus explaining the name of this formation ('tiger bush').

The spatiotemporal dynamics of this patterned vegetation community feature a downslope to upslope development trend. This phenomenon is related to the water harvesting role played by the bare soil strip to the benefit of the vegetation strip. In addition to rainfall, this latter strip captures organic residue borne by runoff water and wind. The downslope part of the vegetation strip is subject to erosion, leading to the development of patches of bare soil.

This vegetation community is especially well adapted to Sahelian environmental conditions, with higher primary production in terms of biomass than in ecosystems with continuous plant cover. The productivity of these environments could be preserved or restored on the basis of this natural functioning.

Source: Valentin & d'Herbés, 1999

Agrosystem productivity in Sahelian and Sudano-Sahelian regions is based on its spatiotemporal organization so as to achieve optimal and sustainable production of agricultural resources needed by local communities:

- spatially, cultivated areas are associated with uncultivated areas, thus enabling organic resource exchange and transfer between these two types of area (see next page, e.g. ring-shaped village lands)
- temporally, crop-fallow rotations promote restoration of available organic resources.

Two key elements enhance productivity in the arid and semiarid setting of the southern Saharan region:

- Trees have several nutrient and water cycle functions, including production (wood, fruit, fodder, medication, etc.) and cultural (e.g. sacred groves) functions. These trees are generally located in forests bordering village lands, in fallow areas, or associated with crops in parklands or hedges.
- Livestock farming—despite some extent of overlap with cropping activities—is often associated with crop farming. Farmers have domesticated livestock that produce meat and milk, representing a form of capitalization. Draught animals are also widespread in many regions (horses, oxen, donkeys, etc.). Finally, nomadic herders wander through farming areas during their transhumance movements to feed their animals, thus ensuring fertility transfers via dung recycling.

→ FOCUS | Ring-shaped village lands

Typical of traditional self-sufficient agropastoral systems, village lands in West African savanna areas are organized in concentric rings over a decreasing gradient of agricultural intensification and land control (Prudencio, 1993; Pélissier 1966; Ruthenberg, 1980).

There are three main types of ring:

• Village gardens reserved for continuous vegetable growing with intensive soil fertility management practices (livestock manure, domestic waste spreading). Such rings ensure inhabitants' food security.

• So-called 'bush' fields where semi-permanent cropping is more or less associated with continuous cropping according to the soil properties, food and cash needs, as well as livestock availability. Cropping is alternated with fallows of various durations, which then constitutes a reservoir of cropland and different types of biodiversity.

• A ring of wooded grasslands or forests that have not been cultivated for several decades is subject to community ownership. It serves as a source of fodder, fuelwood and other wood and non-wood products.

Trees are often present in the landscape. Cropping areas generally host many multipurpose trees. This pattern creates heterogeneity in the agricultural landscape at different scales—from the tree in fallows to different types of land use, all of which is connected by energy and matter flows promoted by agrosilvopastoral practices. Growing crops after tree fallows is thus beneficial to crops since they can take up nutrients that the trees have tapped from deep soil horizons during the fallow period. Moreover, the livestock dung found in fields where they are enclosed at night may subsequently be transferred to crop fields to serve as fertilizer. This may be viewed as a strategy for reducing climate and phytosanitary risks in cropping areas. Concentric flows of nutrient and energy resources also ensure productivity in environments where few nutrients are available for plants and under highly random water supply conditions. These factors, combined with biodiversity (from microorganisms to plants) and with community social organizations, strongly contribute to the viability of these agrosocioecosystems.

▲ **Aerial view of Djoumté village and its ring of village gardens (groundnut and millet crops) during the rainy season. Northern Cameroon.**
J.-J. Lemasson © IRD

In semiarid savanna regions with low population densities, crop-fallow rotations have long helped achieve sufficient productivity. However, this cycle has been upset by increased population pressure on lands and the introduction of new crops (*see below*). When the human population increases, crop-livestock farming integration, and associated fertility transfers, are essential to ensure sufficient cropland productivity.

The presence of wooded parklands in areas under very high population pressure is also crucial, especially in dry regions with a heightened climate risk.

Although not traditionally widespread, some water management techniques also enable production or yield enhancements during the rainy season, and especially at other times, via small-scale irrigation of crops (often vegetables) around a well, in a lowland area, or along a stream or river. The crops grown are also adapted to these dryland regions. Millet is an emblematic crop of sub-Saharan dryland regions (*see page 10*).

▲ **Agriculture et élevage au Bénin.**
La culture de céréales (mil et sorgho) et l'élevage sont deux ressources importantes du milieu rural au Bénin.
M. Donnat © IRD

→ FOCUS | Fallows – the disappearance of a keystone of savanna agriculture

Land-use patterns in savanna agricultural systems commonly involve a cropping phase of a few years followed (after a drop in yield) by the abandonment of cropping for variable lengths of time. This second so-called fallow phase restores the soil fertility and agricultural and ecological potential of the environment through regrowth of the shrub or tree layer. Moreover, rural communities do not consider fallowing just as an agriculture dormancy period—they also view fallow land as a productive area where crop and livestock farmers can harvest fodder, wood and fruit resources, as well as medicinal plants. The crop-livestock rotation system is thus an African savanna resource management strategy.

This crop-fallow cycle has been upset to various degrees by increased population pressure, the introduction of new crops and in turn by the increased demand for farmland. Fallow periods have shortened, sometimes leading to uninterrupted cropping. The production functions of the remaining fallow lands are being reduced by the increase in wood extraction and intensified grazing in small areas. With this shortening of the fallow period, natural regeneration is becoming less efficient, with a concomitant decline in biodiversity. There is an alarming water supply dysfunction and erosion trend on lands that are degrading at an increasing rate. These phenomena overall have created a crisis situation on traditional lands, with very substantial socioeconomic impacts.

Research carried out over the 1994-2000 period by a consortium of West African and European institutes and universities highlighted the importance of trees in agrosystems, especially for their fertility restoration role (Floret & Pontanier, 2000). Agroforestry stands in which crops are grown in the presence of trees, are widespread in intensively cropped Sudano-Sahelian regions. They help maintain the presence of trees, and thus their functions, on these lands. Fallow substitution methods have been proposed that are generally based on agroforestry techniques—short fallows with fast-growing species, alley cropping, etc. However, expensive techniques for restoring exhausted land—which are too sectorial, not technically adapted and do not sufficiently account for the village land dimension and social aspects (e.g. land issues)—have not always fulfilled the hopes of societies which are not very ready to accept innovations that do not generate immediate benefits.

▲ **Agriculture in Niger.**
Sorghum drying.
A. Luxereau © IRD

Sorghum—or even maize—is cropped in areas with relatively abundant rainfall or sufficient water supplies (lowlands, floodplains, clayey land, etc.). Other food and cash crops are also present. Groundnuts and cowpeas are major legumes in local peoples' diets (plant proteins). They are also interesting sources of nitrogen in rotations. On large floodplains, irrigated land development programmes often promote highly intensive crop farming for rice or vegetable production.

→ FOCUS | Millet cropping – a peasant farming system tailored to Sahelian conditions

At a conference in 1992, Serpantié and Milleville stated that: "Sahelian farmers have found that millet crops are suitable for making effective use of short humid periods, often when grown in very poor but sometimes abundantly manured soils. They have adapted their cropping and production systems according to the environmental hazards that prevail. Under extensive cropping conditions in sandy soils, they benefit from an undemanding crop that can be grown with little tillage on large areas, while the yields obtained are relatively poor but steady. They can also benefit from the rapid growth and substantial yield potential of this crop when grown on tilled and abundantly fertilized soils, but the risks and water requirements are high. They are—along with livestock farming—the backbone of Sahelian production systems. Both types of cropping system are often combined on farms. These adaptive traits should be identified and taken into account in plant breeding programmes, and in research focused on developing new cropping techniques. Studies should seek to find technical alternatives, while not dissociating the crop from the cropping systems in which they are grown when assessing possible improvement strategies."

Source: Serpantié & Milleville, 1993.

▲ **Transporting millet, Burkina Faso.**
Young people carrying bowls of harvested millet along the Bobo Dioulasso road. .
J.-P. Guengant © IRD

RETHINKING THE MANAGEMENT OF AGRICULTURAL AND NATURAL SYSTEMS THROUGH ECOLOGICAL ENGINEERINGE

In the current setting of increasing socioeconomic[1] and climatic constraints, dryland farmers are changing strategies to adapt to and address a dual challenge, i.e. to produce more, and better, in order to meet the high food needs of growing populations. The challenge is thus to viably and sustainably increase crop, forest and livestock production (Tilman *et al.*, 2002). The rapid adoption of higher yielding production methods that do not utilize substantial natural resources and are resistant to climate hazards is therefore essential.

Small-scale family farming still prevails in these regions (*see below*). These families are primarily seeking to ensure their food security. In relatively random climatic and socioeconomic conditions, intensification is geared mainly towards fulfilling subsistence production needs rather than striving to maximise production and profits. New parallel and mainly commercially-oriented agricultural strategies are developing. They could be managed by small farmers under favourable commercial conditions (e.g. on the outskirts of cities), or by large companies investing in substantial production resources to address target markets (e.g. export-oriented vegetable production companies in the Senegal River valley).

All family and non-family farmers strive to enhance their resource productivity (land, labour)—small farmers to cope with labour shortages associated with rural outmigration, for instance, and commercial companies to boost profits.

→ FOCUS | Family farming – the main agricultural system in West African drylands

A highly diverse range of family farms ensure a major share of agricultural production in arid and semiarid regions of West Africa. The term 'family farming' reflects the fact that decision making, capital inputs and labour are almost exclusively familial. Family farms are often small (95% cultivate an area of less than 5 ha in sub-Saharan Africa), and they fulfil different functions: production, job provision, natural resource management, preservation of rural cultures and rural landscape maintenance.

[1] For further information on the socioeconomic constraints, *see p. 50.*

The first response to cope with the high population growth situation under way over the last few decades was to extend cropland. The use of chemical inputs or improved varieties—the basis of the green revolution on other continents—has not developed in West African agricultural production systems, except with regard to cash crops such as cotton and groundnut. This solution is still possible but hampered by the low investment capacity of family farms and the prohibitive cost of synthetic chemical inputs. Although this solution seems feasible in the short term, other commercial and family farming solutions must be sought in sub-Saharan Africa in the light of climate change projections and the degradation of fossil and minable reserves.

Ecological intensification of agrosilvopastoral systems—as a new paradigm for agricultural development—could help meet this productivity improvement challenge while preserving natural resources and production means (Griffon, 2006). The aim of such intensification of ecological processes that govern these systems is to obtain an environment-friendly and low fossil resource input agricultural system that is both productive and sustainable.

The complexity of the studied systems must be managed in order to achieve these goals, while taking the functioning of emblematic natural ecosystems in the concerned agroecological region as a model—savanna for West African drylands—and traditional practices and local know-how resulting from long-term adaptation to cope with environmental constraints—agrosilvopastoral practices.

Ecological engineering now proposes alternative strategies for managing crop and livestock farming systems that are more tailored to changing social and environmental needs in these regions (*see next column*).

→ FOCUS | Ecological engineering—an approach to identify good trade-offs and innovate!

Ecological engineering is a hybrid concept focused both on science and action, whose scope has fluctuated with controversies since its emergence some 30 years ago (Mitsch, 2012). Ecological engineering is defined here in the broadest sense, as "ecosystem management and the design of sustainable, adaptive and multifunctional development initiatives inspired by or based on mechanisms that govern ecological systems" (Dutoit, 2013). It is modelled on the initial proposal of Odum and Odum (2003), "the environmental manipulation by man using small amounts of supplementary energy to control systems in which the main energy drivers are still coming from natural sources".

According to Mitsch and Jorgensen (2003), ecological engineering aims to restore ecosystems disturbed by human activities and to develop sustainable ecosystems of human and ecological value. Intervention strategies are based on the self-organizing and -maintenance capacities of ecosystems.

This approach also fostered the agroecology concept defined by Altieri (1995), whereby ecological concepts and principles are applied in the design and sustainable management of crop and livestock farming systems. Research is supported by an ecology-based scientific approach (biodiversity, food webs, population dynamics, nutrient cycles, landscape ecology, etc.) and by a practical experimental approach, thus enabling the testing of new practices and the comparison of ecological theories to real situations. Beyond ecological science, the science of complexity can also provide conceptual frameworks (interactions, self-organization, emergence, multiscale, nonlinear dynamics, etc.) to help explain ecosystem functioning and come up with innovative solutions to better manage them.

▲ **Vegetable crops in Niger.** Onion and legume crops.
F. Boyer © IRD

Promoting biodiversity

Biodiversity—as defined by the shapes, composition and internal structures of the constituent organisms—is essential in ecosystem functioning.

Biodiversity determines the productivity of these ecosystems, their viability and stability over time when subject to external disturbances. Living organisms, whether they be plants, animals, macro- or micro-organisms, are adapted to their surrounding conditions. Such adaptations are specific to each species or even individual and enable these organisms to grow and reproduce in given conditions. Interactions between individuals and groups of individuals also give rise to spatial structures that ensure the species' survival. A termite mound, for instance, is a complex organized structure that hosts a termite population, while also sheltering other species. This diversity helps ensure the stability and productivity of ecosystems and, more broadly, of all ecosystem services, such as production and regulation services, etc.

Biodiversity can be viewed through the lense of the species composition and functional diversity, e.g. trees draw nutrients up to the surface via their deep roots to benefit grasses through litter mineralization, perennial grasses create preferential nutrient recycling zones in their rhizospheres, termites recycle lignin-rich organic matter in dryland environments, earthworms blend litter with soil, etc. Each of these organisms plays a part in ecosystem functioning and in the services they provide. Their sometimes complex interactions also determine the functions. Some interactions are essential, such as mutualism or symbiosis between microorganisms and plants (e.g. mycorrhizal fungi and trees), facilitation of the growth of some organisms by others, the redundancy of species that provide the same service—in this way the service is preserved even if one species disappears, etc.

Different biological or ecological processes related to biodiversity can thus be strengthened through ecological engineering to the benefit of agrosilvopastoral systems present in arid and semiarid regions of West Africa:

- by making effective use of the diversity and activity of soil microorganisms for the benefit of plants
- by combining different plants and promoting their joint action.

▼ Onset of the rainy season. Kindi, Burkina Faso.
© D. Masse

PROMOTING SOIL MICROORGANISM DIVERSITY FOR THE BENEFIT OF PLANTS

Soil microorganisms may be invisible to the naked eye but they are an essential constituent of life on Earth. Because of the many functions of these organisms, they represent a vital Earth support system as they have a key role in the functioning of major biogeochemical cycles (C, N and P cycles, etc.) by releasing nutrients required by plants. Their activities are directly dependent on the quality and productivity of soil, which supports plant growth.

For instance, rhizobia (soil bacteria) are associated with plants of the legume family, i.e. soybean, bean, lupin, groundnut, etc., in a symbiotic relationship which results in the formation of nodules on roots (sometimes on stems)—these are special organs in which bacteria fix atmospheric nitrogen in a form that can be readily assimilated by plants.

Moreover, mycorrhizal fungi colonize roots and form a so-called mycorrhizal symbiotic association with almost all plants. Mycorrhizae may explore a larger soil volume via mycelial strands of the fungus and thus enhance the uptake of water and nutrients, including phosphorus, by the plant.

Promoting these microorganisms and their activity thus contributes to the ecological intensification of agrosilvopastoral systems or the rehabilitation of degraded dryland soils

▲ **Relationships between plant species, soil and microorganisms. Senegal. Harvesting inoculated cowpea plants**
M. Neyra © IRD

▲ **Relationships between plant species, soil and microorganisms. Senegal. *Acacia mellifera* inoculated plants (right) with selected rhizobia and fungi, and non-inoculated plants (left), 3 months after planting.**
M. Neyra © IRD

→ EXAMPLES | **Soil microorganisms to benefit plants in Senegal**

Microbial symbiosis to combat desertification along the Great Green Wall

The pan-African Great Green Wall (GGW) project is designed to combat desertification along the Sahelian belt via **ecological restoration** and integrated socioeconomic development.

In Senegal, the GGW agency has developed initiatives to promote the regrowth of tree and herbaceous vegetation as well as new income-generating activities associated with vegetable growing (e.g. onions), fruit growing (*Zizyphus mauritiana*, *Tamarindus indica*) or fodder production. Researchers, especially in soil microbial ecology, have proposed to introduce microorganisms that are beneficial for tree growth with the aim of intensifying agricultural production.

In this setting, two strategies based on the symbiotic microbial potential were adopted to restore degraded soils and increase plant productivity in nutrient-poor soils:
• input of arbuscular mycorrhizal fungi and/or nitrogen-fixing bacteria (inoculation technique)
• use of mycotrophic plants, i.e. bearing mycorrhizogenic and ruderal fungi, growing along roadsides, in vacant lots, abandoned cropland, that will stimulate the symbiotic microbial potential of soils.

Phosphorus and nitrogen availability is often a plant growth limiting factor in the Sahel region. Most agricultural species—forest fruits and other multipurpose woody plants, vegetable or annual legume plants—depend on the presence of fungal and bacterial symbionts that promote plant mineral nutrition. Inoculation of these organisms is especially efficient in conditions where irrigation is possible. Moreover, at the beginning of forest tree and crop planting, it is possible to apply natural phosphate—a mineral that abounds in West African soils—which, under the effect of mycorrhizal structures, has a 'starter effect' by boosting the phosphorus pool that can be utilised by plants.

Soils in Sahelian areas generally host a very low number of microbial propagules. Controlled microbial inoculation of woody plants is carried out in nurseries prior to their planting in these areas, thus enhancing their productivity and the microbial potential of degraded soils.

At sites with a higher number of microbial propagules, the aim is to increase the soil microbial potential by promoting mycotrophic and nitrogen-fixing pioneer grasses (e.g. *Zornia glochidiata*, *Panicum* spp.) adapted to water stress conditions. Mycorrhization and tree height growth are stimulated in soils under the influence of mycotrophic grasses, with positive impacts on soil microbial activity. Moreover, the presence of grass cover highly colonized by arbuscular mycorrhizal fungi boosts the mycorrhizal potential of soils under tree stands.

Little information is available, however, on the diversity of mycorrhizal fungi and rhizobia that enhance the tolerance of plant species in the Sahel to abiotic factors such as water stress. Knowledge on the ecophysiological mechanisms underlying the adaptation of symbiotic microorganisms to water stress, with or without their host plants, is highly important when choosing strains to breed for plant cover regrowth.

Grasses associated with mycorrhizal fungi for the afforestation of saline soils

Soil salinization is a growing environmental problem, especially in arid and semiarid areas. Around 800 million ha of land are impacted by salt throughout the world.

About 6% of the land in Senegal is affected by salinization, especially in the coastal region, e.g. in the Sine and Saloum lowland valleys. Two halophytic grass species (i.e. plants that tolerate brackish or saline environments) are found growing in these almost bare saline soils (locally known as *tann*): *Sporobolus robustus* Kunth and *Leptochloa fusca* (L.) Stapf. These grasses, which represent a major source of supplementary fodder for livestock in the dry season, are associated with arbuscular mycorrhizal fungi and nitrogen-fixing bacteria. These symbiotic relationships partially enable the plants to tolerate soils with moderate salt levels.

