

CARBON IN DRYLAND SOILS

Multiple essential functions



Les dossiers thématiques du CSFD Issue 10

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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 region, 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 decision-making powers or legal status. Its operating budget is financed by contributions from the French Ministry of Foreign Affairs and International Development and of Ecology, Sustainable Development and Energy, as well as the French Development Agency. CSFD members participate voluntarily in its activities, as a contribution from the Ministry for Higher Education and Research.

More about CSFD:

www.csf-desertification.eu

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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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It was time to appraise the benefits of carbon storage in dryland soils in terms of both plant productivity and the environment, and especially in combating the greenhouse effect. The importance of maintaining soil carbon reserves in dryland areas in order to preserve or even enhance soil fertility has long been recognized. There is, however, a tendency to underestimate the potential of these soils in combating the greenhouse effect via carbon sequestration in soil. As this issue could only be discussed by specialists, we compliment Martial Bernoux and Tiphaine Chevallier for this excellent *Dossier*.

A brief review of the history of soil science is necessary to outline and gain insight into the shift from the 'organic matter and fertility' concept to the 'carbon, environment and fertility' concept.

The authors point out that the current trend is to use the term 'soil carbon' instead of 'soil organic matter'. However, all soil and land management practices conducive to carbon sequestration actually also favour organic matter storage in the soil.

Soil organic matter (formerly called 'humus') has long been recognized as a fertility factor, although it was not until the late 19th century that its formation and action was scientifically explained. Note that in 1809, A.D. Thaer—the most renowned European agronomist in the first half of the 19th century—published a four-volume document entitled *The Principles of Rational Agriculture* that was the 'bible' for major farmers for over 50 years. The quantified and modelled soil and land management system described by Thaer, which is nowadays referred to as being sustainable, was actually based on a partially ill-founded theory, i.e. the 'humus theory' (Feller *et al.*, 2006), whereby it was assumed that a large portion of plant dry matter is derived from soil humus. In other words, managing plant productivity would involve managing soil organic nutrient recycling. This hypothesis is still being put forward but not directly regarding plant nutrition. The humus theory was subsequently refuted by J. Liebig (1840), who demonstrated that plant nutrition is exclusively mineral based. The immediate upshot of the mineral theory was the notion that fertility should essentially be managed by soil mineral recycling and that soil organic matter does not require management.

This was the advent of the 'N-P-K age'. Since then, the importance of soil organic or organomineral management—to maintain an optimum stock of soil organic matter—has returned to the forefront, but it was not until 1992 that carbon somewhat usurped the place of organic matter.

1992 was the year of the Earth Summit in Rio de Janeiro, of the global recognition that our planet has to be managed better, of the increased public popularity of ecology and the advent of the anthropogenic greenhouse effect issue. It was also in 1992 that the first two scientific articles were published on carbon sequestration by plants and soils (Bernoux *et al.*, 2006). As the aim is to achieve atmospheric CO₂ fixation in soils, carbon sequestration refers primarily to an increase in soil organic matter via recycling of plant and animal matter. Climate change has become such a prominent global issue that reference is generally made to carbon storage rather than organic matter storage, even when it comes to agriculture and fertility. It should be kept in mind, however, that all current agroecological alternatives put forward by researchers, especially in developing countries, and which aim to provide a win-win solution, i.e. improve plant and livestock productivity in an environment-friendly way, simply involve efficient management of soil organic matter reserves, with one result being an increase in carbon stocks.

This *Dossier* by Martial Bernoux and Tiphaine Chevallier provides insight on this situation.

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Soil carbon—environmental and societal challenges

The carbon cycle has been a core environmental issue in recent decades, especially regarding the United Nations Framework Convention on Climate Change (UNFCCC). For many years, carbon was only considered through the lens of global warming mitigation via the reduction of concentrations of atmospheric CO₂, a major [greenhouse gas](#)* (GHG). Political responses were thus focused mainly on industrial, transportation and energy sectors—major GHG emitters.

Country concerns, as reflected in research programmes, were therefore initially focused on greenhouse gas fluxes: quantification of global fluxes, identification and quantification of GHG sources and [sinks](#) (storage process), and especially the reduction of carbon emission sources and the increase in sinks**. Forest initiatives were also accounted for, but secondarily, via carbon [sequestration](#) in woody biomass. Agriculture and soil carbon were, however, overlooked in international negotiations.