▲ Beneficial effects of inoculating 4 month old jujube (*Ziziphus mauritiana*) plants with the mycorrhizal fungus *Glomus aggregatum* in the greenhouse.
© A. Bâ

▲ Beneficial effects of inoculating 8 month old jujube (*Ziziphus mauritiana*) plants with the mycorrhizal fungus *Glomus aggregatum* in the greenhouse.
Amally multipurpose garden located alongside the Great Green Wall in Senegal.
© A. Bâ

For further information (in French): http://senegal.ird.fr/la-recherche/tous-les-projets/environnement-et-ressources/lcm

▲ *Acacia seyal* **growing in a saline soil with** ***Sporobolus robustus*** **grass cover in the Sine Saloum natural region. Foundiougne, Fatick region, Senegal.**
© D. Diouf

These grasses also form clumps upon which multipurpose tree species grow: *Acacia seyal* Del. and *Prosopis juliflora* (Swartz) DC. The grasses generate a soil microenvironment favourable for the germination and growth of these bushes in saline soil. Two nonexclusive mechanisms are involved: (i) soil remediation via salt accumulation, and (ii) stimulation of adapted microflora, which boost the salt tolerance of the bushes. Gaining insight into symbiotic microbial communities in these grass/tree associations according to the salinity level and season could help determine rehabilitation pathways via the afforestation of saline areas while controlling the simultaneous introduction of grasses and microbial symbionts.

For further information (in French): http://senegal.ird.fr/la-recherche/tous-les-projets/environnement-et-ressources/lcm

Rhizobium inoculation of soils to enhance cowpea crop production

In agriculture, the technique of inoculating soils with preselected symbiotic microorganisms represents a prime opportunity to increase agricultural production. This technique has been tested with rhizobia on cowpea (*Vigna unguilacata*) crops in Senegal. Cowpea is an important food legume in cereal/legume-based cropping systems in the Sahel because of its contributions of proteins and other elements essential for the nutritional balance of local people. Inoculation enhances the atmospheric nitrogen fixation process via microbial symbiosis.

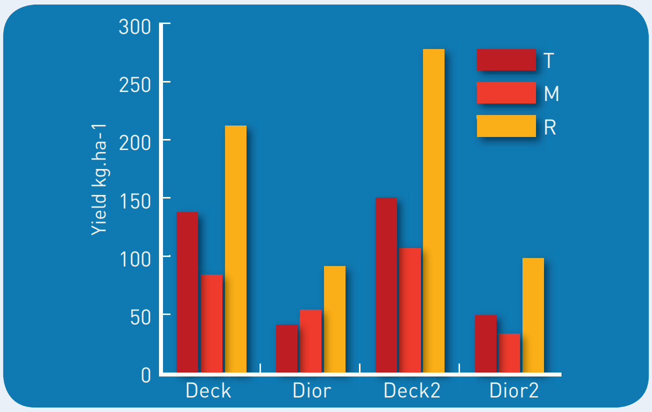
The *Laboratoire Commun de Microbiologie* (UCAD/ISRA/IRD)* in Senegal has set up a network of research and demonstration sites in rural communities in partnership with farmers ** with the aim of: (i) conducting experiments in real field conditions, (ii) transferring the inoculation technique to local stakeholders, and (iii) creating ideal sites for researcher/farmer exchanges and sharing with regard to research issues.

A large-scale survey on natural rhizobium and mycorrhizal fungus diversity in cowpea fields (1999-2005) revealed the presence of high microbial diversity depending on the soil moisture and pH conditions. Participatory field inoculation trials were conducted with microbial strains selected according to their geographical distribution in cowpea fields, under annual rainfall conditions ranging from 300 to 800 mm/year on different soil types (sandy, clayey), and under various cropping practices. The results of these trials highlighted the positive effects of cowpea inoculation, especially by rhizobia (*see chart below*), with 40-170% increases in dry seed yields. Moreover, in some conditions, higher resistance to water stress and parasite infestations was noted in plots where rhizobia had been introduced. The technology was subsequently adopted by farmers, extension agents and farmers' organization representatives.

It is now necessary to ensure an available supply of high quality and effective inoculum, which currently hinders the transfer of this technology. One company is trying to address this challenge in collaboration with farmers' associations.

For further information: Neyra *et al.*, 2012..

* It includes Cheikh Anta Diop University in Dakar, the French *Institut de Recherche pour le Développement* and the *Institut Sénégalais de Recherches Agricoles*.
** Partnership with farmers' organizations, the Senegalese Ministry of Water Resources and Forests and the *Agence Nationale de Conseil Agricole et Rural*, under the coordination of the *Conseil National de Concertation et de Coopération des Ruraux*.



Effects of cowpea inoculations on different soil types (Deck or Dior). Ouarkhokh, Senegal.
T. Uninoculated soil
R. Soil inoculated with a rhizobium strain
M. Soil inoculated with an endomycorrhizal fungus
Source: Do Rego *et al.*, 2015.

ASSOCIATING AND UTILIZING THE MUTUAL BENEFITS OF PLANTS

Natural ecosystems such as savannas have high plant diversity. Savanna plants—grasses, trees and bushes—compete for resources, but they also coexist and support each other which helps ensure the resilience of these environments. Some plants are thus able to tap specific resources, in turn making them available for other plants. The most representative example concerns legumes, which are able to fix atmospheric nitrogen via symbiosis with microorganisms. Once fixed, this nitrogen is introduced in the soil through the mineralization of litter generated by these plants, in turn benefiting other plants.

The relationship between woody and herbaceous plants further illustrates this beneficial interaction—trees tap resources from deep soil layers and redistribute them to grasses through their roots or the litter they produce.

Some agricultural, forestry and livestock production practices are modelled on these ecological processes. Many crop plots thus often include several species, e.g. cereals with different growth cycles, legumes planted between the cereal crops, etc. Agroforestry stands are also very widespread in Sudano-Sahelian regions.

Associating legume and cereal crops

Through the atmospheric nitrogen fixation process, legume-cereal associations enhance the effective use of environmental resources in low nitrogen input systems relative to the corresponding pure crops. This positive impact involves an overall yield gain relative to pure crops (monocultures), along with a significant and almost systematic enhancement in cereal protein content, irrespective of the proportion of cereals in the crop mix.

In some conditions, associations also provide a way to reduce weed, disease and pest pressure, which is generally considered as a crop production limiting factor. Moreover, associations are an interesting alternative to chemical control, which is too expensive for farmers and, above all, highly polluting.

Mixtures of species also have other advantages such as reducing soil erosion through better cover and rooting, enhanced lodging resistance, reduced risk of nitrate leaching and better interannual production stability. Moreover, crop associations (intercropping systems) seem highly promising for the development of sustainable food production under low natural resource conditions, especially regarding water, as is the case in West African dryland regions.

→ FOCUS | **Between-plant interactions – facilitation and competition**

Plants interact through the impacts they have on ecosystem abiotic and biotic components. Contrary to competition, facilitation is when the presence of a species has a positive effect on the establishment, growth, survival and reproduction of another species (Callaway, 2007).

Facilitation has an important role in ecosystem structuring and functioning in environments with substantial abiotic constraints such as drylands (Bertness & Callaway, 1994). Facilitation works in different ways:

- via direct mechanisms, when a species modifies the abiotic conditions of the environment in a way that benefits other species: in drylands, facilitation often occurs through enhanced access to water, shortages of which represent the main constraint to plant growth. Some plants tap water from deep soil horizons ('hydraulic lift') and make some of this water available for other plants with shallower root systems. By the shading they provide, some plants can also hamper evaporation and thus increase soil moisture. Facilitation may also occur via other resources such as nutrients, e.g. legumes that fix atmospheric nitrogen and make it available to other plants. It can also be the result of the mitigation of an unfavourable climate stress, e.g. for plants whose leaf temperature is reduced to below the lethal threshold by the shade of other plants
- through other living organisms: some plants develop mechanisms to repel herbivorous organisms, thus facilitating the growth of other herbaceous plants that animals may graze. Plants also attract pollinators or seed dispersing animals, which is beneficial for the reproduction of other plants. Facilitation sometimes occurs via soil microorganisms such as mycorrhizae
- through a negative effect on common competitors.

The different facilitation and competition mechanisms may mutually interact or conflict. The balance between the positive and negative effects is complex and depends on the species and age of both the facilitated and facilitator plants. A positive effect of one species on young individuals of another species can actually become negative for adults of the same species. In environments with a high seasonal rainfall component, a species can have a positive impact on water resources in the dry season while competing for light in the rainy season.

Monitoring and gaining insight into these facilitation mechanisms underlie many ecological engineering initiatives in dryland areas that take advantage of these interactions to boost the provision of ecosystem services upon which they intervene.

Agroforestry practices

Savannas are complex systems in which trees have a key role (see above). Trees are also very common in some agroforestry-based cropping systems.

Trees have a utilitarian value for households and a commercial value on local, regional and sometimes (but less often) international markets (e.g. shea butter and gum arabic). They enable income diversification while safeguarding the livelihoods of local inhabitants. The preservation or planting of trees in agrosystems also helps preserve soils and nutrient cycles, while enhancing biodiversity relative to pure annual crops, while trees also serve as a biomass stock (including carbon) in ecosystems and can generate microclimatic conditions that could offset meteorological fluctuations. This has prompted researchers and development stakeholders to assess the potential benefits of promoting agroforestry practices.

Wooded parklands—a type of agroforestry system—represent an element of centuries-old adaptive strategies of rural societies in sub-Saharan Africa. Farmers have long been clearing wooded savannas to serve as cropland. Useful trees are preserved in these selective clearing operations. These systems are then enhanced via the introduction of new species or by natural regeneration of the species present. Different types of agroforestry parklands have thus been developed over time, including *Faidherbia albida* and shea tree parklands.

Several attempts have been made to densify tree stands in crop fields, but this is not always an easy task. Beyond certain stand density thresholds, underground competition between the crop and associated trees for water and light often nullifies the benefits related to soil enrichment and microclimate improvement (Ong & Leakey, 1999). However, assisted natural regeneration of trees and shrubs—a widespread practice amongst inhabitants of the Sudano-Sahelian region—sometimes locally facilitates the extension and densification of tree stands in cultivated areas (Garrity *et al.*, 2010). The extension and improvement in the performance of wooded parklands could thus be possible if based on stakeholder experience, as is the case in assisted natural regeneration projects focused on the tree layer, for instance (*see next page*).

→ EXAMPLE | **Legume-cereal crop associations in northern Burkina Faso**

Legume-cereal crop associations are crucial in agrosystems in Sudano-Sahelian parts of Burkina Faso. Recent research carried out in northern Burkina Faso was focused on key socioeconomic factors regarding these associations and farmers' practices. Sorghum-cowpea and millet-cowpea are the most common crop associations. Farmers claim that these practices are geared towards meeting cultural, food, nutrition and economic needs. The choice of species and varieties in these associations is essential for optimizing their performance and is dependent on their complementarity regarding nitrogen use, as well as their spatiotemporal complementarity in light energy use. Because of the complementarity between associated species and the greater competitiveness of cereal crops for soil nitrogen and light usage, we hypothesize that cereal varieties to be used in associations should have a root system that is highly competitive for soil nitrogen use, good stem growth, an above-ground architecture and biomass production that will enable the dissemination of a suitable amount of light to the underlying plant cover.

For further information: Zongo *et al.*, 2016.

▲ **A cowpea-sorghum crop association. Burkina Faso.**
© F. Zongo

→ FOCUS | Assisted natural regeneration to reconstruct complex agroforestry systems

Assisted natural regeneration (ANR) is an agroforestry approach which aims to induce or stimulate natural regeneration of multipurpose tree species and/or their development and integration in agricultural areas (fields), where they could increase overall yields. This age-old practice involves saving and maintaining spontaneous naturally regenerated plants at preferred densities in crop fields (Samaké *et al.*, 2011).

ANR projects can be designed in two ways, either without fences but with hands-on involvement of local inhabitants as in Niger (Maradi and Aguié regions) (Larwanou *et al.*, 2006; Reij & Botoni, 2009; Reij, 2009), or in enclosed protected areas, like the initiative coordinated by the NGO newTree in Burkina Faso.

Since 2003, newTree has been launching plant cover restoration projects with the aim of densifying the tree cover in Burkina Faso, in areas where intensive crop production coexists with very low natural regeneration. The partners involved in this programme—farmers, administrative authorities, etc.—sign a contract and land agreement statements—documents that include both customary and administrative rights—for each site. A hedge is planted inside the fenced area. Management plans are then drawn up according to the partners' needs to ensure sustainable use of the restored areas. The involvement of women in decision making on management of deferred grazing sites is a decisive step in this process.

In late 2007, over 135 000 trees and shrubs were counted on 225 ha of degraded land (Mrs Kaguembèga, *pers. comm.*, 2011). Moreover, deferred grazing has helped preserve some rare species: *Boscia angustifolia, B. senegalensis, Maerua angolensis, M. crassifolia, Salvadora persica* and *Boswelia dalzielii.* Fuelwood and coproducts such as fodder, straw for roofing, traditional medicine products, etc., diversify and increase the income of local inhabitants. These results are evidence that forest degradation is not irreversible and that deferred grazing—if accepted and respected by all partners—has a positive impact on landscape dynamics.

However, the main difficulty to overcome with ANR is to have forest areas that are mutually available for grazing use by crop/livestock farmers and nomadic herders. Such grazing rights are included in customary land-use rights that are recognized by rural communities. However, in rangelands that are normally utilized by herders, trees and shrubs are, like grass, considered as a renewable community resource.

Knowledge regarding ANR enhancement and reproduction biology, levels of which vary markedly according to the species and country, must be improved: phenology, pollen and seed dissemination methods and distances, conservation conditions, pretreatment, seed stand inventories and mapping, genetic variability, studies on factors that are conducive to vegetative propagation, optimal domestication conditions, studies on the optimal carrying capacity, woody fodder crop management techniques, impact of trimming, pruning, topping and umbrella pruning on species survival, etc.

Faidherbia albida parklands in the southern Sahel are the most successful example of agrosilvopastoral integration (Peltier, 1996). Many characteristics of this tree are highly favourable for agroforestry uses—a phenological cycle that is the reverse of that of other trees, atmospheric nitrogen fixation that can enrich the agrosystem, roots that can tap water from deep horizons, and foliage with some forage value (*see next page*).

▲ **Shea fruit (*Vitellaria paradoxa*). Benin.**
M. Donnat © IRD

In the Sahel, shrubs like *Guiera senegalensis, Piliostigma thonningii* and *Piliostigma reticulatum* prevail more than ever, often in low density monospecies stands, in millet and sorghum fields and in very open landscapes. They have a substantial socioeconomic and agroforestry role and seem to be used to a high extent in local traditional soil restoration practices (Kizito *et al.*, 2007; Lahmar *et al.*, 2012; Wezel *et al.*, 2000, *see next page*). Further south, trees such as shea (*Vitellaria paradoxa*) are typical of Sudanian to Guinean savanna landscapes from Senegal to the Sudanian and Ethiopian rim (Teklehaimanot, 2004). Shea trees produce edible fruit and cooking oil (extracted from the nuts) that are consumed locally. They are also a source of nut-derived shea butter, which is being exported to an increasing extent worldwide (Pelissier, 1980).

Finally, trees in the sub-Saharan region also have a key land ownership function. A few studies have focused on gaining further insight into the stakeholders and their parkland management decision-making status (Asse & Lassoie, 2011). The transformation of rural societies in tropical regions is a highly dynamic process driven by heavy climatic constraints in a high population growth setting, changes in rural-urban exchanges and in economic and environmental policies. Understanding how these social transformation dynamics interact with agroforestry parkland dynamics is a major research challenge and a definite asset for drawing up management policies tailored for these areas.

Preserving native multipurpose shrubs in crop fields

Shrubs—especially *Piliostigma reticulatum* and *Guiera senegalensis*—often abound in farmers' fields in semiarid parts of West Africa. This green resource is essential during the long months of drought.

These two shrub species are found in Sudano-Sahelian and Sudanian landscapes in coastal regions from the Atlantic (Mauritania/Senegal) to the Red Sea (Sudan/Eritrea). These shrubs form pure or mixed stands whose densities can reach 2,000 shrubs/ha under favourable soil conditions. But they also grow in poor, hardpan and degraded soils in multi-stem clumps with a crown height and radius of around 1.5 m. *P. reticulatum*, in particular, is often found growing along the edges of fields in the form of shrubs or even trees several metres high.

These two species with tannin-rich foliage are browsed by livestock and are somewhat resistant to bush fires. They readily propagate via seeds, suckers and layering (*G. senegalensis*) and cut back stool shoots. Animals that feed on *P. reticulatum* pods also contribute to its spread.

Farmers know these shrubs well and use them in many ways, e.g. in traditional medicine, handicrafts and various domestic applications, while they even have cultural value in some areas. Farmers do not voluntarily or involuntarily plant or seed these two species to ensure their propagation, but they readily preserve them when they emerge in their crop fields.

→ FOCUS | *Faidherbia albida* - an agroforestry species with many virtues

Faidherbia albida is a nitrogen-fixing species (Leguminosae family) that is an integral element in traditional food cropping systems in Sudano-Sahelian areas of sub-Saharan Africa. This species is of interest for the production of wood and excellent quality off-season fodder, as well as for its beneficial impacts on associated crops, i.e. good food crops (cereals) or export crops like cotton. Three characteristics of this tree account for these impacts:

- *F. albida* has a phenological cycle that is the reverse of that of other trees (leaf growth in the dry season, defoliation in the rainy season), which has the dual advantage of generating supplementary fodder during shortage periods while limiting competition for light water and nutrient resources with food crops during its growth and maturation. This phenological asset also provides shady shelter for livestock in the dry season.
- Its tap root can grow to dozens of metres depth, enabling it to take up water from deep horizons, thus avoiding competition with grass species.
- Its symbiotic interactions with nitrogen-fixing bacteria enable it to participate in soil fertility restoration in the agrosystem. This results in the formation of root nodules within which bacteria convert atmospheric nitrogen into ammonium that can be assimilated by plants.

▲ ***Faidherbia albida* in a lowland sorghum field in southeastern Niger.**

When farmers begin tilling their fields in preparation for crop planting—at the onset of the rainy season, or even much earlier depending on the location or circumstances—the shrubs present are cut back to ground level. The trimmed stems and branches are used as fuel while the residue is burned. The cut shrub branches can also serve as mulch. The crop (generally a cereal) is sown directly in the mulch using a hand tool. At bolting of the cereal crop, the large leafless stems are gathered to use as fuel.

Burning is common practice in West African cropping systems and generates a direct supply of mineral elements that the soil needs, except nitrogen which volatizes during burning. However, mulch management has an impact on soil ecological processes via leaf and branch decomposition, thus preserving nutrients such as nitrogen while enhancing the soil organic matter content.

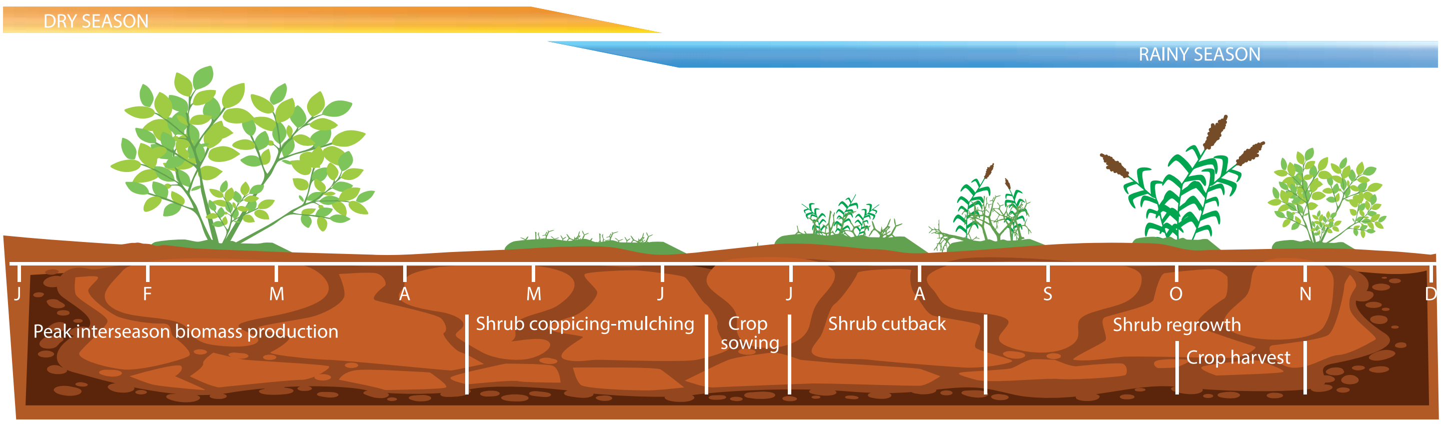
Research results on these two shrub species in Burkina Faso and Senegal (*see Focus on next page*) revealed that they provide essential services and facilitate the growth of plants living in their immediate vicinity (water and mineral nutrition, and even protection). Moreover, these species enhance the soil properties and maintain biological activity in the soil, thus reducing risks to the environment (carbon storage, reduced runoff and erosion, etc.), so ecological management of these shrubs is therefore highly warranted.

▲ In the foreground, a *Piliostigma reticulatum* shrub on the left and *Guiera senegalensis* shrubs on the right. Kaya, Burkina Faso.
© R. Lahmar

▲ *P. reticulatum* shrubs growing in a farmer's field. These are the result of yearly regrowth. Yilou, Burkina Faso.
© R. Lahmar

▲ Cutting and burning of *G. senegalensis* clumps at the beginning of the cropping season. Maradi, Niger.
© R. Lahmar

▲ Cutting of clumps and mulching with *P. reticulatum* branches at the beginning of the cropping season. Yilou, Burkina Faso.
© R. Lahmar



▲ **Native shrub management in cropping systems in semiarid areas of West Africa. Example of Piliostigma reticulatum, Yilou, Burkina Faso.**

Dry season: *P. reticulatum* growth, which reduces erosion and intercepts dust.
Rainy season: it is coppiced at the onset of the season to leave room of the main crop. It is cut back during the rainy season. The shrub is reformed via regrowth.
From Lahmar *et al.*, 2012.

→ EXAMPLE | **Two research projects on native shrubs in crop fields in the Sudano-Sahelian zone**

Burkina Faso: research on the Piliostigma reticulatum–sorghum association

The Crop-NEWS project* (Crop-news systems for improved soil and water conservation in African drylands) is a long-term experimental project that focuses research on associations between native shrubs (*P. reticulatum*) and annual crops (sorghum) in Burkina Faso. The project is set up on the campus of the International Institute for Water and Environmental Engineering (2iE) at Kamboinsé (jointly coordinated by CIRAD and 2iE). Two combined factors—shrub density and tillage—are tested in quadruplicate on plots of similar size to farmers' plots (13.6 m x 20 m). Four shrub densities are assessed, i.e. 0, 500, 1 000 and 2 000 clumps/ha, which are close to shrub densities commonly found on farms. The types of tillage tested include direct seeding with a *daba* (conventional short-handled hoe) at 0.8 m x 0.8 m spacing, and *zaï* (*see p. 35*) also with a 0.8 x 0.8 m honeycomb planting design. Sorghum residue is quantified and maintained yearly at equal weight on all plots. *P. reticulatum* was sown in a nursery in June 2012 and transplanted in the experimental plots in August 2012. The following aspects are monitored and measured yearly:

• sorghum biomass and seed development and production
• soil moisture at 3 m depth
• sorghum and *P. reticulatum* root development related to the shrub management strategy
• soil samples are collected and analysed after each harvest according to a predefined multiannual protocol
• many other measurements and tests are conducted according to needs, e.g. the degradation rate of *P. reticulatum*-derived mulch.

This project is specifically devoted to testing the hypothesis that these agrosystems are able to ensure long-term aggradation, or restoration, of degraded soils—a major challenge in the African tropics.

For further information: www.wassa-eu.org

* Four international projects are involved: Agroecology-based aggradation-conservation agriculture (ABACO), Woody Amendments for Sudano-Sahelian Agriculture (WASSA), Search for trade-offs between production and other ecosystem services provided by tropical agroforestry systems (SAFSE), CONNEcting knowledge, scales and actors; an integrated framework for adaptive organic resource management targeting soil aggradation and agroecosystems' resilience in sub-Saharan Africa (ConneSSA, https://connessa.uni-hohenheim.de).

Senegal – gaining further insight into the biological functioning of shrub-cereal crop associations

As part of international collaborations*, experiments have been under way in Senegal since the mid-2000s involving the integration of local shrubs in cropping systems: *Guiera senegalensis* in Thiès region and *Piliostigma reticulatum* in Nioro region.

These studies have highlighted the capacity of these two shrubs to redistribute water in soil for the benefit of surface horizons ('hydraulic lift' phenomenon) and to generate islands of fertility. Associations of these shrubs with cereal crops were found to enhance food crop yields.

Ongoing research aims to identify the underlying ecological processes. The hypothesis is that the presence of shrubs leads to the development of ecological niches conducive to the development of microbial communities involved in the supply of nutrients to the associated crop, thus promoting its growth. The research aims are to determine:

• the effects of the hydraulic lift phenomenon on microbial communities and the functions associated with these microorganisms
• the impact of crop associations on nematode communities and on the structure of soil food webs
• if microbial communities that are beneficial for the growth of plants growing near shrub roots colonize the associated crop
• the diversity of mycorrhizal fungi and their impacts on water and nutrient flows
• the identity of microorganisms that promote cereal crop growth and isolate them.

For further information: www.oardc.ohio-state.edu/senegal-pire/t01_pageview3/Home.htm

* PIRE/NSF project, Partnerships for International Research and Education/Hydrologic Redistribution and Rhizosphere Biology of Resource Islands in Degraded Agroecosystems of the Sahel: A PIRE in Tropical Microbial Ecology

◀ **Senegalese flora – *Faidherbia albida***
J.-J. Lemasson © IRD

▲ An agroforestry plot at Figuil in the far northern region of Cameroon (during the rainy season).
© R. Bellefontaine

▼ **Tifadine argan plantation (near Tiznit, southern Morocco)**: view of a 3 year old reforested plot that is not enclosed but is protected by local people who had made a request to the Water and Forestry Service.
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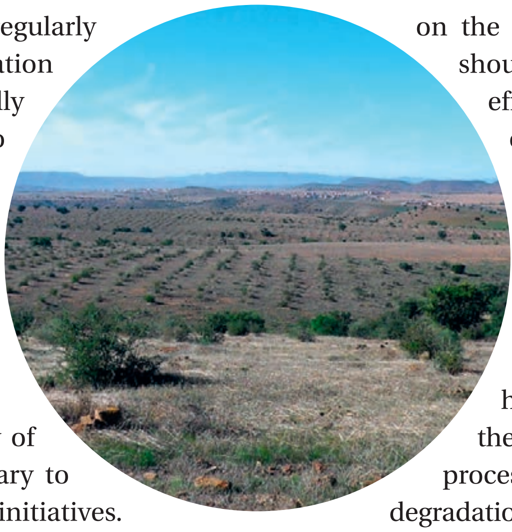
Ecological restoration of dry tropical forests

Environmental conditions favourable for dry tropical forests, i.e. with regard to the climate and a relatively high soil chemical content, are also often favourable for human activities. These forests have regularly been subject to intense degradation and deforestation pressure, generally for the conversion of forests into cropland. Growing environmental concerns related to the decline of agricultural activities in some areas have led to requests for the ecological restoration of these forests.



In-depth knowledge on the ecology of these dry tropical forests is necessary to ensure the success of restoration initiatives. However, these ecosystems have been the focus of far fewer studies than temperate forests and rainforests upon which dry tropical forest regeneration mechanisms have all too often been modelled (Vieira & Scariot, 2006). Wooded areas in dryland regions (savannas, forests, fallows, etc.) nevertheless have their own specific regeneration processes, with vegetative propagation and pollen, seed and fruit dissemination by wind and animals being important features, and where the phenology of seed production as well as regeneration barriers (very harmful violent or late human-caused fires, competition with introduced grazing grasses) usually depend on the rainfall seasonality. These features should be taken into account to effectively carry out restoration operations.

Once the social expectations concerning a restoration project (degraded soil restoration, wood production, ecosystem service production, biodiversity and habitats, etc.) have been identified, the key step in the ecological restoration process is to gain insight into the degradation mechanisms and land-use change dynamics. Drawing up restoration projects and identifying initiatives tailored to local constraints and potential are additional major steps, with active participation of the concerned communities and institutions also being essential (Griscom & Ashton, 2011).

Ecological restoration of wooded areas in dryland regions can be passive when the environment is somewhat resilient and has sufficient regeneration resources—forests spared from deforestation, wooded savannas and trees outside forests (rangeland trees, hedges and river bank corridors). Overcoming the degradation factors can thus be sufficient to stimulate the natural tree cover densification process. This densification should be combined with deferred grazing of local or transhumant herds by the building of fences or, less often, by getting nearby communities to strictly accept the deferred grazing conditions in exchange for advantages such as the set up of rural fuelwood markets (Bellefontaine *et al.*, 2000) or free fruit harvesting (Achour *et al.*, 2013). Deferred grazing is, however, seldom respected for more than 10 years.

In areas with high water and heat stress, etc. (arid and semiarid areas, cyclone areas, boreal areas, etc.), forest restoration initiatives could take advantage of the ability of some woody species to naturally regenerate by vegetative propagation (sucker induction, layering, cuttings in riparian areas), in addition to the implementation of artificial methods that are inexpensive (surface root injuries, root segment cuttings, air layering) or relatively inexpensive (propagation of stem or branch cuttings under a rough frame, grafting) (Bellefontaine *et al.*, 2005; Harivel *et al.*, 2006; Meunier *et al.*, 2008; Belem *et al.*, 2008; Morin *et al.*, 2010; Noubissié-Tchiagam *et al.*, 2011; Zida *et al.*, 2014).

Active ecological restoration of wooded areas in dryland regions could be an option when the regeneration potential is too low or when the soils are highly degraded. Planting might then be necessary to promote active restoration (Griscom & Ashton, 2011). The presence of planted trees and shrubs could then make the environmental conditions more conducive to natural regeneration by mitigating the risk of water stress in open environments or by improving soil fertility (Padilla & Pugnaire, 2006). After a few years, they could also attract seed dispersing animals. The choice of species is then especially important and should be tailored to the local biotic and abiotic conditions.

From a historical standpoint, active restoration initiatives rely mostly on lowland plantations and monocultures of exotic species selected for their rapid establishment potential (Parrotta *et al.*, 1997). However, these plantations have a low biodiversity value and sometimes represent a risk of colonization of surrounding environments by invasive exotic species. The use of local species and planting of mixed species are also favoured to an increasing extent for restoration. Moreover, the nucleation restoration technique, which has generated encouraging results in Mediterranean and humid tropical regions (Corbin & Holl, 2012; Rey Banayas *et al.*, 2008), could be beneficially used in dryland areas. This technique involves planting woody species in an isolated manner or in small batches leading to the formation of regeneration patches that gradually fuse. This represents an economically interesting and ecologically viable alternative to lowland planting.

◀ ***Sclerocarya birrea:*** induction of 1.8 m high suckers 6 months after a 4 cm diameter root wound at Figuil, northern Cameroon.
© R. Bellefontaine

◀ Rough propagation frame.
© Q. Meunier

→ FOCUS | **Sexual reproduction and low-cost vegetative propagation**

In Africa, travellers who cross—from south to north—Guinean, Sudano-Guinean, Sudano-Sahelian and Sahelian zones will pass through dense dry forests, then open forests, savanna, steppe, and ultimately sandy desert areas located in a maze of fossil rivers and temporary streams with sparse vegetation. On a south-north axis, gradually as the soil aridity increases, the vegetation regenerates predominantly from seed and then via stool shoots, root suckers or layering (Catinot, 1994). Woody species gradually lose their seminal reproduction potential at the edges of their distribution range. Flowering, fruit set and fruiting are hampered as the environmental conditions become unfavourable.

Abundant fruiting, efficient dispersal potential and various types of vegetative propagation enable trees and shrubs to recolonize areas. Sexual and asexual (vegetative) reproduction are inseparable and both strategies should be promoted by foresters in arid and semiarid regions:

• Sexual reproduction is vital for the genetic variability of woody species and enables plants to quite quickly adapt to environmental change. In arid and semiarid regions, seed propagation alone cannot maintain a sufficient density of woody species because many seeds die during the following long dry season due to fires and/or overgrazing. Moreover, increases in population growth and livestock herds in some regions regularly lead to mutilation of trees and shrubs of all sizes, thus reducing their seed production potential, vitality or may even eventually kill them. Deferred grazing after planting or timber harvesting is a long process and seldom complied with under forest management schemes based on natural or artificial seeding (direct seeding) with successive dry seasons that decimate seedlings during their first 3 years after germination.

• Vegetative propagation can be natural or artificial. Natural asexual propagation—involving totipotency (whereby each cell has the potential to differentiate into any cell type in the organism)—occurs by the multiplication of parent tree cells from certain tissues or organs at or in the vicinity of the parent tree. Artificial vegetative propagation involves the rooting of above-ground stems (air layering), sucker induction from surface root wounds, propagation from root cuttings and grafting. These long-standing techniques are seldom implemented in developed countries, where the focus is more on micropropagation and somatic embryogenesis. They also are often overlooked by African foresters, except for the propagation of branch cuttings and stool shoots. Vegetative propagation generates clones, i.e. individuals that are genetically identical to the parent plant. The main goal is to propagate remarkable trees in sufficient numbers, thus enabling the domestication of multipurpose woody species that farmers would like to propagate in their fields.

Low-cost vegetative propagation (LCVP) involves rustic cost-effective techniques that are readily understandable by rural farmers in arid and semiarid zones in developing countries.

These LCVP techniques generate faster growing plants that can be used by foresters and rural farmers. Compared to seeding, LCVP reduces the time for plants to reach maturity, especially for dioecious species in which, depending on the species, organs usually emerge 5-20 years after planting. Moreover, female plants are mainly grown in fruit plantations. Hence, a substantial economic savings can be achieved in fruit production by early determination of the gender of nursery plants or even at the seed stage. Molecular markers now enable early gender identification.

In Africa, few woody plant species are currently domesticated, apart from commercial fruit trees and olive trees. Studies are under way to assess genetic variability and vegetative propagation in various species:

• in North Africa: argan (*Argania spinosa* L. Skeels), pistachio (*Pistacia vera* L.), carob (*Ceratonia siliqua* L.)

• in the southern Sahara: baobab (*Adansonia digitata*), jujube (*Ziziphus mauritiana*), desert date (*Balanites aegyptiaca*), West African locust bean (*Parkia biglobosa*), shea (*Butyrospermum parkii*), marula (*Sclerocarya birrea*), tamarind (*Tamarindus indica*)

• further south: *Ricinodendron heudelotii*, bush butter (*Dacryoides edulis*), wild mango (*Irvingia gabonensis*), *I. wombolu*, white star apple (*Chrysophyllum albidum*), *Uapaca kirkiana*, etc.

For further information: Bationo *et al.*, 2005; Belem *et al.*, 2008; Bellefontaine, 2005; Bellefontaine & Malagnoux, 2008; Harfouche *et al.*, 2012; Harivel *et al.*, 2006; Meunier *et al.*, 2008; Morin *et al.*, 2010; Noubissié-Tchiagam *et al.*, 2011; Zida *et al.*, 2014.

▼ Argan roots visible 4 months after air layering (after removal of the plastic sheet surrounding the peat substrate).

▼ This marcot is replanted in a suitable substrate and protected from wind and sun exposure. Semi-hardwood cuttings can then be removed after a few months.

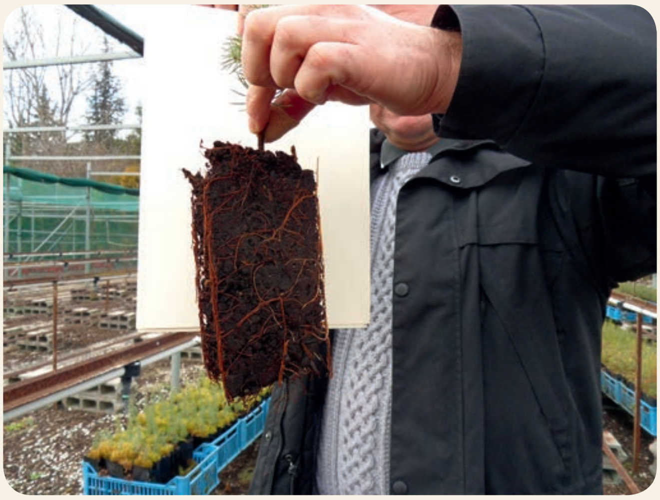
→ FOCUS | Quality seeds and plants with vigorous and balanced root systems for successful reforestation

The germination capacity of a forest species seed batch depends on the seed harvest and storage conditions and characteristics, including pretreatments. However, in semiarid parts of Africa, although the storage process and seeding conditions are generally better known, the same currently does not apply with regard to the seed harvesting, pulping, husking and drying conditions, which are still seldom specified. High variability in the germination of seeds depending on their origin is due to a dormancy state determined by the extent of fruit ripeness, to the plant genotype and to seed storage conditions. In such cases, a seed is incapable of germinating even when placed in ideal germination conditions. This commonly occurs in areas with a long dry season or where optimal germination conditions (humidity, temperature, oxygen, light) are seldom present at the same time. Mechanical, chemical, physical, physiological or biological seed pretreatments can help break dormancy, whose duration differs markedly within the same species, between seed batches and even between individual seeds. Pretreatments should be specifically applied to seeds that usually undergo deep physiological dormancy and that have been stored in good conditions.

The plants should also be reared under good conditions. Techniques involving polyethylene planting bags with or without a bottom, prestressed concrete clay ball, etc., are still used even though they are now obsolete. However, root malformations such as root mats (entwined roots) can hamper growth or lead to high plant mortality. Even when cut, these roots will not grow properly, leading to plant death. For years, root deformations upset the physiological functioning and proper development of roots, both of which are essential for tapping soil water and mineral resources. These deformations are particularly detrimental in semiarid zones where woody species have developed a drought adaptation strategy whereby a powerful, extensive and deep root system initially develops in priority over the development of above-ground plant parts. Any infringement to the proper development of this root system affects the plant's survival capacity as of the first dry season.

In order to produce plants with a high quality rooting capacity, it is essential to use suitable planting media, such as individual off-soil anti-root matting pots with large-mesh bottoms, a substrate using locally available materials, water and mineral nutrition adapted to local climatic conditions, supplemented by the introduction of bacterial or fungal symbionts. It is essential to train nursery gardeners on these new practices.