More recently, following the publication of the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in 2001 and the Millennium Ecosystem Assessment in 2005, ecosystem [vulnerability](#) took a more pivotal position in scientific and public discussions and issues. Soil vulnerability to climate change, i.e. the vulnerability of organisms they contain or support, their functioning in the ecosystem and thus the services they provide (e.g. erosion control, *see next page*), is poorly understood. Few studies have focused on the post-disturbance sensitivity and recovery potential of [ecosystem services](#) and functions related to the carbon cycle (essential in soil functioning), at plot or more general levels, especially in highly vulnerable dryland regions.

* Terms defined in the glossary (page 40) are highlighted in [blue](#) in the text.

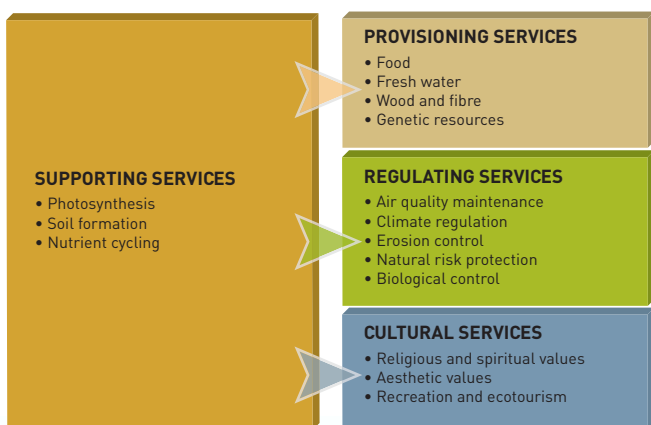
** The term 'mitigation' refers to the reduction in carbon emission sources and the increase in sinks.

▼ A rural landscape in Benin.
A sorghum field at Nalohou.

M. Donnat © IRD



It was not until the 2008 and 2009 food price crises and hunger riots—mainly in Africa—that the debate became focused on the complex role of agriculture and the functioning of soil and stored carbon. Soil functioning associated with the hosted organic matter and carbon enables provisioning of many ecosystem services that are essential for human societies on local (soil fertility) and global (atmospheric exchanges, *see p. 10*) levels.



▲ Soil ecosystem services.
Source: Millennium Ecosystem Assessment, 2005.

Moreover, although agricultural and forestry activities generally account for a third of GHG emissions, agricultural and forest soils contribute significantly to reducing atmospheric carbon concentrations (via carbon sinks in biomass and soil), while also helping maintain food security.

Many changes have taken place since 2009 in terms of global environmental governance, and new structures have been set up (e.g. a reform of the Committee on World Food Security and the creation of its High Level Panel of Experts). Along with agriculture and food security, soils—and soil carbon which is essential for soil fertility—has become a major issue in international debates. Soil carbon is now a recognized indicator of the ‘health’ of soils and the agrosystems they support. Maintaining sufficient soil carbon levels is no longer simply a climate concern.

This *Dossier* is focused on assessing the multi-functionality of soil carbon and highlighting its synergistic role relative to environmental and societal challenges, especially in dryland regions which are often wrongly considered to have little to do with the carbon debate.



Soil carbon—multiple functions benefiting societies and the environment



© Houcine Angar

▲ Two wheat plots in a catchment basin: one managed under direct seeding (left) and the other under conventional seeding. Aroussa, Siliana Governorate, Tunisia.

Water erosion is highly marked on the conventionally seeded plot, while the crop on the direct seeded plot is darker coloured—a sign of a better nitrogen supply. Project to support the development of conservation agriculture in Tunisia (FGEF/AFD funding).

SOIL ORGANIC MATTER—GENESIS AND EVOLUTION

Soil consists of four main components: inorganic particles, organic matter, water and air. Soil organic matter (SOM) corresponds to all live and dead organic materials in the soil, including plant roots, soil microorganisms and microfauna, as well as decomposed and nondecomposed plant residue. SOM thus contains key elements that are essential for plant nutrition: carbon (C), hydrogen (H), oxygen (O) and nitrogen (N). It also includes minor elements, such as sulphur (S), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and trace elements.

SOM is a continuum of relatively complex and perpetually recycled materials. It 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 so-called ‘exogenous’ organic matter (EOM not produced on the field plot), such as compost or manure.