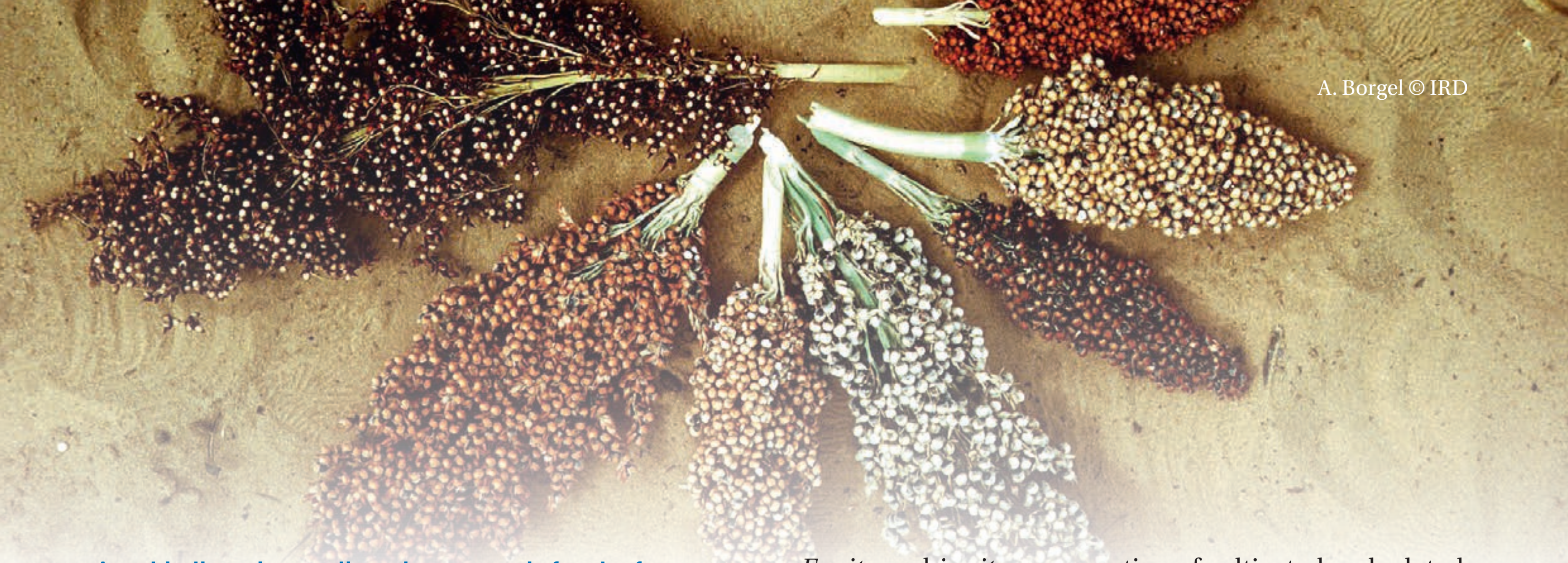
◄ **An unselected argan plant propagated by cuttings, grown in a 20 cm deep off-soil honeycombed rack to promote root self-girdling and ramification.**
© R. Bellefontaine



◄ **Plant grown in containers installed 30 cm above the soil ('off-soil').**
© R. Bellefontaine

◄ **This type of container helps avoid entangled roots by directing them downwards where they become necrotic upon air contact and form new lateral roots within the container, thus enhancing the efficiency of the root system once the plant is placed in the soil.**
© R. Bellefontaine

For further information: Bellefontaine *et al.*, 2012; Le Bouler *et al.*, 2012.



Agrobiodiversity – a diversity reservoir for the future

Global food and nutrition security is currently hinged on just 12 cereal species and 23 vegetable species (Altieri, 1999), while over 7,000 plants are actually grown or harvested in the natural environment for food. However, the intensification of a few major species and varieties is not sufficient to meet the needs of a growing population and an increasingly variable and hard to manage environment. These new social and climatic conditions could only be addressed by taking advantage of local species and varieties that are currently under-harvested.

Ex situ and *in situ* conservation of cultivated and related species, as well as of local know-how and associated agricultural practices, are ways to boost resilience to global change.

Family farming is based on high diversity in crop species and varieties, along with all of the knowledge and agricultural practices associated with this agrobiodiversity. The *Duupa* agrosystem in northern Cameroon, for instance, relies on 84 plant species that are cropped or protected in the fields (Garine, 1995).

→ FOCUS | Promoting the long-standing diversity of crops – the case of fonio

Many crop species have been neglected, underused and the topic of very little research and promotion. As these species are produced locally, they are highly adapted to their cropping environment and often have significant cultural value. They contribute to food security by being readily or freely available to local inhabitants, while also generating substantial income. Fonio (*Digitaria exilis*) is one of these species.

Fonio—described as a 'treasure' by Vodouhe *et al.* (2007)—is a seed crop that is regularly consumed by several million people in a region stretching from Senegal to Lake Chad. Long regarded as a marginal cereal, fonio is experiencing a resurgence of interest associated with the development of postharvest technologies and of new products for urban African and international markets. But fonio production is also of strategic interest to overcome food insecurity. This cereal, which ripens before other cereals, has a key role in bridging the hunger gap for millions of rural farmers and consumers. This species also generates supplementary income for farmers and, more particularly for rural women. Depending on the year, the per-kilo price of fonio can be 1.5- to 2-fold higher than that of rice.

Fonio—which is adapted to growing in drought conditions in poor infertile soil—is currently being investigated in national and international research programmes geared towards the development of fonio cropping. The Agropolis Resource Centre for Crop Conservation, Adaptation and Diversity (ARCAD) project* thus aims to develop an open multifunctional platform devoted to the establishment and optimal use of agrobiodiversity in Mediterranean and tropical regions. The diversity and potential of fonio is the topic of special attention in research under way in the 'Cereals in Africa' (African rice, millet, sorghum, durum wheat and fonio) subproject. Initially focused on Guinea, multidisciplinary methodological developments were shared in the framework of national fonio genetic diversity characterization projects (Niger, Senegal), thus promoting the creation of a permanent multidisciplinary research network on this cereal crop and the development of a sustainable conservation and usage scheme for these genetic resources.

* For further information on the ARCAD project: www.arcad-project.org

▲ **Harvesting fonio in Guinea.**
© A. Barnaud

Crop diversity concerns species, but also varieties, i.e. local or farmer varieties that are named and managed by farmers. They are not always as distinct, homogenous and stable as commercial varieties. Local varieties are very important since they host high genetic diversity while being adapted to local conditions (Mercer & Wainwright, 2012). Genetic diversity within a species is reflected by the adaptive potential, while varietal diversity is a guarantee that the species is able to adapt to new conditions and needs (Ortiz, 2011). These adaptation capacities represent potential genetic improvement capacities to cope with future environmental conditions.

The high genetic diversity of crops adapted to local conditions is the result of local farmers' agricultural and plant breeding practices (e.g. in millet and fonio, *see below*).

→ FOCUS | What plant and social adaptations are possible?

During the domestication process, humans have selected traits of interest for human food production. This has led to a rise in crop yields but also to a decrease in genetic diversity in crop species relative to their wild ancestors. Breeding programmes often make use of these ancestral species or closely related wild species (Hajjar & Hodgkin, 2007) to improve the resistance of crop species to abiotic (drought, salinity, poor soils) and biotic (pest insects, diseases) factors.

Adaptations of crop plants to local conditions are the result of farmers' agricultural and plant breeding practices. To cope with future climatic conditions, farmers develop strategies such as using more drought-resistant varieties, developing water harvesting systems, while practicing intercropping, agroforestry and diversified farming practices (Altieri, 2009).

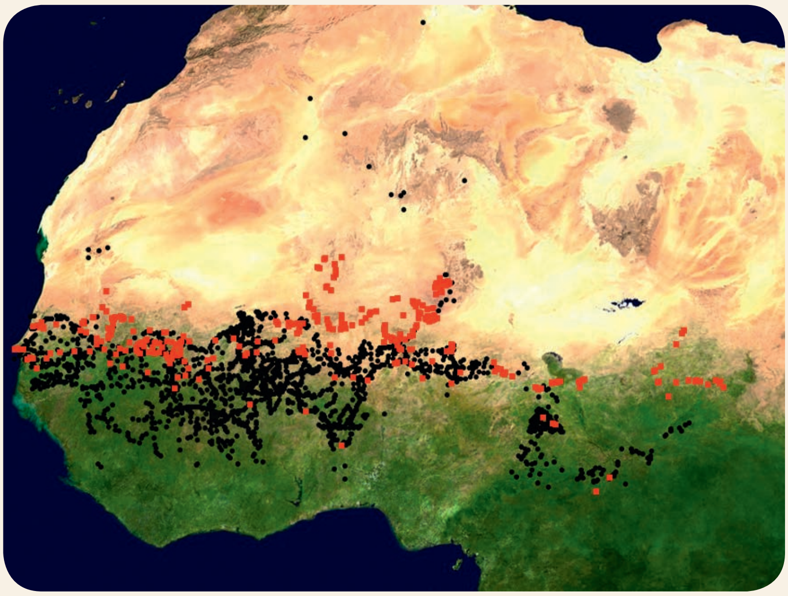
Promotion of wild plant diversity – the case of millet

Cultivated millet (*Pennisetum glaucum* ssp. *glaucum*) was domesticated from the wild type (*P. glaucum* ssp. *monodii*) around 4 800 years ago in a region located between Mali and Niger (Clotault *et al.*, 2012). Its domestication led to an estimated 30% loss of diversity (Oumar *et al.*, 2008). Wild pearl millet has greater resistance to arid conditions, so it is of considerable interest for identifying genes and polymorphism involved in the adaptation to harsh climatic conditions. This could help improve the resistance of cultivated millet to future climatic conditions.

In Africa, the millet flowering cycle is reduced as a partial response to arid conditions. In the 1970s, a long drought period affected West Africa with a 150 km southward shift in the isohyet for 100 mm precipitation. During this period, farmers bred millet to reduce its flowering cycle by 1.44 days on average over 27 years. This evolution and varietal adaptation were found to be specifically associated with one allele (PHYC gene) whose frequency doubled in varieties. During this heavy drought period, farmers mobilized intraspecific diversity of millet to address the new climatic conditions (Vigouroux *et al.*, 2011).

Identifying genes involved in the resilience and adaptation of crop plants to climate change

The 'Population genomics of the adaptation of wild pearl millet' project (MILDIV) aims to highlight genetic variations in wild pearl millet associated with the climate gradient extending from Senegal to Sudan. Detected genetic variations will be correlated with phenotypic variations by genetic association methods in order to highlight genetic adaptations to which the adaptive factor and its phenotypic expression are associated. The approach chosen for this project involves genome-wide sequencing using advanced high-throughput sequencing methods. These identified genes will be used to develop tools for rapid determination of the best plants adapted to harsh future climatic conditions. This will help to accelerate millet breeding programmes.



▲ Distribution range of wild pearl millet (red) and cultivated millet (black) in West Africa.
Georeferencing of millet seed accessions in the IRD collection.
Map by C. Berthouly-Salazar/IRD.

Promoting organic matter and nutrient cycles

Ecosystem balance and functioning are dependent on the extent of materials, energy and information that flow via the different component parts, i.e. soil, plants, animals, atmosphere, etc. (Frontier & Pichod-Viale, 1998).

Organic matter serves as a vector for these material and energy flows within ecosystems, while also determining the cycles of major chemical elements, such as carbon, nitrogen and phosphorus (Swift *et al.*, 1994). Any changes in the organization of ecosystems and associated material and energy flows have an impact on ecosystem productivity and sustainability.

In ecosystems, organic matter is a renewable resource that must be efficiently managed to ensure the different ecosystem services. The organic matter dynamics involve different types of carbon (an organic matter measurement unit) that are manipulated by various stakeholders and components (humans, plants, animals) that produce, consume or process this organic matter throughout the various food webs (Manlay *et al.*, 2007).

In agrosilvopastoral systems, especially in Sudanian and Sudanian-Sahelian areas, agrosystem productivity is largely based on organic resource management (Manlay *et al.*, 2004; Nye & Greenland, 1960; Pieri, 1989; Tittonell *et al.*, 2007). In a high climatic risk or socioeconomic constraint setting, all land use changes lead to modification of organic compartments and transfer processes that have evolved over time in ecosystems and on village lands. For instance, the loss of fallow lands reduces plant biomass and pastoral resources available for livestock which ensure the transfer of fertility from uncultivated to cultivated areas. Conversely, good management of organic resources and nutrient and energy flows supported by these resources guarantees the sustainability of farming practices.

Organic matter and nutrient cycles can be enhanced at different levels:

- the quality of organic resources used in agricultural practices—certain litter-producing plants such as legumes that generally have a high nitrogen content can be favoured. Manure is processed organic matter and composting stabilizes organic matter decomposition while enriching it with nutrients such as mineral nitrogen
- practices that promote organic matter recycling on lands, such as integrating trees, crops and livestock, which seems to be a key element in ensuring the sustainability of some agrosystems.

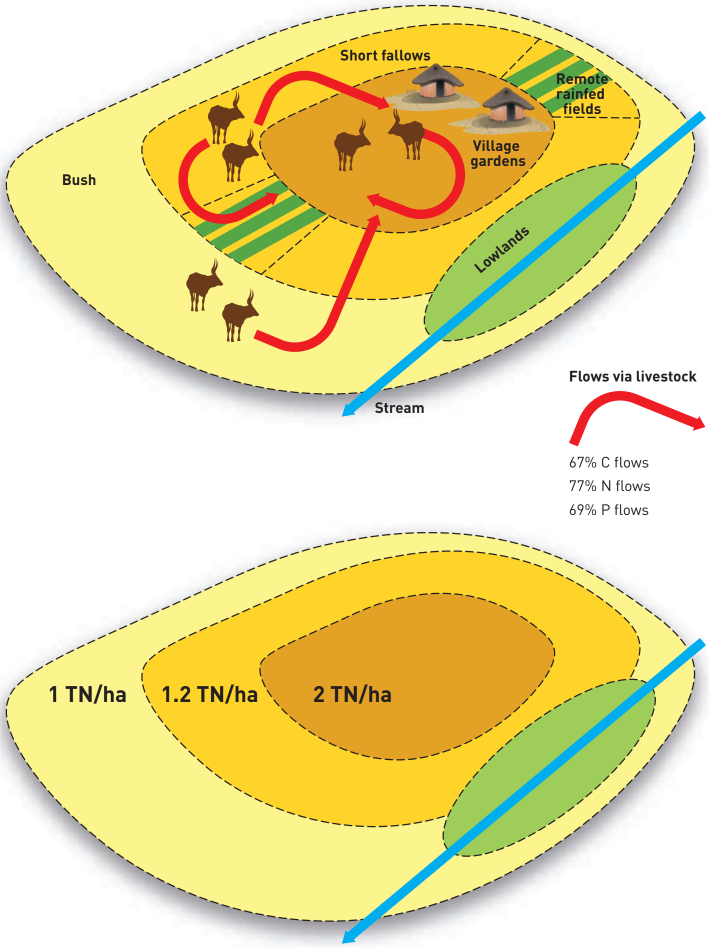
◄ Mixed sheep, swine and cattle herd in the late dry season, Tsiafajavona, highland region of Madagascar.
© K. Naudin

STRENGTHENING LIVESTOCK/CROP FARMING INTEGRATION WHILE PRESERVING NATURAL RESOURCES

Is the agrosilvopastoral system tailored for savanna regions?

Savannas, which are generally made up of a grassy layer with scattered trees and bushes, are hampered by bush fires and the presence of herbivorous animals (Koppel & Prins, 1998). Savannas have high numbers of many different herbivorous mammals (gazelles, antelopes, wildebeests, buffalos, etc.) occupying specific trophic niches. This ecosystem hosts the largest terrestrial mammals and the greatest herbivore biomass per unit area. Savannas are thus recognized as being one of the most productive ecosystems in terms of animal biomass (Mooney *et al.*, 2001; Abbadie *et al.*, 2006).

This high diversity, heterogeneity and complexity is found in agrosilvopastoral systems that are traditionally restored and managed by rural communities (van Keulen, 2006). As already discussed, locally managed lands are conventionally organized in three major areas exclusive of the residential site: village gardens, bush fields and rangelands (wooded savannas or forests). The landscape is thus marked by an alternation of mainly woody plant cover and annual crops. Livestock has a key role in fertility transfer within the locally managed lands (*see adjacent figure*).



▲ **Nitrogen stock per landscape unit and cattle herd driven fertility transfers resulting in concentric fertility rings.**
Source: Manlay *et al.*, 2004.

→ FOCUS | Soil organic matter is essential for soil fertility

Soil organic matter corresponds to all live and dead organic materials in the soil, including plant roots, soil microorganisms and microfauna, as well as decomposed (or not) plant residue. This continuum of relatively complex and perpetually recycled materials builds up via an ongoing supply of dead plants and animals, in addition to organic matter (e.g. root exudates) derived from the metabolism of living organisms. This soil compartment also benefits from external organic matter inputs (e.g. compost and manure).

Soil organic matter—by supplying mineral nutrients for plants and the physical fertility via its effects on the soil structure—enhances the chemical fertility of the soil. It is an important soil quality component for plant production.

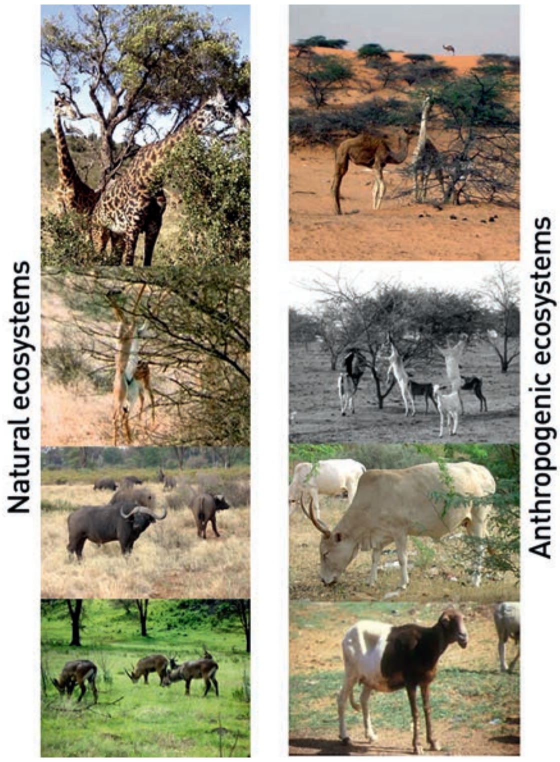
Soil organic compound transformation is a complex process involving various factors, mainly: (i) the organic substrate nature, (ii) the microbial communities involved, and (iii) the characteristics of the environment in which the processes occur. These factors spatiotemporally interact at multiple scales, from the soil aggregate to the ecosystem or agroecosystem. These different factors can be engineered to orient the productivity of the soil and hosted ecosystem or agrosystem.

Source: Bernoux & Chevallier, 2013.

In agrosilvopastoral systems, there is also high species diversity in cultivated plants coexisting with uncultivated plants (legumes, cereals, fruit trees, etc.), and livestock species (poultry, pigs, horses, sheep, cattle, goats, etc.). These animal species occupy complementary trophic niches, as is also the case with wild savanna herbivores (*see adjacent*).

Moreover, as in natural savannas, fires and ruminant animals have a key role in preserving the heterogeneity of agrosilvopastoral systems:

- livestock farmers, or hunters, deliberately light fires at various intervals (up to once a year in domestic and bush fields, and less frequently in rangelands, savannas and forest areas)
- herders lead their herds to grazing areas and preferential resting areas. The spatial heterogeneity is thus accentuated by night paddocking, which leads to trampling and overgrazing. This practice also helps focus fertility in certain areas (e.g. in domestic gardens), while creating areas where grasses are grazed at a more intense pace, thus enhancing the fodder quality during the rainy season at peak forage plant growth (Augustine, 2003; Fynn, 2012). These livestock farming practices have similarities with the natural behaviour of African savanna buffalos (Winnie *et al.*, 2008).



▲ Species diversity and similar trophic niches occupied by wildlife in natural ecosystems and by livestock in anthropogenic systems.
© Google & J. Vayssières, 2014

Livestock farming is highly present in tropical dryland regions. This activity is particularly suited to the climatic constraints that prevail in these areas, especially when hardy breeds are used (Nozières *et al.*, 2011). This high level of adaptation could be explained by: (i) the mobility of animals that are able to reach areas where fodder and water are still available (Leclerc & Sy, 2011), and (ii) the capacity of animals to store and utilize body reserves according to the seasonal availability of fodder resources (Mandonnet *et al.*, 2011).

Livestock (especially ruminants) is present in most dryland farms and areas. Livestock and crop farming are often combined on family farms in developing countries (Herrero *et al.*, 2010), thus guaranteeing sustainable production in low-input agricultural systems that prevail in dryland regions via animal manure inputs (Vigne *et al.*, 2013).

Population growth in rural areas gradually leads to spatial saturation, cropping of parts of rangelands and reduced fallowing times. These land-use dynamics, which are quite widespread in drylands, threatens conventional systems that involve fertility transfers from rangelands to crop fields, sometimes leading to the departure of wandering herds from village lands. For instance, in the Senegal groundnut cropping area, cattle herds currently leave for transhumance almost year-round. There has hence been a significant decline in the presence of livestock on most village lands in the region. The livestock stocking rate has dropped from around 3 to 1 TLU/ha* in less than 50 years, prompting a significant reduction in available organic animal manure.

▲ Zebu farming, Senegal.
A young herder and his zebu herd.
J.-J. Lemasson © IRD

* TLU: tropical livestock unit. Unit used to determine grazing fees and consumption. It corresponds to a herbivorous animal of 250 kg live weight.consommations.

→ FOCUS | Crop-livestock farming systems viewed as food webs

By analogy with natural ecosystems, a farm—or a combined crop-livestock farming area—could be represented and analysed as a food web with humans at the top of the chain, where crops and plant communities on rangelands constitute primary production, with ruminants and other livestock being intermediate links.

This representation is closely in line with the main crop-livestock integration principles, i.e. using, in one activity, part of the biomass produced by another activity (and vice versa). As shown in the adjacent diagram, this integration could be analysed in terms of biomass recycling. Rangelands—even forests, crops and any other source of primary production, including trees outside forests—generate plant biomass which is partially used for livestock feed. These animals, in turn, produce organic manure which serves as a nutrient supply for plants.

Crop-livestock integration has long been described solely from a qualitative standpoint. Quantitative methods sparked by food web analysis methods and focused on nutrient and energy cycles have been implemented in recent years to quantify the extent of crop-livestock integration in various regions worldwide: Ethiopia, Kenya and Zimbabwe (Rufino *et al.*, 2009), Réunion (Vayssières *et al.*, 2009), Madagascar (Alvarez *et al.*, 2013), West Indies (Stark *et al.*, 2014) and, more recently, in West African drylands (Bénégabou *et al.*, 2014). These studies revealed high diversity in the extent of this integration between regions and within the same soil-climate zone. This high diversity within the same zone implies that there is substantial leeway for change, based on the overall assumption that farming systems could be more efficient, productive and environment-friendly with greater crop-livestock integration and energy and nutrient (including nitrogen) preservation during their cycles.

▲ **Biomass recycling on combined crop-livestock farms.** Organic matter is recycled on a combined crop-livestock family farm. Arrows indicate transfers between compartments and losses during these transfers.
© Source: Rufino *et al.*, 2006

Livestock farming and productivity in agrosilvopastoral systems

In savanna regions, it is now recognized that, at a certain animal stocking level, the presence of ruminants promotes primary production (de Mazancourt *et al.*, 1999; Hayashi *et al.*, 2007). Livestock, especially large ruminants, accelerate nutrient recycling via plant biomass digestion and highly nutrient-rich dung production. In agrosilvopastoral systems, ruminants thus boost nutrient supplies—particularly nitrogen and phosphorus—required for crop growth (de Mazancourt *et al.*, 1999; Roux *et al.*, 2006).

The presence of ruminants also leads to substantial nutrient cycle reorganization (Daufresne & Loreau, 2001), ultimately enhancing the productivity of cultivated ecosystems in savanna areas:

- in rangelands, ruminant grazing of plant biomass reduces herbaceous plant production layer but may also promote tillering of grasses, which in turn could stimulate above-ground biomass production if the grazing pressure is not too high. Moreover, grazing reduces the amount of biomass that could potentially

▼ Transhumance of Fulani herds in Mali.
Transhumance of Fulani herds and zebu cattle crossing the Niger River at Diafarabe in Mali.
G. Fédière © IRD

burn, thus indirectly serving as a fire control while improving organic matter conservation. In crop fields, the input of organic matter via livestock helps reduce the pressure of weeds such as *Striga hermonthica* in drylands cropped with dry cereals (millet, sorghum) and legumes (groundnut, cowpea)(Kayeke *et al.*, 2007; Dzomeku & Amegbor, 2013)

- ruminants can digest cellulose in rough fodder and crop residue, which means they can make effective use of biomass that is otherwise inedible for humans and monogastric livestock (pigs, poultry).

Livestock farming can nevertheless have non-beneficial impacts, especially on the environment and biodiversity. The increase in livestock numbers and farms, improved sanitary conditions and the development of road transport of livestock have negative environmental impacts under some conditions, as shown by the vegetation state and soil degradation observed around wells in the Sahel, sometimes affecting an area several dozens of kilometres from the well. In overgrazed rangelands, natural tree and shrub regeneration can be disrupted, leading to a loss of woody plant diversity and productivity. These effects are also aggravated by bush fires started by livestock farmers to stimulate rapid regeneration of grasses. Finally, livestock roaming through agricultural land during the dry season often hampers the implementation of beneficial cultivation practices such as tree and shrub planting and grass sowing (e.g. improved fallows). Conflicts between crop and livestock farmers are ongoing, especially in areas where natural resources (land and fallows) are shared. Hence, it is sometimes necessary to find a smart land sharing trade off to manage forest, agriculture and pastoral areas.

Enhancing the resilience of agrosilvopastoral systems via livestock management

According to the scale, there are three preferred ways to increase the resilience of agrosilvopastoral systems via livestock farming:

- on the plot scale: increase available fodder resources
- on the farm scale: reduce nutrient losses, especially nitrogen, by feeding livestock with supplementary fodder, spreading manure or dung generated by night paddocking on crop fields, and periodically stabling livestock on farms
- on the territorial scale: develop the area to facilitate the presence and mobility of livestock and enable fertility transfers, while reducing the impact of livestock on natural resources, especially trees and shrubs.

Apart from crop residue, which is widely utilized for livestock feed, the main forage resources are naturally found on rangelands (mainly grasses and shrubs) and are provided by trees present in the fields (e.g. *Faidherbia albida* in the groundnut cropping area of Senegal). Organic manure supplies can be increased, thus enhancing the crop fertilization potential, by increasing forage resource availability.

At the plot scale, fodder production can be increased by planting forage trees (Vandenbeldt & Williams, 1992; Ibrahim & Tibin, 2003), introducing forage legumes and/or controlling animal stocking rates in order to optimize rangeland primary production. Increasing the sheltered fodder storage capacity, rather than in trees or on roofs, also helps reduce losses, while ensuring better fodder preservation until the lean season. This technical solution is especially beneficial as it concerns high food value fodder such as groundnut and cowpea haulms.

Nitrogen is the most limiting mineral in dryland farming systems. The introduction of livestock in the biomass cycle alters the nitrogen cycle, with a concomitant risk of nitrogen loss (Rufino *et al.*, 2006). The presence of livestock increases the number of steps in which biomass is processed, manipulated, and/or gas exchanges are possible. This presence thus increases the risk of gaseous nitrogen (ammonia) loss. In dryland areas, this risk is accentuated by high temperatures and low relative humidity. Otherwise, the possible loss of liquid nitrogen, i.e. nitrate (NO_3^-), is likely limited because of the low rainfall in drylands (Vayssières & Rufino, 2012). These nitrogen losses are potentially harmful for the environment (e.g. contributing to global warming and eutrophication of aquatic environments), while also causing overall ecosystem productivity loss.

It is possible to intervene at different steps to reduce gaseous nitrogen loss, so it is recommended to:

- regularly collect animal dung and, if possible, store it in a manure pit to limit production losses (Blanchard *et al.*, 2013)
- cover manure pits with a tarp to reduce storage losses (Tittonell *et al.*, 2010)
- bury organic manure during spreading to reduce losses in the field (Murwira, 1995). A broad range of animal dung management practices are implemented in West Africa (*see photos below*).

It is harder to limit these gas losses with wandering livestock herds because a substantial amount of the dung is directly dropped and left in the field or rangeland. Most of the measures proposed above can be applied when livestock is kept in a stable or paddock for at least part of the time (e.g. during fattening periods).

Finally, on the territorial scale, maintaining short fallows (Odru, 2013) or corridors within the concerned area (Brottem, 2014), is a solution for keeping animals year round. However, these systems must be designed to link different zones within the area, from the periphery of the village to the centre in order to facilitate fertility transfers between these zones. In parallel, increasing the herd size, in a reasonable manner relative to the fodder supply available within the area, helps increase these fertility transfers and thus to ecologically intensify agricultural production on the village land scale. This strategy is complicated to implement because it requires collective coordination and organization within the concerned communities. This capacity can be enhanced via participative mapping and modelling.

▼ **Diversity of animal dung management practices in West Africa.**

Night paddocking of cattle on a crop plot at Sare Yoro Bana.
Casamance, Senegal.
© J. Vayssières, 2014

Dunghill on a family farm at Bary-Sine.
Groundnut cropping area, Senegal.
© J. Vayssières, 2014

Manure pit on a family farm at Koumbia.
Cotton cropping area, Burkina Faso.
© M. Blanchard, 2010

→ EXAMPLE | A project to improve organic manure production in Burkina Faso

In mixed crop-livestock farming systems in western Burkina Faso, farmers spread organic manure and mineral fertilizer to manage soil fertility in their fields. However, for economic reasons, mineral fertilizers are not substantially used and only 9% of organic fertilizer needs are met.

Organic manure production is actually based on relatively non-diversified techniques that make effective use of only a small fraction of the biomass produced on farms (household waste, animal dung and crop residue)—only 12% of the crop residue produced is thus used for organic manure production. Farms are poorly equipped with regard to infrastructures, thus promoting the use of organic resources produced on the farm: only 33% of farms have a dung pit on the concession and 7% have a pit in the field. Moreover, farmers do not effectively manage the biomass decomposition conditions (C/N ratio, aeration, humidity) and the organic matter produced is thus of low quality, 83% of this organic matter has carbon and nitrogen contents of below 12 g C.100 g DM^{-1} and 0.6 g N.100 g DM^{-1}, respectively (Blanchard *et al.*, 2014). Organic manure spreading is often limited to fields near the concession and the dung pit since only 50% of farms have a cart to haul biomass (Vall *et al.*, 2006).

In this setting, the aim of the 'Agropastoral and soil fertility innovation' project (Food Fertipartenaires, 2008-2014) was to enhance soil fertility by increasing organic manure production on farms and improving their management. The project was based on a design approach in partnership with farmers running innovative farming systems.

This project helped strengthen the innovation capacity of farmers through the acquisition and development of new technical specifications on organic manure production. The project thus contributed to the development of low labour investment field composting techniques, involving: (i) one-shot pit filling at the end of the dry season (year n) and emptying the pit during the dry season of year n+1, (ii) the use of unchopped cotton stems, (iii) no turning over of compost, and (iv) rainfall as the only water supply. *Ex post* assessments of the project revealed that organic manure production on farms had increased through the multiplication of production sites distributed between the concession and the fields, thus reducing transport times. Manure use thus increased by 3.4-fold between 2007 and 2011. The project also led to a reformulation of organic manure spreading standards according to the quality of the available organic matter and the type of soil cultivated (*see below*), thus differing from standards generally calibrated according to high quality organic manure (Berger, 1996).

Organic manure application recommendations

	Organic manure application (kg DM ha^{-1} $year^{-1}$)	
Type of organic manure	**Sandy soils**	**Clay soils**
Rich manure	2 381	2 054
Medium quality manure	5 112	4 410
Rich compost	4 047	3 491
Medium quality compost	5 337	4 604

Table source: Blanchard *et al.*, 2014.
For further information on the Food Fertipartenaires project (in French): http://food-fertipartenaires.cirad.fr

→ FOCUS | A research programme on the effects of ramial chipped wood on soils and crops in Burkina Faso

The aims of Woody Amendments for Sudano-Sahelian Agriculture (WASSA) programme, funded by the European Union and conducted jointly by IRD, the University of Ouagadougou and the *Institut des sciences et industries du vivant et de l'environnement* (AgroParisTech), are: (i) to assess whether savanna soil properties and cultivated plant performances could be specifically improved using ramial chipped wood (RCW) amendments, and (ii) to determine the availability of branch resources on village lands.

The impact of soil amendments *Piliostigma reticulatum* RCW, blended or not with mineral nitrogen, on sorghum crops and the soil was studied, in comparison to conventional crop residue inputs, during three crop seasons under 700 mm mean annual rainfall conditions. At low dosages (1,5 t DM ha year), RCW inputs only barely improved the performance of sorghum crops compared to equivalent straw inputs, but slightly more compared to the control without inputs. However, the differences were seldom significant partly because of the high spatial and interannual variability in the monitored variables. There was also very little impact on the chemical properties (available carbon, nitrogen and phosphorus). RCW inputs nevertheless markedly stimulated termite activity (by 4- to 18-fold as compared to other treatments). Comparison of the results with those of other studies did not reveal any overall trend that could be applied to dry tropical conditions. Various ramial wood action processes dependent on local ecological conditions were noted.

An assessment of the availability of RCW resources for agroecological use in two village areas (under dry and subhumid climatic conditions) also helped develop models for the prediction of ramial biomass stored and produced per tree. Biomass that could be the most available, without competing with other current or future uses, would include thin branches and shrubs, i.e. 1.75 and 8.51 t, respectively, of dry matter cultivated in dry and subhumid areas.

However, these estimates are not very sure, partly due to the high spatial heterogeneity. They nevertheless suggest that it is essential to densify tree and shrub stands to be able to sustainably fulfil branch needs, even for modest amendment scenarios.

Source: Barthès *et al.*, 2010.
For further information: www.wassa-eu.org

RESTORING SAVANNA SOIL BIOTA BY SPECIFIC ORGANIC INPUTS

Organic soil fertilization is the main soil organic matter management strategy in sub-Saharan Africa. Organic resources are often limited in these areas and woody residue (small branches and leaves), combined with legal sustainable use of shrub prunings and ramial chipped wood, is a substantial organic resource.

The application of tree branches on soils for their conservation or restoration mimics what occurs in natural wooded ecosystems. In dryland areas, RCW inputs in crop fields thus mimic organic inputs that naturally occur in savanna soils, which are considered models of fertility and stability. The impact of these tree branch inputs is closely linked with their biochemical properties (high barely polymerized lignin content, balanced mineral content), which stimulates fungal rather than bacterial growth, but these qualities are only obtained with small diameter wood inputs. Food web diversification leads to diversification in forms of soil organisms, improvement of soil properties, while ultimately enhancing plant growth. Carbon inputs serve as a source of energy to maintain ecosystem organization, while also being sustainably stored in a stable form.

A review of scientific knowledge on the impact of RCW inputs in soil on agroecosystems suggests that this practice generally has a positive effect on soil properties and crop plant performance (Barthès *et al.*, 2010, *see previous page*). But the review also found that few studies have been carried out in arid regions and questions the relevance of the control (a treatment without fertilizer inputs) used to assess the benefits of RCW inputs as compared to other fertilization practices.

▼ **Wood residue inputs for soil restoration. Kindi, Burkina Faso.**
© D. Masse

▲ ***Zaï/Tassa* on the Badaguichiri plateaus, Tahoua region, Niger.**

LOCAL PLANT NUTRITION

Many observations in natural environments revealed that some plants survive by concentrating nutrients around their root system. *Zaï*—an agricultural practice that mimics ecological processes—is applied by some farmers in Sahelian regions of Burkina Faso and Niger.

In Moré (a local language in Burkina Faso), *zaï* means 'rising early and hurrying to prepare your land', by breaking up the hardpan before seeding. This traditional method helps recover degraded land with hardpan (*zipellé*), or very degraded land (*zipédaaga*) in Yatenga (region in northern Burkina Faso). This practice involves digging small 20-40 cm diameter and 10-15 cm deep pits with a hoe during dry periods, and then throwing in one or two handfuls of organic manure. This enables occasional localized regeneration of these degraded soils, which combines breaking hardpan, runoff and organic element capture, localized input of organic matter and minerals, and rejuvenation of the microbial community, thus facilitating agricultural production in very harsh regions.

Studies carried out by Roose *et al.* (1999) in Burkina Faso showed that crop yields increased using this method—from 0.2 $t.ha^{-1}$ of cereal grains in the control plot to 1-1.7 $t.ha^{-1}$ in the *zaï* managed plot. Zougmoré *et al.* (2005) also showed that adding compost or manure in the pit, at a dose of 300 g per pit, generated 8-fold higher yields than could be obtained without manure input (800 $kg.ha^{-1}$ of sorghum grain). Somé *et al.* (2004) obtained similar results when studying the effects of *zaï* on cowpea crops: *zaï* led to the production of 200 kg ha^{-1} of cowpeas and 1 200 $kg.ha^{-1}$ of haulms, while zero production was obtained in the control treatment. Fertilizer input (NPK), at 80 $kg.ha^{-1}$, or combined with compost, generated 900 $kg.ha^{-1}$ of sorghum on gravelly *zipellé*, compared to 690 $kg.ha^{-1}$ with compost alone.

Fallowing of fields managed with this agricultural *zaï* technique also leads to gradual establishment of vegetation (grasses, woody plants), after which a different type of management is used, i.e. 'forest *zaï*'. This practice can be illustrated by the experience of Mr. Yacouba Sawadogo, a farmer whose activity began in the village of Gourga (Yatenga region) in the early 1980s. From a plot cultivated using the *zaï* technique, after weeding, he grew and maintained seedlings of tree species that had been sown in one of every three pits in the crop field. At harvest, the stems were broken at 1 m height to protect the young seedlings from wind erosion and to keep them out of the view of livestock. Forest cover was reconstituted after a few years (5 years), with shrubs being used as brushwood or poles (first fuelwood harvests).

Zaï facilitates cropping on degraded land by enabling runoff management, manure and seed conservation, fine particle concentration, fertilizers and water in pits, in the immediate vicinity of plants, especially at the beginning and end of the rainy season. Moreover, the rejuvenation of biological activity enhances the soil properties and creates an environment favourable for crop growth. Through this rehabilitation practice, uncultivated areas can be recovered and farming made possible. In addition, pressure on land and natural resources can be reduced.

However, despite its many advantages, *zaï* cannot overcome all agricultural production constraints in the Sahel:

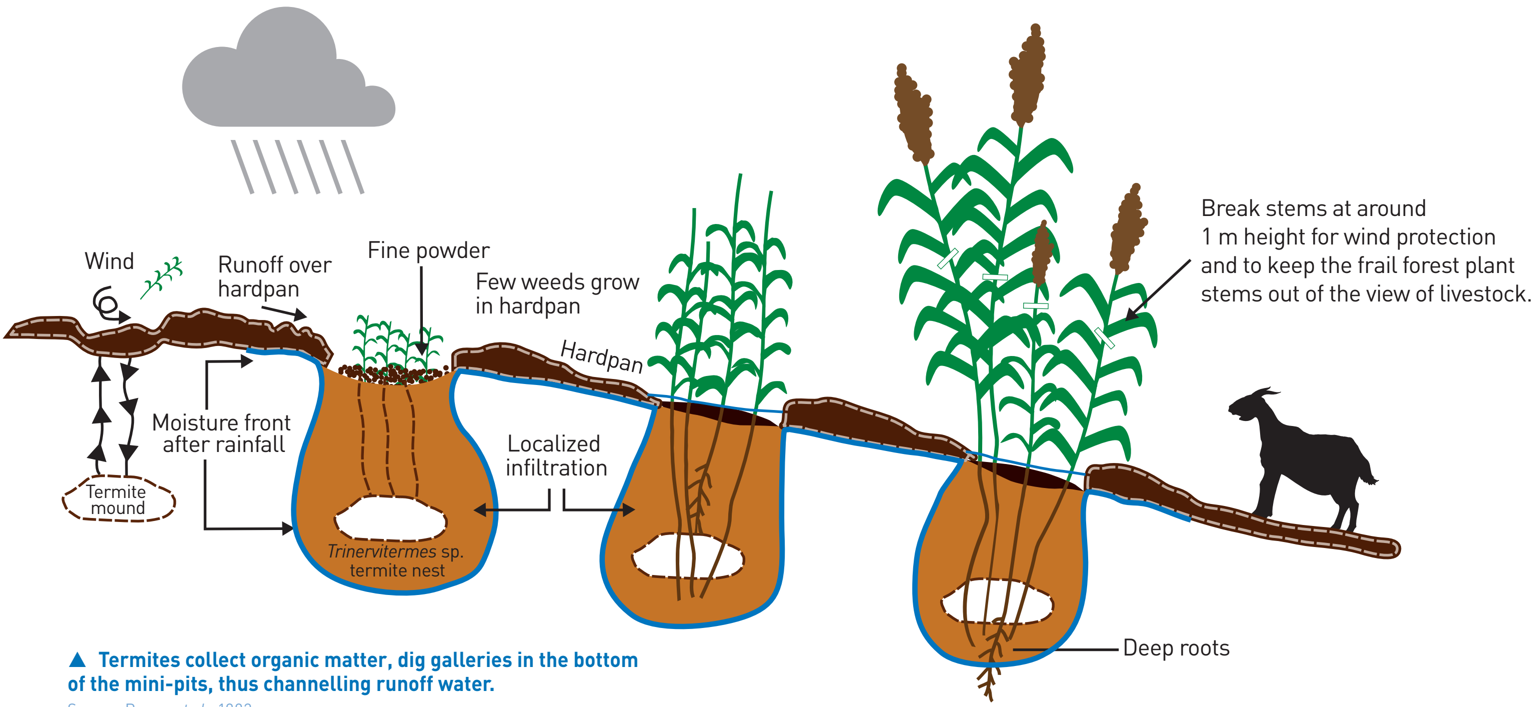
- this technology is only efficient in the Sudanian-Sahelian zone, with 300-800 mm of annual rainfall
- as *zaï* holes have to be dug during the dry season, there is a substantial amount of heavy and time-consuming labour involved. According to Roose *et al.* (1995), *zaï* requires 300 h of hoeing, or around 3 months work for one man, to restore 1 ha
- the availability of manure, water, labour and transport are also essential factors when using the *zaï* technique
- finally, to ensure its success, *zaï* requires water management beyond the plot scale, i.e. the landscape or catchment scale, especially by setting up stone bunds in fields to control runoff and retain organic matter on the site.