Photosynthesis is the main primary source of organic matter—plants synthesise this material by harnessing sunlight. Organic inputs are generally of plant origin in most **agroecosystems**. This phenomenon occurs on the soil surface (falling leaves, crop residue, exogenous inputs in agricultural soil) and in the surface **horizons**, where the root density and biological activity are greatest. Plant debris is then decomposed by the action of microorganisms (bacteria, fungi) and microfauna. This is called:

- **Humification** (or humus formation): humus is the first layer, which contains a high amount of soil organic matter, more or less decomposed plant debris and various living organisms (bacteria, fungi, soil fauna). This organic matter persists for a relatively long time, depending on the physicochemical conditions of the soil (pH, moisture, temperature, texture, clay and silt contents). Very little humus is found in drylands, mainly due to the low plant input.
- **Mineralization**: this process produces inorganic compounds in gaseous (CO_2 , N_2O , etc.) or dissolved (nitrogen and phosphate nutrients) forms that are available to plants. SOM mineralization is thus a plant nutrient source. In hot dryland regions, this process is very slow, but accelerates considerably when it rains.

> FOCUS | Organic carbon—the main constituent of organic matter

Soil organic carbon (SOC) represents around 50% of organic matter, and the terms ‘soil organic matter’ and ‘soil organic carbon’ are often confused and used interchangeably in texts. However, COS is mainly used for topics related to organic stocks, i.e. quantity per unit area (e.g. t/ha), whereas SOM is applied for topics concerning soil quality or fertility, i.e. the content or concentration per unit of soil (e.g. mg organic matter per mg soil). Organic carbon is now increasingly recognized and recommended in various international initiatives for monitoring soil quality.

It is thus essential to pay close attention to what is being measured, i.e. organic matter or carbon. There is a conversion ratio between the two and the SOM/COS ratio most frequently used is 1.724 (van Bemmelen factor, named after the Dutch chemist Jakob Marten Van Bemmelen [1830-1911] who was famous for his work on humus). This ratio may, however, range from 1.5 to 2.5, and a recent literature review indicated that 2 is the most suitable ratio in most cases (Pribyl, 2010).

Two forms of soil carbon—organic and inorganic

Soil carbon can be organic, i.e. a constituent element of SOM, but it may also be found in mineral form (‘inorganic carbon’). Throughout the world, inorganic carbon pools include the atmosphere (as CO_2) and oceans (HCO_3^-), and this element may also be in solid form (carbonate sediment and rocks).

In carbonate rocks and soil, inorganic carbon is mainly in the form of calcite (CaCO_3) or, to a lesser extent, associated with magnesium [dolomite, $\text{CaMg}(\text{CO}_3)_2$]. More occasionally, it may be found in other forms, e.g. sodium carbonate (Na_2CO_3) or siderite carbonate (FeCO_3), and other even more marginal forms.