▲ **Soil preparation for the *Zaï* technique in Burkina Faso (Ziga, Yatenga).**
© T. Kaboré

▲ **Organic matter deposits in mini-pits in Burkina Faso (Ziga, Yatenga).**
© T. Kaboré

▲ **Sowing seeds in a *Zaï* managed plot in Burkina Faso (Ziga, Yatenga).**
© T. Kaboré

▲ ***Zaï* and stone bunds in crop plots in Burkina Faso (Ziga, Yatenga).**
© D Masse



▲ **Termites collect organic matter, dig galleries in the bottom of the mini-pits, thus channelling runoff water.**
Source:Roose *et al.*, 1993.

Making better use of available water

Water supplies are limited (300-900 mm annual rainfall, less than 6-month dry season) and irregular in arid and semiarid areas of West Africa. This low and random supply is a crop yield limiting factor and thus its management must be improved.

Water supply management currently involves capturing rainwater and surface runoff, whereas many variables must be adjusted to meet the water demand under chronic shortage and drought risk conditions. Based on research carried out in Burkina Faso in the 1980s, processes implemented to streamline water supply and demand in agroecosystems were recorded (*see page 40*).

This management could be improved in several ways: (i) adapting to random water supplies and drought risks, (ii) preserving water in crop fields by hampering runoff, and (iii) accounting for the essential role of trees regarding soil and water in drylands.

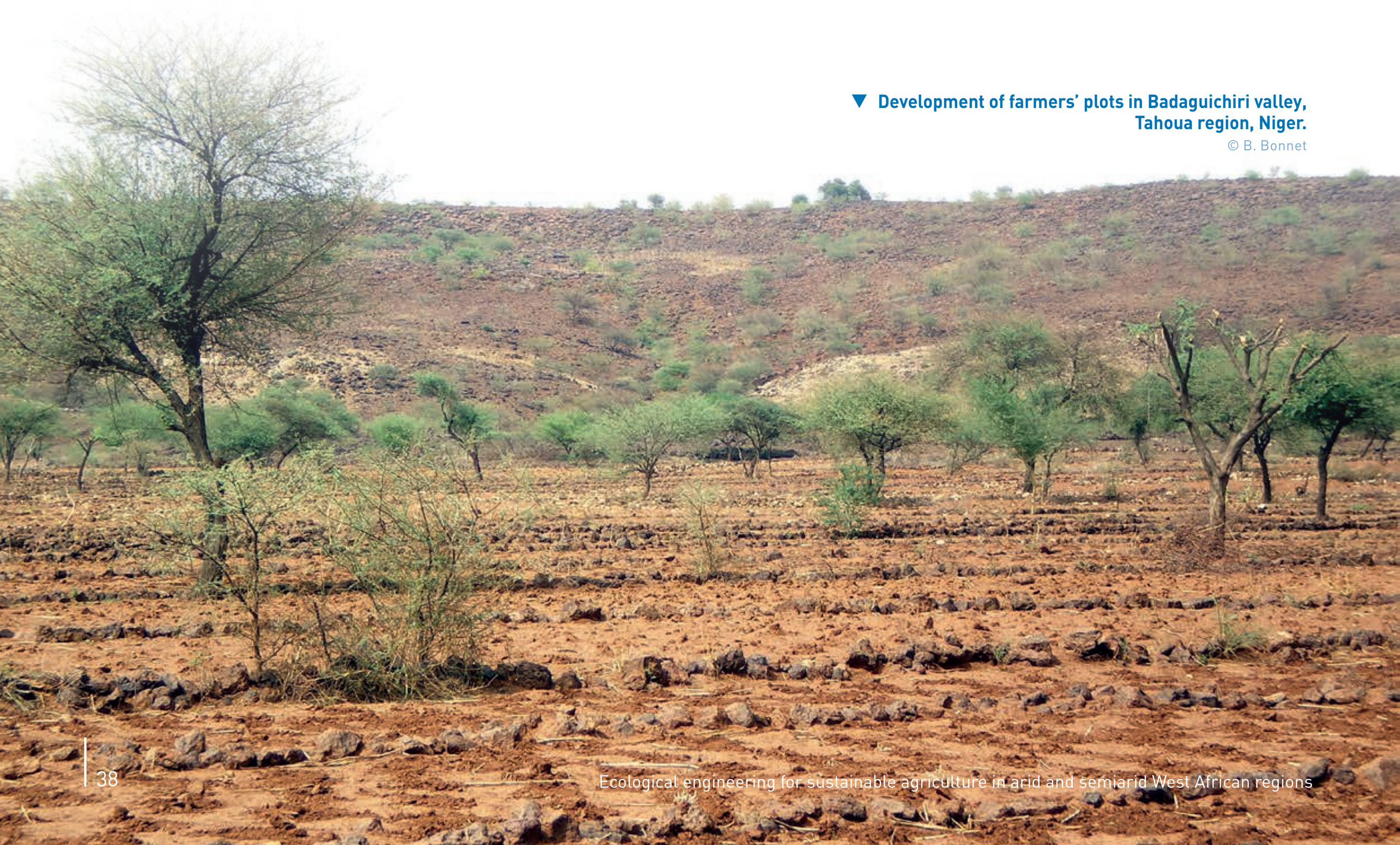
Finally, wastewater from human activities could be a valuable resource, especially around cities. Wastewater recycling, and especially its use in agriculture, enhances sustainable water management, which is crucial as water resources become scarcer, especially in the most arid areas. Wastewater use projects have thus helped intensify tree production around cities (*see page 40*).

ADAPTING TO ERRATIC RAINFALL AND DROUGHT RISKS

Overall farming and *ad hoc* community organization

Manual family farming, with diversified rainfed cereal cropping under tree cover—often more or less combined with livestock rearing—is the main agricultural production system in these dryland areas. This system is geared towards self-sufficiency and marketing of surplus production. Seed storage reduces farmers' vulnerability to interannual climate or biological hazards. Flood recession crops (sorghum), parkland trees (fruit and forage trees) and irrigated lowland vegetable crops use groundwater available in the dry season. The

▼ **Development of farmers' plots in Badaguichiri valley, Tahoua region, Niger.**
© B. Bonnet



responsiveness, e.g. when seeds are sown at the time of the first rains, and the low mobility, with plots located in different places within the area, enables farmers to benefit from the random rainfall distribution and various accessible environments (slopes, lowlands) via flexible access to the lineage-based land management system.

Cropping techniques to reduce plant water needs

Existing plot water management strategies are limited to techniques that facilitate rain infiltration (rainy season weeding, preliminary hoeing or *zaï* in areas with a short season and with compact or hardpan soils, localized mulching), construction of stone bunds and antierosion walls on steep land, and small-scale manual irrigation of gardens with water from lowland cesspools.

Some plot cropping techniques also aim to manage the water demand via crop choices tailored to the reduced water supply conditions, i.e. millet in the north and, gradually southward, sorghum, maize, rice and tubers. Timing of the crop cycle, photoperiodism, resistance and rooting depths are also the main adaptive traits of local varieties. Extensive cropping techniques (low density, low fertilization) with weeding represent another means of reducing evapotranspiration (Serpantié & Milleville, 1993).

▼ **Rainfed rice on *Stylosanthes guianensi* cover.**
Lake Alaotra, Madagascar.
© K. Naudin

▼ **Methods to streamline water supply and demand in agroecosystems.**
Two criteria are compared here: the conventional or recently-introduced aspect and the ecosystem process involved in the considered water management practice.

Functions	Ecosystem process involved	Specific organisms or components involved	Low-impact farmer or enhanced engineering	High-impact engineering
Water harvesting	Atmospheric water harvesting	Specialized trees and shrubs	Artificial sensors	
	Rainwater and exogenous runoff harvesting at the station scale (depending on the extent of infiltration)	Debris, litter, organisms maintaining the apparent porosity, organisms that destroy hardpan (e.g. termites, burrowers, herbivore trampling)	- Localized mulch to rehabilitate the infiltration process - Surface weeding (*iler* surface weeder, *daba* hoe) - Localized planting holes (*zaï*)	Tillage
	Rainwater and exogenous runoff harvesting at the landscape scale	Alternating strips of vegetation and bare soil to enhance water harvesting (tiger bush)	Microdams, dike networks, terraces, half moons, crop-fallow mosaics	- Earth bench terraces - Dams
Water storage	Usable water supply	- Organic matter and clay - Specialized trees and roots (baobab, rubber trees, yam, cactus, etc.)	Organic manure Clay enrichment Long fallows	Hydrophilic amendments
Water use savings	Increasing the water extraction depth	- Taproots - Specialized plants	Millet, groundnut, associated trees	Large pumps and water distribution
	Reducing transpiration and safeguarding the critical phases	Thorns, varnish, natural herbicides, adapted phenology, elimination of the grassy layer, efficient physiology	Low densities, weeding, calendar, photoperiodism, varietal improvement	Herbicides
	Water redistribution and optimizing interseasonal water use	Water redistribution (trees), layering	- Wooded parks - Underground dams - Small pumps	Impoundment dams
	Increasing the residual water uptake capacity	Specialized plants in clay soils, acacia	Dry season sorghum (*muskuari*), cucurbit catch crops	

→ FOCUS | Wastewater reuse in tree plantations

In arid and semiarid areas, various countries (including Egypt, Kuwait and Tunisia) have managed plantations of fast-growing species using partially treated water from nearby wastewater treatment plants (Bartolone & Arlosoroff, 1987; Braatz & Kandiah, 1996). In 1996, Mexico City tested wastewater recycling on an area of around 90 000 ha. Braatz & Kandiah (1996) reported that 7-8% of the total urban wastewater produced in California State (USA) is used for irrigating green areas.

On sandy Saharan land, in the vicinity of major tourist cities, different pilot plantation projects have been launched in Egypt (Qena, Luxor, Aswan, Wadi Na Troum, Abu Rawash, etc.). They promote wastewater reuse (WWR) from various cities for forestry purposes. For economic reasons, these waters often undergo two treatment cycles (primary and secondary) before being used for irrigation of artificial forests planted in (sometimes saline) desert soils. Visitors are generally impressed since most of the plots are set up in a stark desert environment without grass cover. The project at Luxor shows that a relatively convincing forest environment can be created thanks to the shade provided by the trees (*Acacia saligna*, *Morus* spp. and *Eucalyptus camaldulensis*) and the onset of decomposition of their leaves. Grass cover also emerges, which suggests that silvopastoralism could be possible as long as the livestock carrying capacity and various deferred grazing regulations are respected. These WWR-managed plantations are still considered as pilot experiments for various reasons (still restricted choice of species, silviculture yet to be developed, soil variations and infiltration of surplus wastewater into the water table). Moreover, all partial failure risks have yet to be overcome. Beyond silviculture issues, the main WWR problems to be overcome concern the water and nutrient dynamics in soils, types of tree rooting, interactions with livestock farming practices, and finally rights of use of these new timber resources.

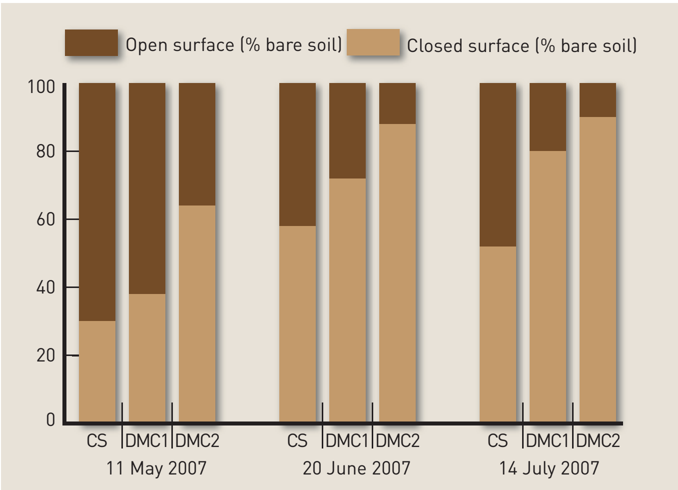
▲ **3 year old eucalyptus trees grown from uncertified seed in Luxor desert sand and irrigated with wastewater, Egypt.**
© R. Bellefontaine

PRESERVING WATER IN PLOTS BY REDUCING RUNOFF – AN EXAMPLE OF USING PLANT MULCH

Mulch provides physical soil protection

In tropical areas, heavy impacts of raindrops on soils that have sparse plant cover due to agricultural development or overuse of natural resources is conducive to soil erosion and ultimately soil degradation.

In arid and semiarid regions under irregular but harsh rainfall regimes, plant mulch made up of residue of plants that were grown prior to the current crop could protect the soil from the direct impact of raindrops, reduce lateral flows responsible for runoff losses, while enhancing water supplies available for plants (*see figure below*). This mulch substantially reduces direct losses by evaporation but could also directly intercept rainwater that in turn would evaporate without reaching the soil, which could partially reduce their efficiency under frequent light rainfall conditions.



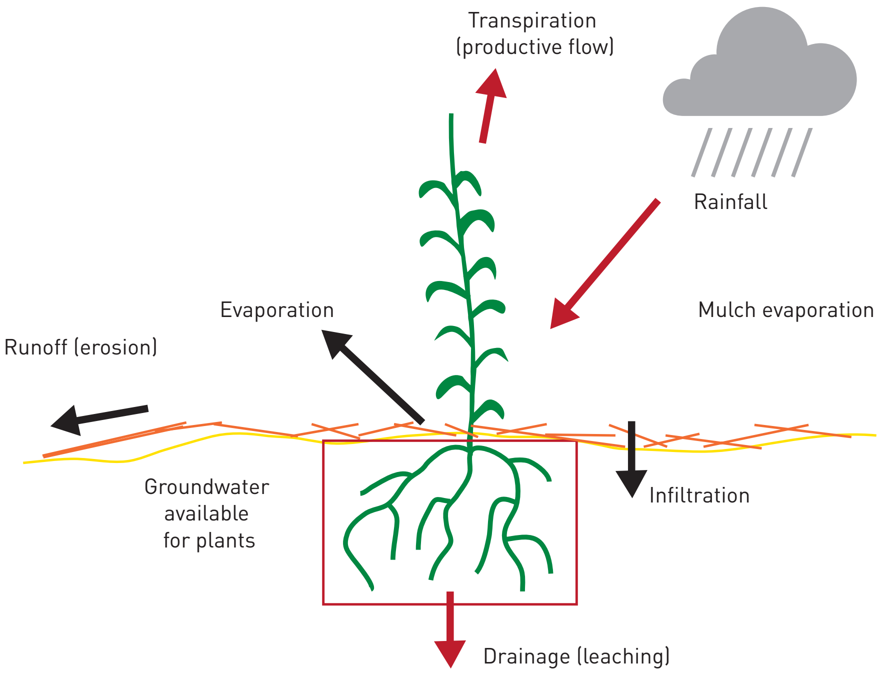
▲ **Soil surface states under a cotton cropping system, 2007, southern Mali.**
The three dates are at the beginning of the cotton crop cycle.
Beige. Percentage of hardpan surface.
Brown. Percentage of porous surface.
CS. Sorghum/cotton rotation with conventional tillage without mulch.
DMC1. Sorghum/cotton rotation without tillage and with mulch.
DMC2. Sorghum+*Urochloa ruziziensis*/cotton rotation without tillage and with mulch.
Source: Sissoko *et al.*, 2013.

▲ **Barrier and tortuosity effects of mulch (even partial) on surface runoff in Mexico.**
© A. Findeling

These conservation agriculture techniques could thus curb the erosion process. They are based on no-tillage, surface protection, diversified crop rotation and/or intercropping with the main crop. The presence of plant residue on the soil surface can improve the soil surface status by reducing the proportion of hardpan that is unfavourable for water infiltration, as indicated by the results of a study carried out in Mali (*see figure below*).

In dryland areas, crop plant biomass has many uses and is often subject to high pressure from grazing livestock (Autfray *et al.*, 2012). The limited quantity of remaining residue is only sufficient for constituting a partial mulch layer.

▼ **Impact of mulch on the water balance by modifying soil runoff, infiltration and direct evaporation.**



As the presence of mulch—even at very low levels—substantially reduces runoff, it is able to control erosion, as demonstrated in a study in Mexico where different mulch levels (1.5-4.5 t/ha) were tested over a several year period (*see adjacent figure*). The gradual increase in applied quantities of mulch quickly reduced runoff losses by 2- to 4-fold. Mulch provides a natural barrier to runoff, slowing the flow and increasing the sinuosity of its pathway, thus giving water more time to infiltrate the soil. This modification in the runoff/infiltration ratio is generally the major benefit of mulch, and available water supplies are considerably enhanced with the extent of mulching.

Partial mulching is also very effective against erosion. Application of just 1,5 t/ha of mulch leads to a 2- to 10-fold reduction in soil loss, i.e. up to 0.4 t of carbon/ha/year retained on the plot as compared to non-mulched plots, regardless of whether or not they have been tilled. Conversely, mechanical tillage enhances rainwater harvesting during the first rains but this technique is subsequently conducive to rapid surface crusting, in turn rapidly and markedly increasing runoff on fragile soils, especially if the tillage is too intense.

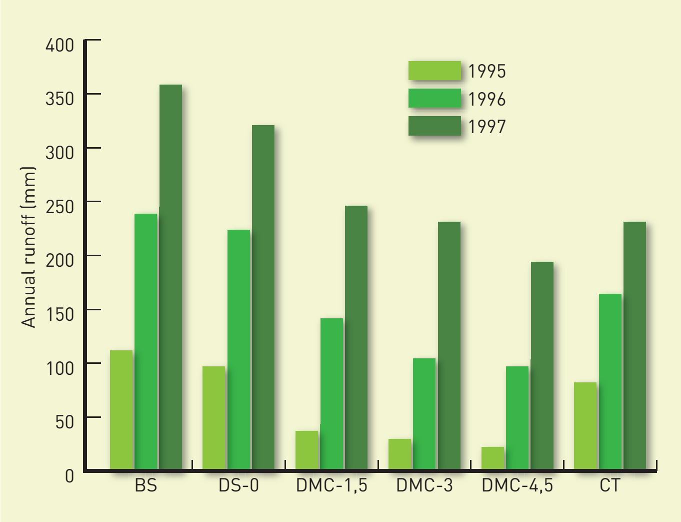
Conservation agriculture enhances biological activity in soils...