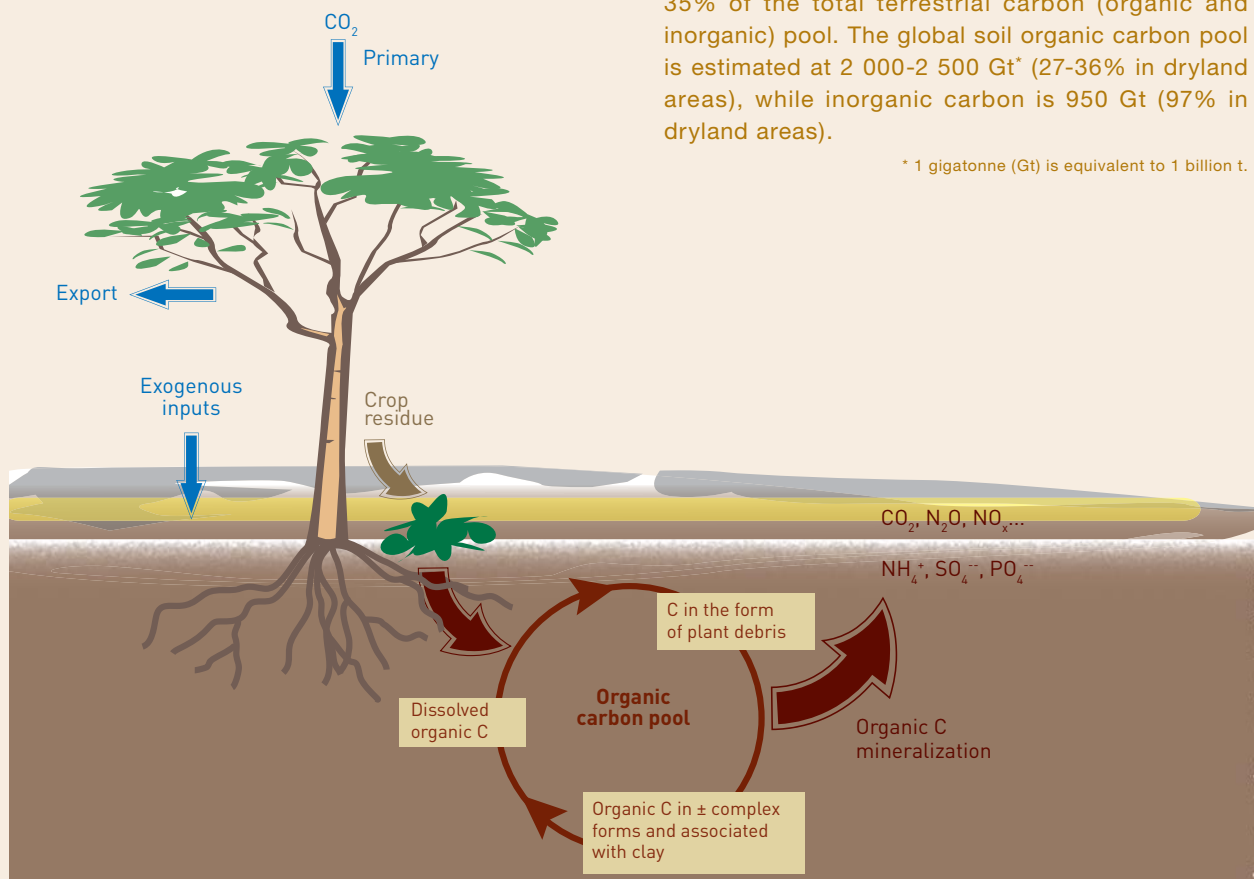
The materials may be primary—carbonates are then derived directly from the fragmentation of carbonate bedrock (lithogenic carbonates)—or secondary, i.e. derived from the formation and evolution of soil (pedogenic carbonates). Pedogenic carbonates may have very different forms. They are precipitated in soil pores, around roots, or in the form of nodules or crystalline minerals, etc.

Carbonates have a different distribution in the [soil profile](#) than that of the organic material. The latter is concentrated in the top few centimetres of soil whereas carbonates are generally distributed in deeper horizons.

The global inorganic carbon pool represents roughly 35% of the total terrestrial carbon (organic and inorganic) pool. The global soil organic carbon pool is estimated at 2 000-2 500 Gt* (27-36% in dryland areas), while inorganic carbon is 950 Gt (97% in dryland areas).

* 1 gigatonne (Gt) is equivalent to 1 billion t.

▼ Organic carbon dynamics and different soil forms.