No-tillage and the presence of plant cover promotes soil biological activity. Some invertebrates that are favoured by conservation agriculture techniques are considered to be 'soil engineers' that create, via their activity, microporosity which in turn improves water infiltration. In the far northern region of Cameroon, plots managed using conservation agriculture techniques have significantly more earthworms than plots without tillage or cover, or tilled plots (*see adjacent figure*). These effects on the soil structure and porosity maintain conditions favourable for good water dynamics.

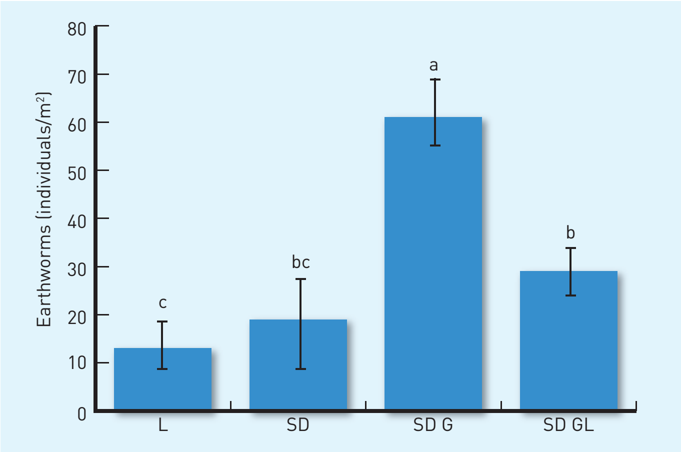
...and the quality of the crop water balance

Mulch hampers soil water evaporation. Although it is hard to directly quantify this parameter, modelling estimates in Mexico showed that this evaporation could be reduced by 10-40% depending on the quantity of mulch applied (Scopel *et al.*, 2004). Water loss by direct interception by mulch is limited, and this layer has a low interception capacity (1-3 mm/ha).

This mulch, even very partial, thus considerably improves the quality of the crop water balance, systematically increasing the available water supply at the onset of the dry season, thus enabling crops to function longer before their photosynthetic activity declines and they undergo the effects of water stress.

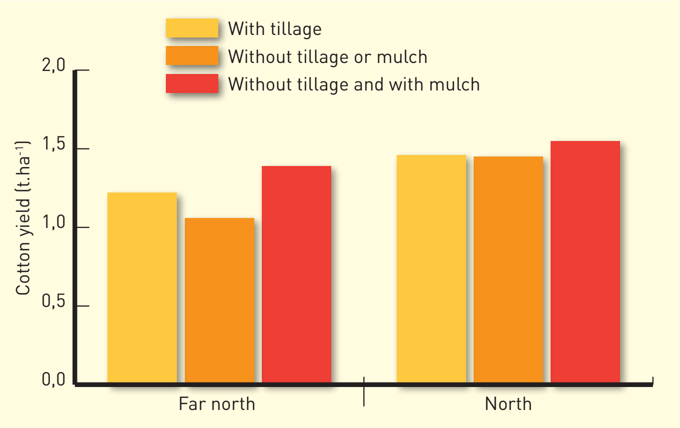


▲ **Impacts of tillage and residue management on total annual runoff on a 7% slope at La Tinaja, Mexico, in 1995 (359 mm rainfall), 1996 (576 mm) and 1997 (693 mm).**
BS. Control, bare soil
DS-0. Direct seeding without mulch
DMC-1.5. Direct seeding with mulch (1.5 Mg ha^{-1})
DMC-3. Direct seeding with mulch (3 Mg ha^{-1})
DMC-4.5. Direct seeding with mulch (4.5 Mg ha^{-1})
CT. Conventional tillage
Source: Scopel *et al.*, 2005.



▲ **Earthworm abundance (*Oligicheta* class) according to cropping techniques, northern Cameroon.**
L. Conventional tillage without plant cover
SD. Direct seeding without plant cover
SD G. Direct seeding in plant cover and rotations with grasses
SD GL. Direct seeding with plant cover and grass + legume rotations
The letters a, b and c represents groups of non-significantly different values. Error bars represent the standard error.
Adapted from Brévault *et al.*, 2007.

Hence, under low rainfall conditions, conservation agriculture techniques significantly improve—as of the first year—rainfed crop yields. In northern Cameroon, this was noted only in the driest regions, such as in the far north (*see figure below*).



▲ Seed cotton yield in farmers' plots under different types of soil management. Northern and far northern regions of Cameroon.
Source: Naudin *et al.*, 2010.

However, the worst situations occur when there is an absence of tillage and physical protection. When direct seeding techniques are implemented without mulch, the adverse effects of rainfall on surface crusting are combined with high erosion of surface sediment, while not benefiting from tillage (even temporary advantages). There is a tenuous balance between efficient mulching and this disadvantageous situation. Hence, depending on the prevailing conditions (soil type, slope, rainfall), precautionary measures involving adjustment of the biomass threshold are required in order to significantly modify the terms of the water balance.

These impacts on primary productivity in the plot depend on the efficiency of the mulch layer to more or less markedly modify the terms of the water balance (reduced runoff and direct evaporation), and this efficiency highly depends on local conditions (soil, slope, rainfall intensity, etc.). This direct effect via the water balance can increase production in areas with a structural rainfall deficit, while buffering risks due to the random rainfall conditions in these regions. These conservation agriculture techniques based on mulching and direct seeding could thus be a relatively effective way to boost food security. Finally, reduced erosion, stabilized soil carbon stocks and stable biological activity are all long-term benefits that help secure production and may add to the short-term effects via water balance modifications.

In these regions, however, there is high competition for plant biomass for domestic and nondomestic uses, especially for feeding livestock during the often long harsh dry season. Farmers are thus faced with difficult choices regarding the use of this biomass. It is therefore essential to generate references on the impacts of partial export of crop residue (for livestock feed) on a number of functions of this biomass, especially with respect to soil protection. This would provide farmers with elements required to decide on trade-offs between the absolute need to feed their livestock and eventual rainfed crop production risks to take.

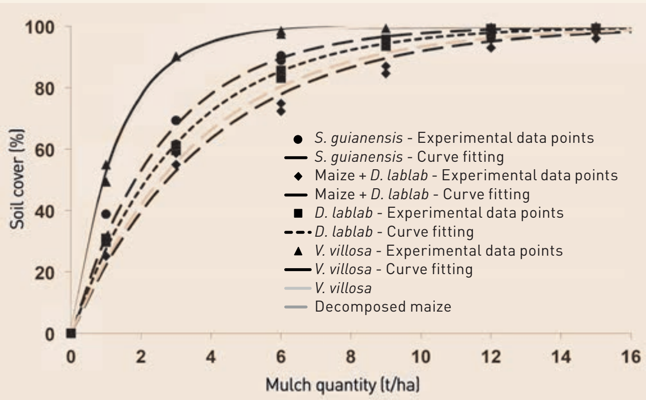
The combination of no-tillage with partial mulching—despite the effectiveness in enhancing the water dynamics—could nevertheless lead to other technical problems such as increased difficulty in controlling weeds on the plot after the first rains. Here again, a trade-off should be found according to farmers' abilities to control these weeds by other means.

Finally, although these conservation agriculture techniques could be highly efficient in quickly improving production in dryland areas, they are not universal or systematically effective techniques. Other techniques with mechanical effects on runoff and its control could also be efficient under these conditions (stone bunds, basins, *zaï*, half moons, etc.). Moreover, combining these techniques with mulching is also often a very interesting option.

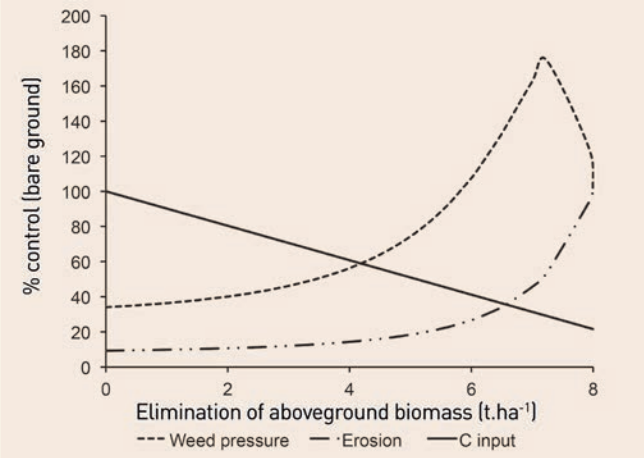
→ FOCUS | What soil cover for specific agroecological functions?

Most of the effects of mulch depend on their roughness and capacity to cover and protect the soil. These characteristics depend on the quantity of mulch applied on the soil, as well as the nature and type of residue involved (*see figure below*). Hence, the quantity of mulch to leave on the plot to maintain a given cover will differ depending on the plants used. For instance, when using *Vicia villosa,* less than 3 t/ha of mulch will provide 90% soil coverage, contrary to *Stylonsanthes guianensis* for which over 10 t/ha would be required to achieve this coverage (*see figure below*). When using a plant with a very high coverage potential, there is more leeway for exporting part of the biomass while still protecting the soil. This biomass management thus depends on the relationship between the quantity left on the ground and the agroecological functions of the mulch—erosion protection, heat protection, water balance, carbon recycling, nutrient recycling, biological activation, weed control, etc.—and which of these functions should be promoted. The relationship between the extent of coverage and the efficiency of an agroecological function or a given agroenvironmental service will differ depending on the species, and the thresholds required to achieve minimal efficiency might also differ.

This also means that, according to the biomass initially produced on the plot and its nature, response curves can be plotted in terms of the efficiency of different agroecological functions according to the quantity of mulch exported and depending on the farmer's decision regarding several potential uses of this biomass. Hence, clearly all functions are not affected in the same way and some last longer, or they may be effective even with low quantities of mulch. Farmers thus have to decide on the amount of biomass to export while favouring the function they most wish to maintain.



▲ **Variations in soil cover according to mulch input quantities and to different crop combinations and types of cover.**
Source: Naudin *et al.*, 2012.



▲ **Theoretical relationship between biomass exports and different production factors such as crop weed pressure, erosion control and organic matter inputs.**
Simulation performed for *Stylosanthes guianensis* producing 8 t ha^{-1} of aboveground biomass (data recorded in Madagascar).
Source: Naudin, 2012.

RECOGNIZING THE ESSENTIAL ROLE PLAYED BY TREES ON THE SOIL AND WATER IN DRYLAND AREAS

Trees have a vital role in the water cycle and balance in given regions. Tree canopy rainfall interception reduces the dynamic energy of water droplets, hence enhancing infiltration in the soils upon which they fall. This intercepted rainwater generally evaporates and adds to the leaf evaporation of water taken up by the roots. The relatively large quantities of water stored in tree roots and trunks can be remobilized and evaporated when the roots cannot fulfil the atmospheric water demand during very dry periods. Trees—by generating high soil porosity along living or dead root pathways—help boost soil water reserves.

Through their deep perennial roots, trees can tap water in soil horizons that are not exploited by most grassy plants, especially in dryland regions. Only roots of certain trees are able to penetrate hardpan and compact horizons. The ten deepest roots (15-68 m depth) were monitored in species growing in arid or semiarid environments (Canadell *et al.*, 1996). Moreover, the spatial expansion of roots enables trees to explore a broader area than that actually occupied by the tree. For instance, stands of phreatophytic species (species able to tap water from the water table via their deep root system) pump phreatic water that has infiltrated areas 10- to 100-fold greater in size than the areas they occupy.

Major interactions between soils, aquifers and plant cover occur via the deep roots of certain tree or grass species. The root systems of these species are capable —at night and in the absence of transpiration—to redistribute water vertically (bottom to top, or vice versa) and horizontally from the the most humid soil areas to the driest areas by exudation. This so-called 'hydraulic redistribution' process first benefits the plant, as the stored water is then remobilized by diurnal transpiration, whereas associated plants seldom benefit, despite the fact that scientific publications have demonstrated that water released in the soil surface layer could be transpired by neighbouring plants. However, on a local scale, this evaporated water increases the ambient humidity and reduces the temperature, thus directly impacting evapotranspiration at local or even greater scales (regional climatic conditions).

Moreover, the deep fine root dynamics could also significantly contribute to soil carbon sequestration. The physicochemical action of roots on the soil organic matter residence time and stabilization could lead to an atmospheric carbon sink. Finally, some elements (nitrogen, calcium, potassium and magnesium) could be transported by water flows ('nutrient pump') from areas where they are available in water, generally in deep soil horizons, to other areas where they are lacking, i.e. generally at the surface as a result of leaching. The same process is involved in the rise of cations derived from bedrock weathering to the surface.

▲ **Baobab tree on a wooded savanna. Tambao region, Oudalan province, Burkina Faso.**
A. Schwartz © IRD

▲ **Trees of Benin.**
Shea tree (*Vitellaria paradoxa*), Atacora region in northern Benin..
C. Lissalde © IRD

Managing landscapes and associated ecological processes

Drastic environmental modifications—due particularly to climate change and increased human pressure on resources—threatens biodiversity and the services it provides to human societies, especially to the benefit of agricultural production. Reduced rainfall and land-use intensification (disappearance of fallows, deforestation, bush fires) have already substantially eroded natural plant cover, which sometimes only remains in the form of isolated trees and rangelands for livestock grazing.

USING LANDSCAPE ECOLOGY TO MANAGE AGROSYSTEMS – AN EXAMPLE OF CROP PEST CONTROL

Little is currently known about the effects of these disturbances on ecosystem services, including ecological regulation of crop pests via their natural enemies. Uncultivated areas are often habitats for high diversity of crop insect pests. In the Sahel, there is high pest pressure on food crops due to the overall lack of pesticide treatments. In this setting, the simplification of agricultural landscapes could promote insect pest outbreaks, with dramatic impacts on food security in rural communities. Preserving, enhancing or restoring ecological control of crop insect pests is a key challenge to meet for successful adaptation of agricultural production systems to environmental change. A better overall understanding of the ecological and social conditions of the considered environment is essential to be able to identify and implement the relevant levers (*see adjacent*).

The crop field is the scale generally focused on for crop pest protection. From an ecological engineering standpoint, it is not appropriate to consider biological regulation just at this scale. The landscape—as a mosaic of habitats shaped by the diversity of crop fields and cropping practices—is the preferred scale for monitoring the population dynamics of a target pest, and for designing and assessing regulation and control strategies.

On the agrosilvopastoral scale, the management of uncultivated areas is a potential lever for curbing insect pest colonization of crops and promoting ecological regulation services. Agroforestry stands are essential in this respect.

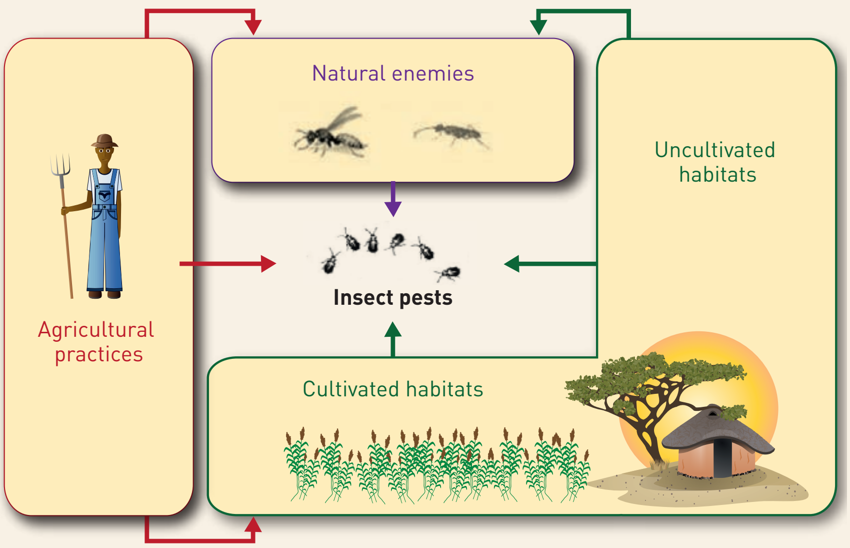
▼ A mosaic of groundnut and millet plots under an acacia stand (Bambey, Senegal).
© T. Brévault

→ FOCUS | **Crop pest control processes and levers**

Ecological regulation of crop pests is one ecosystem service provided by biodiversity (Crowder & Jabbour, 2014). This regulation depends on the resources used by the pest in its habitat (bottom-up regulation) and on the natural enemies (top-down regulation), such as predators and parasitoids:

- at the crop field scale, the characteristics of crop varieties and cropping practices (e.g. crop species associations) are potential levers for farmers (Ratnadass *et al.*, 2012)
- at the agrosilvopastoral scale, uncultivated areas can also be habitats for different natural enemy species, thus serving as supports for ecological regulation of crop insect pests (Rusch *et al.*, 2011). Ecological regulation of pests generally increases with the landscape complexity (Bianchi *et al.*, 2006; Chaplin-Kramer *et al.*, 2011). The landscape composition and configuration determines the quantity and quality of the resources, as well as their accessibility to pests by serving as a biological corridor or, conversely, as a barrier that hampers pest colonization of crops (Mazzi & Dorn, 2012). The landscape composition and configuration are also crucial in determining the abundance and diversity of natural enemy communities via the type of resources (shelter, food source, alternative host, etc.) provided by cultivated and uncultivated habitats (Tscharntke *et al.*, 2008; Rusch *et al.*, 2012).

Biodiversity erosion and subsequent loss of the ecological regulation function—associated with the disappearance of natural habitats or uncontrolled pesticide use—increase the susceptibility of cultivated ecosystems to pest outbreaks.



◀ **Crop insect pest population control levers.**
Source: Clouvel *et al.*, 2015.

AGROFORESTRY STANDS – WHAT PEST CONTROL ROLE?

There is substantial renewed interest and a real development challenge for agroforestry systems in tropical dryland regions of West Africa. Agroforestry contributes to nutrient cycles and produces biomass in agrosystems. While these impacts have been quite well documented, some regulation services like pest control have not been the focus of many studies.

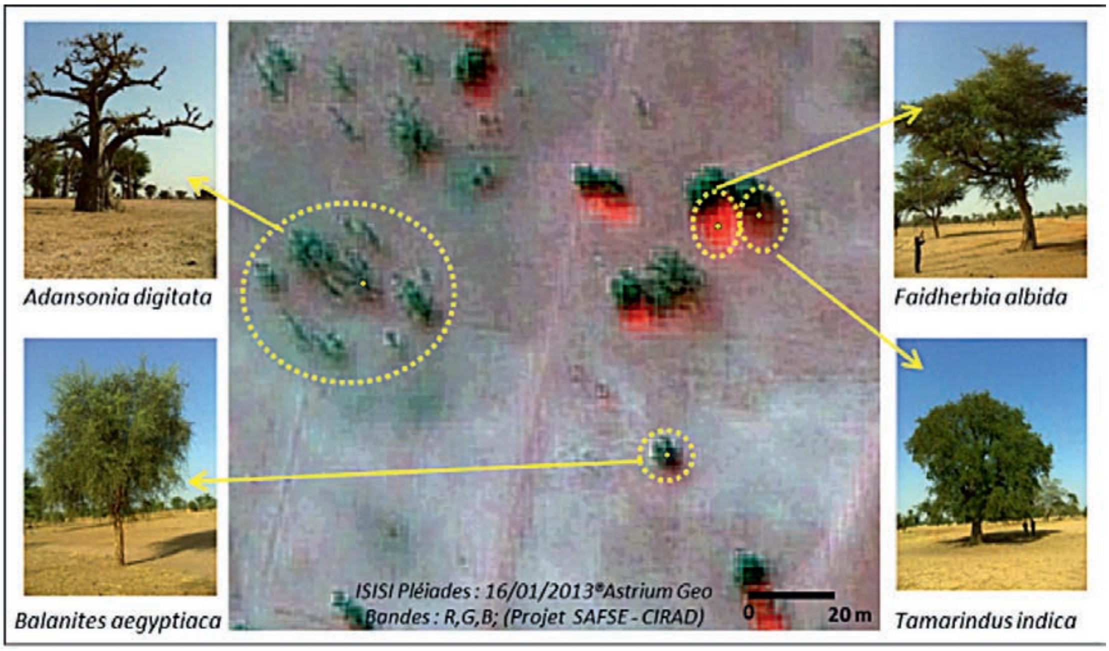
Agroforestry systems—tree-crop associations in diverse mixtures—are structurally heterogeneous, multilayered (like forests), thus offering insect pests a more diversified range of habitats than a simple mosaic of annual crops. These agroforestry systems thus play a "source" or "relay" role for insect pest populations that colonize crops. Agroforestry systems can offer an environment conducive to the development of these insect pests prior to their infestation of crops.