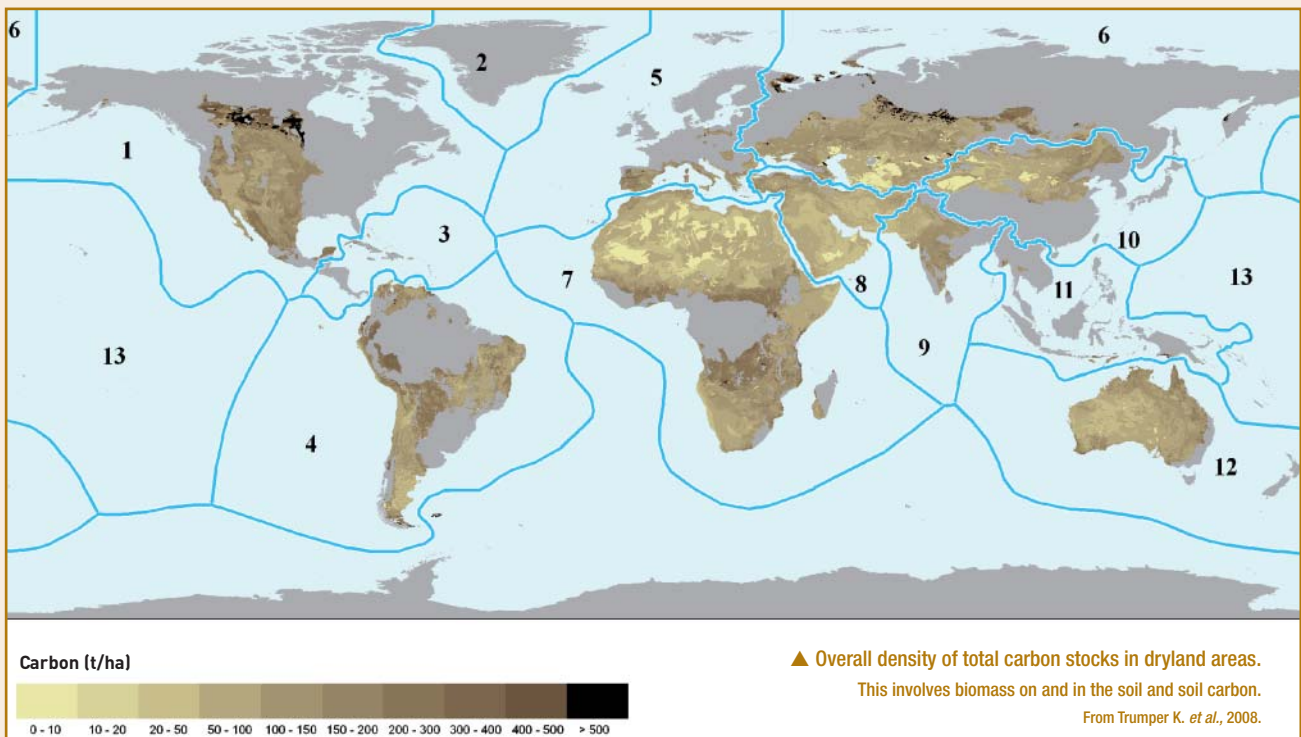


Organic carbon depleted soils...

Dryland soils naturally have low organic carbon content due to the low productivity of the agroecosystems they support. Nevertheless, due to the extent of the areas concerned, organic carbon pools in arid and semiarid regions are far from negligible, accounting for about 750 Gt of carbon. Depending on the classification criteria, dryland regions represent 40% of the land surface, but less than 30% of total soil organic carbon stocks. The soils concerned are mainly **Aridisols** and **Entisols** according to the classification of the Food and Agriculture Organization of the United Nations (FAO). Various estimates have been made to quantify the total carbon stock in dryland areas, but the results depend to a great extent on how 'dryland region' is defined.

► Comparison of total global carbon and dryland carbon stocks.
From Trumper K. *et al.*, 2008.

Region	Total carbon stocks (Gt)		% of regional carbon stocks in dryland areas
	Per region	Drylands	
North America (1)	388	121	31
Greenland (2)	5	0	0
Central America and West Indies (3)	16	1	7
South America (4)	341	115	34
Europe (5)	100	18	18
Northern Eurasia (6)	404	96	24
Africa (7)	356	211	59
Middle East (8)	44	41	94
South Asia (9)	54	26	49
East Asia (10)	124	41	33
Southeast Asia (11)	132	3	2
Australia/New Zealand (12)	85	68	80
Pacific (13)	3	0	0
Total	2 053	743	36



...and soils with a high inorganic carbon content

Dryland soils contain large amounts of inorganic carbon, usually in the form of carbonates. Nearly 97% of soil inorganic carbon (SIC) stocks worldwide are in soils of arid regions where annual rainfall is under 750 mm (Cerling, 1984). Studies in Arizona (Schlesinger, 1982) and China (Wu *et al.*, 2009) have shown that SIC levels were positively correlated with temperature and negatively correlated with precipitation. In dryland areas, SIC pools account for a large proportion of the global terrestrial carbon stock, i.e. about 64%. In soils of these regions, SIC quantities can be 2-10 times higher than the SOC pool. (...)