Agroforestry systems can also facilitate the proliferation of the natural enemies of these crop pests. Hence they contribute to the ecological regulation of pest populations by offering their natural enemies "shelter and cover" (hosts or alternative prey, food, shelter), especially during the dry season. These agroforestry systems thus have an ecological regulation role regarding insect pests.

At the landscape scale, the tree (or shrub) density, diversity and distribution in the area determines the movements of arthropod pest populations as such vegetation corridors provide links between habitats. Management of these habitats is thus a potential lever to reduce insect pest colonization of crops and promote ecological regulation services.

The tree density and spatial distribution in an agroforestry stand depends on farmers' practices. The development of some practices can affect this density, e.g. animal draught, which leads to uncontrolled cutting of seedlings. The history of the stand and practices it is subjected to thus modify the habitats of insect pests and their natural enemies (as is the case with the millet head miner; *see adjacent*).

The increased functional biodiversity (here natural enemies) is thus considered as an ecosystem resilience factor against environmental disturbances (climate, land use, biological invasions, etc.). Note that spatial data acquisition, management and analysis tools that combine remote sensing, very high resolution satellite image processing and geographical information systems must be implemented to deal with the range of spatiotemporal scales involved.



▲ **Tree identification from very high resolution Pléiades satellite images, Senegal.**
Source: Soti, 2013.

→ EXAMPLE | **Case of the millet head miner in Senegal**

In Senegal, the millet head miner, *Heliocheilus albipunctella* (de Joannis; Lepidoptera, Noctuidae) is a major constraint to the intensification of millet crops (Youm & Owusu, 1998; Ba *et al.*, 2013), which is one of the cereals most consumed in rural areas. This miner began infesting millet crops (causing up to 85% seed yield losses) following a long drought period in the early 1970s (Vercambre, 1978; Gahukar, 1990).

Adults emerge from the soil 1-2 months after the onset of the rainy season. After mating, females lay their eggs on millet heads during flowering. After hatching, early larval instars perforate glumes and eat the inside flowers, while older instars cut the flower stocks and form typically spiral-shaped galleries on the head. At the end of the development stage, the full-grown worms pupate in the ground (pupae) where they remain in diapause throughout the dry season. When no pesticide treatments are conducted, the intervention of natural enemies (such as the parasitoid *Habrobracon hebetor*) is a major element in controlling populations of this pest.

There are different levers to better manage, activate and strengthen processes for controlling this pest:
• at the cropping system scale: facilitation between species by intercropping millet with other species (endogenous or introduced)
• at the farm scale: avoidance strategies by adjusting sowing dates and using crop varieties with different cycle lengths
• at the territorial scale: natural regulation of local *H. albipunctella* populations by their natural enemies.

The ultimate goal is to develop individual and collective action strategies, in collaboration with stakeholders in the considered area, that encompass all of the socially mobilizable levers necessary to control populations of this crop pest.

▲ **Top:** larval parasitoid *Habrobracon hebetor* devouring a *Heliocheilus albipunctella* worm.
▲ **Bottom:** *Heliocheilus albipunctella* worm on a millet head.

▲ **Right:** female parasitoid looking for a young worm in which to lay its eggs.
© T. Brevault

Socioeconomic constraints to the development of ecological engineering of agrosilvopastoral systems in drylands

The multifunctionality of agriculture concerns all of its functions, in addition to primary production for food and domestic purposes (natural resource, landscape and biodiversity conservation, territorial balance, employment, etc.).

Family farming is, for instance, considered as a benchmark in multifunctional agriculture as it provides a set of complementary functions in addition to the main food production function. These functions highlight the adaptation of rural societies to local environmental constraints. They can be distinguished in terms of sustainability—environmental, economic, social or even heritage functions.

The diversity of these functions and their maintenance in different agriculture and land-use forms requires access to knowledge and local or scientific techniques, as well as collective or institutional organization forms that set the stage for concerted implementation of tailored solutions at the landscape scale. This *Dossier* presents a nonexhaustive set of technical and practical proposals that aim to shed light on a range of potential ecological engineering solutions that could be applied in situations under high drought and aridity constraints.

Clearly, a number of factors—including socioeconomic and societal—should be taken into account when implementing these initiatives that overarch the practical implementation of proposed solutions. All of the technical and practical proposals described in the previous chapters are based on the assumption that these constraints are analysed and that other types of solution are also proposed.

The issue is how to disseminate new practices to crop and livestock farmers living in an economic setting dominated by high volatility in product selling prices, in a social environment where access rights to essential production factors such as land and water are not secure, as well as in a social and societal setting that governs the production distribution, property inheritance, family labour and social control. Civil peace and insecurity are also at issue. Finally, all technical proposals put forward in the previous chapters have a cost and—in an overall context of family farming poverty and therefore a limited investment capacity—it is essential to raise the question as to who will finance what.

▼ **Field work in Niakhar region, Senegal.**
Millet head harvesting and storage.
J.-J. Lemasson © IRD

To ensure the successful dissemination and adoption these innovative or improved conventional ecological engineering practices by dryland crop and livestock farmers, it is essential to take the socioeconomic constraints facing them into account.

The land question is crucial in these regions. Land improvement and restoration are sustainable investments, but dryland crop and livestock farmers are very often in uncertain situations regarding future land access rights. How could a farmer be asked to improve his land or soil if he is not sure to be able to cultivate it a few years later? Land access rights should be the main parameter to take into account. The aim is not to advocate the generalization of private registered property with marked boundaries, but rather to ensure customary or sovereign long-term land rights for crop and livestock farmers.

Economic issues should also be taken into account:

- **Prices**. An analysis of yearly price patterns for a bag of millet reveals one- to two-fold variations, which is an unbearable situation for farmers. This volatility hampers any possibility of increasing agricultural production. Further reflection on setting up agricultural price stabilization mechanisms is thus necessary, as was the case under the Common Agricultural Policy for 40 years in Europe whereas, paradoxically, the European Union, in conjunction with the World Trade Organization and multinational donors, refuses to consider such practices. All agricultural prices—including those for food and cash crops—should be taken into account.
- **Investments**. New investments to improve soil, harvest water, maintain biodiversity, restore fertility and ecosystem functioning are necessary to promote innovative or improved conventional practices. These investments require capital and labour, while some initiatives will immobilize land for several years before it becomes productive. Who will meet farmers' needs over that period? How will they be able to find the manpower necessary to carry out this sometimes heavy labour? And if the work is mechanized, who will provide preliminary investment to pay for the equipment, its functioning and maintenance? Note that all of this takes place in a low investment capacity family farming setting, with an often nonexistent banking system, and sometimes in situations where there is a low capacity for mobilizing family and village manpower when too many adults have outmigrated to more favourable agricultural regions or cities.

Social and societal issues should also be taken into account when implementing ecological engineering practices. Crop and livestock farming are carried out in quite long-standing social and societal systems that govern, in addition to land access, inheritance of movable and immovable property, overall organization of labour and society and distribution of the products of crop and livestock farming. Any changes in cropping and livestock practices will lead to modifications in the established social order and it is essential to be aware of the resulting potential oppositions and changes. All of this must be foreseen in advance of any initiatives and in collaboration with concerned stakeholders so as to avoid blockages when the initiatives are considered incomprehensible by the technicians.

Moreover, major movements have been under way in recent years, including devolutions where the State entrusts local services with high responsibilities, decentralization where the State entrusts the management of *a priori* uncultivated areas to village communities, or the creation of farmers' organizations which could in turn become full-fledged farmers' unions. These major stakeholders should be taken into account to the same extent as government agents in its decentralized services (agriculture, livestock production, water resources, environment, forestry, etc.) and as elected representatives from new rural communities.

Finally, civil peace and security issues are generally not taken into consideration by researchers, technicians, economists and agricultural scientists despite being crucial for the proper functioning of societies. How could innovative techniques be implemented in insecure situations resulting from explosive social conditions (rural delinquency) or exogenous conditions whose determinants lie elsewhere (geopolitical or military situations)?

Ecological engineering for sustainable agrosilvopastoral systems

Climatic conditions in arid and semiarid West African regions are characterized by high inter- and intra-annual variability.

Moreover, the genesis of soils that support primary production often results in reducing the nutrient content. Human societies that have inhabited these regions for thousands of years use agricultural practices tailored to these constraints.

Agricultural production systems geared towards food self-sufficiency are based on a set of production factors (inputs, crop plants, technical skills) that aim to reduce risks without necessarily seeking to maximize productivity. Like savannas, these so-called rainfed farming systems, which are adapted to scattered or random rainfall conditions, are founded on tree-crop-livestock integration. This integration takes place on the farm scale and sometimes within villages where both crop and livestock farmers live, but also on a broader territorial scale via nomadic herding and transhumance practices.

Population growth over the last century (which will continue during the 21st century), globalization and climate change have and will induce major agricultural changes in dryland areas. Imbalances have already appeared, leading to loss of productivity, sometimes degradation of natural resources, including soils and savannas, and biodiversity. Meanwhile new societal models have emerged, such as urbanization, which is a sustainable and certainly irreversible process.

Agricultural activities are not immune to these changes and must adapt to them. Reducing the agricultural footprint and adapting agriculture to climate change are inevitable. As such, getting back to short (at least regional) food supply circuits seems necessary, with dryland areas having a key role in the agricultural economy of West Africa.

▼ **Dryland savanna fallows in Burkina Faso.**
Young fallow landscape under a tree stand during the dry season.
A. Fournier © IRD

From the driest areas devoted mainly to pastoralism to more humid regions where rainfed agriculture is possible, many practices are adapted to the inherently uncertain Sahelian or Sudano-Sahelian climatic conditions. These sometimes long-standing agrosilvopastoral practices could serve as a working basis for the agroecological intensification of production and land or even labour productivity. Studies on these long-standing practices or organizations should include gaining insight into the ecological processes that govern the functioning of natural ecosystems, such as wooded savannas or dry forests in arid and semiarid regions, in order to set the stage for developing novel and more efficient techniques in this new global setting.

Hence, combining agricultural and ecological research and studies on societies and their organization—which ensures their resilience—will help outline the contours of future agricultural developments in dryland areas. These sets of possible agricultural scenarios in dryland regions should be proposed to crop and livestock farmers, as well as to policy makers, in order to boost their awareness on their possible futures in a context of growing climatic and socioeconomic constraints.

▼ **In the Bassari area. Senegal**
O. Barrière © IRD

For further information...

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Food and Agriculture Organization of the Nations (FAO) - Conservation Agriculture
www.fao.org/ag/ca

Ecological Engineering Applications Group (*Groupe des acteurs de l'ingénierie écologique*, GAIE)
http://groupeacteursingenierieecologique.e-monsite.com (in French)

International joint laboratory (LMI) 'Ecological Intensification of Cultivated Soil in West Africa' (IESOL)
https://sites.google.com/site/iesolafrica (in French)

Agricultural Research for Development (CIRAD) – Agro-ecology
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▲ **Bassari farmer. Senegal.**
O. Barrière © IRD

Glossary

Agroenvironmental service. All services offered by individuals or social groups that contribute to environmental preservation. Examples include services that contribute to sanitation (water and waste recycling), to air and noise pollution control, biodiversity and landscape protection and preservation services, etc.

Agrosystem. A system in which farming activities prevail (*Agence de coopération culturelle et technique*, 1977).

Agroecosystem. An ecosystem in which agricultural production activities occur (*Office québécois de la langue française*, 2005).

Agrosocioecosytem. An ecosystem that encompasses agricultural production activities and the entire social system.

Conservation agriculture. Agriculture based on zero or minimal tillage, permanent soil cover and diversified crop successions (FAO).

Cutting. A plant part that is cut for the purpose of developing roots and then a new plant identical to the parent plant.

Ecosystem rehabilitation. "This process is geared towards rapidly repairing ecosystem functions (resilience and productivity) that have been damaged (or simply blocked) by repositioning the ecosystem on a favourable trajectory (natural trajectory, or an alternative trajectory [to be defined]). [...] In the strict sense, restoration invariably leads to a direct and complete return to the pre-existing ecosystem, whereas restoration in the broad sense, particularly rehabilitation, enables a return to a possible stable alternative stage, or to a simplified 'synthetic' ecosystem as an intermediate step. The alternative stable stages mentioned here could (or not) have been steps in the original ecosystem degradation process. The difference between broad sense restoration and rehabilitation is that the latter often requires the 'forced onset' of a new ecosystem trajectory while the conditions of establishment of irreversibility thresholds are put in question. In contrast, restoration projects concern ecosystems that have the capacity to offset the negative impacts of slight disturbances" (Aronson *et al.*, 1995).

Ecosystem service. Tangible and intangible benefits that humans reap from ecosystems (*Commission générale de terminologie et de néologie*, France, 2013). Examples include provisioning services (food, water, genetic resources, etc.), natural process regulation services (climate and erosion regulation, etc.), etc.

Ecosystem (or ecological) restoration. Process of assisting in the recovery of an ecosystem that has been degraded, damaged or destroyed, often as a result of human activities (*Société Internationale pour la Restauration Écologique*, 2002).

Food web. All food relationships between species in a community and via which energy and matter circulate (dictionnaire de l'environnement).

Functional biodiversity. Biodiversity that has a positive impact on sustainable ecological, economic and social development of farms, sectors and territories (Minagri, 2014).

Grafting. A vegetative propagation method whereby two individual plants are joined by different techniques, with one of them selected for its roots, i.e. the rootstock, upon which the other, i.e. scion, will grow the sought-after flowers or fruits.

Marcot. A stem or an above-ground branch of a plant that produces roots at points of contact with soil.

Mutualism. Beneficial—yet not vital or mandatory—association between two living organisms (Bastien & Gauberville, coordinators. *Vocabulaire forestier : écologie, gestion et conservation des espaces boisés.* AgroParisTech, CNPIDF, ONF).

Root sucker. A shoot that grows from an adventitious bud on a plant root.

Symbiosis. A mutually beneficial association between two organisms of different species (*Office québécois de la langue française*, 1999).

Trees outside forests. Trees on land not defined as forest and other wooded land. This may include trees on 'other land', i.e. agricultural land (including meadows and pasture), built-on land and barren land (FAO, 2001).

ACRONYMS AND ABBREVIATIONS

2iE	International Institute for Water and Environmental Engineering, Burkina Faso
AgroParisTech	*Institut des sciences et industries du vivant et de l'environnement*, France
ANR	Assisted natural regeneration
CIRAD	French Agricultural Research Centre for International Development, France
CSFD	French Scientific Committee on Desertification, France
DM	Dry matter
EMBRAPA	*Empresa Brasileira de Pesquisa Agropecuária*, Brazil
ETP	Potential evapotranspiration
EX-ACT	Ex-Ante Carbon-balance Tool
FAO	Food and Agriculture Organization of the United Nations
GBEP	Global Bioenergy Partnership

GGW	Great Green Wall
IAMM	Montpellier Mediterranean Agronomic Institute, France
IER	*Institut d'Économie Rurale*, Mali
INRA	National Institute for Agricultural Research, France
IRD	*Institut de recherche pour le développement, France*
ISRA	*Institut Sénégalais de Recherches Agricoles*, Senegal
LCVP	Low-cost vegetative propagation
NGO	Non-governmental organization
TLU	Tropical livestock unit
UCAD	Cheikh Anta Diop University, Senegal
UVSQ	University of Versailles Saint-Quentin-en-Yvelines, France
WWR	Wastewater reuse

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Abstract

Against the current backdrop of climatic and socioeconomic constraints, dryland farming systems must evolve in order to adapt and respond to a dual challenge—produce more to meet the substantial food needs of growing populations, while also producing better in viable and sustainable ways. Farming systems in these areas have to progress towards production methods that are more productive, natural resource-efficient and climate-proof.

In this setting, ecological engineering offers new alternatives for the typical agrosilvopastoral systems that prevail in arid and semiarid regions of sub-Saharan Africa. This requires managing the complexity of the studied systems and replicating the functioning of reference natural ecosystems of the concerned agroecological region—e.g. savannas for West African drylands—and traditional practices, local know-how based on a long history of adaptation to environmental constraints.

Different practical options are outlined in this Dossier based especially on West African experience. It is possible to focus on making effective use of the biodiversity of organisms, e.g. plants or soil microorganisms, promoting organic matter and nutrient recycling for associated plants, controlling water cycles, and finally adjusting the landscape organization to foster better crop pest control.

However, an integrated vision of the functioning and evolution of agrosilvopastoral systems is required for developing such an approach. Social issues—land, urbanization and migration—and economic issues—basic commodity markets, poverty, etc. — are key factors to be taken into account for the sustainable development of populations in dryland regions of sub-Saharan Africa.

Keywords:
Ecological engineering, agrosilvopastoral systems, biodiversity, recycling, organic matter, agroforestry

Résumé

Dans le contexte actuel de contraintes climatiques et socioéconomiques, les agricultures des zones sèches doivent évoluer afin de s'adapter et de répondre à un double défi : produire plus pour satisfaire les besoins alimentaires importants de populations en croissance, mais aussi produire mieux de façon viable et durable. Pour cela, les agricultures de ces zones doivent évoluer vers des modes de production à la fois plus productifs, économes en ressources naturelles et résistants aux aléas climatiques.

Dans ce cadre, l'ingénierie écologique propose de nouvelles alternatives de gestion des systèmes agro-sylvo-pastoraux caractéristiques des régions arides et semi-arides d'Afrique subsaharienne. Ceci implique de maitriser la complexité des systèmes étudiés et de s'inspirer à la fois du fonctionnement des écosystèmes naturels de référence à la région agroécologique concernée — les savanes pour les zones sèches ouest-africaines — et des pratiques traditionnelles et savoir-faire locaux issus d'une longue adaptation face aux contraintes environnementales.

À partir des expériences ouest-africaines notamment, différentes options pratiques sont exposées dans ce dossier. On pourra ainsi agir sur la biodiversité des organismes, que ce soit les plantes ou les microorganismes du sol par exemple, favoriser le recyclage des matières organiques et des éléments nutritifs pour les plantes qui sont associées, maitriser les cycles de l'eau et, enfin, agir sur l'organisation des paysages pour favoriser un meilleur contrôle des ravageurs de culture.

Cependant, développer une telle approche demande une vision intégrée du fonctionnement et de l'évolution des systèmes agro-sylvo-pastoraux. Les questions sociales — le foncier, l'urbanisation et les migrations — et économiques — les marchés des denrées de première nécessité, la pauvreté, etc. — sont des déterminants essentiels qu'il convient de prendre en compte pour le développement durable des populations dans les zones sèches en Afrique subsaharienne.

Mots clés
Ingénierie écologique, systèmes agro-sylvo-pastoraux, biodiversité, recyclage, matière organique, agroforesterie

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