MANY FACTORS INFLUENCE THE SOIL ORGANIC MATTER CONTENT

Factors influencing the SOM content can be natural (climate, vegetation type, etc.) or anthropogenic (soil use and management, etc.). This depends on biomass recycling to the soil, exogenous inputs and organic material mineralization and humification rates, with the latter being partially a function of the soil type and certain physicochemical parameters (temperature, moisture, pH, etc.):

- The multiple inputs (exogenous or not) vary with the seasons (dry and rainy) and the type of agroecosystem. For instance, organic inputs are lower in a cropfield than in a forest.
- The residence time of the different forms of SOM in soil vary according to their biochemical composition and their association with soil mineral particles, especially clay. Clay soils thus have a higher SOM content than sandy soils. The residence times range from months to years for the most labile forms, and up to tens—or even thousands—of years for the most stable forms.

- A low soil moisture content hampers SOM biological decomposition processes.

- Temperature influences microbial activities responsible for SOM mineralization. These activities generally increase by twofold with every 10°C increment in temperature. However, the SOM mineralization rate is limited in the long term at temperatures above 50°C.

Cropping techniques that affect these parameters also have an impact on the SOM content (*see p. 14*).

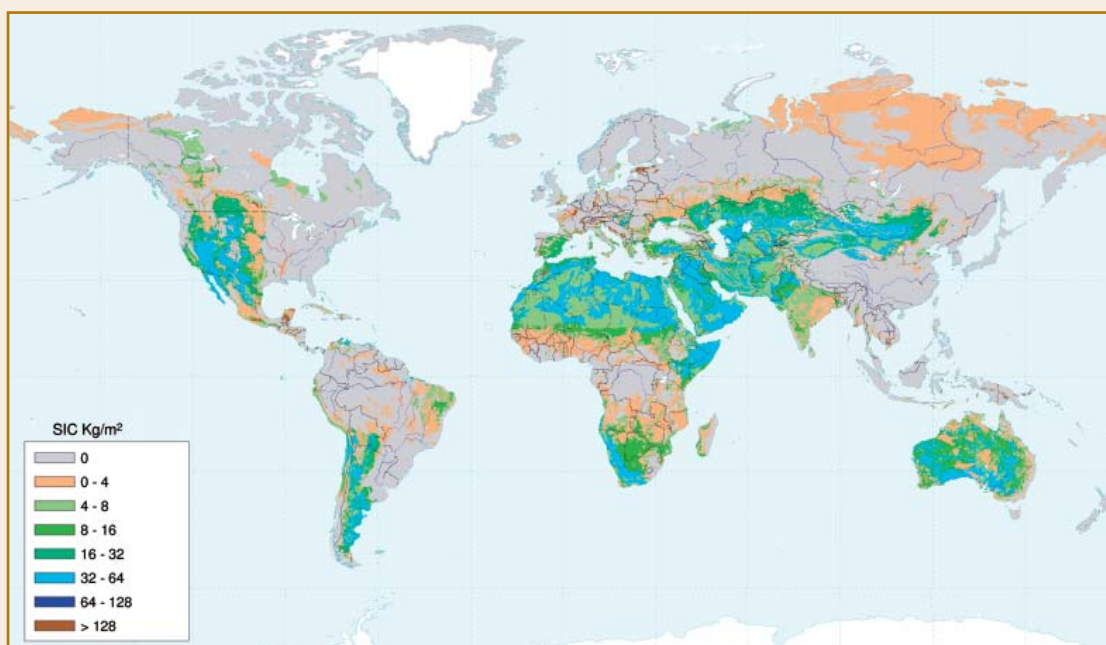
Some regions thus naturally accumulate more organic matter, and in turn organic carbon, than others. The organic carbon content is generally low in dryland soils, i.e. less than 1% of the soil mass, whereas in temperate zones it is 1-2% in cultivated soils and up to 4-5% in grassland or forest soils. Moreover, in dryland regions, there is a balance between low carbon inputs and outputs, which vary markedly during the year and may be very high in the rainy season.

	Biotic (Gt)	Soil		Total (Gt)	Ratio (%)
		Organic (Gt)	Inorganic (Gt)		
Hyperarid and arid	17	113	732	862	28
Semiarid and dry subhumid	66	318	184	568	18
Dryland total	83	431	916	1 430	46
Global total	576	1 583	946	3 104	
Global total ratio (%)	14	27	97		

▲ Estimated dryland carbon stocks.

Source: Millennium Ecosystem Assessment, 2005 (dryland chapter).

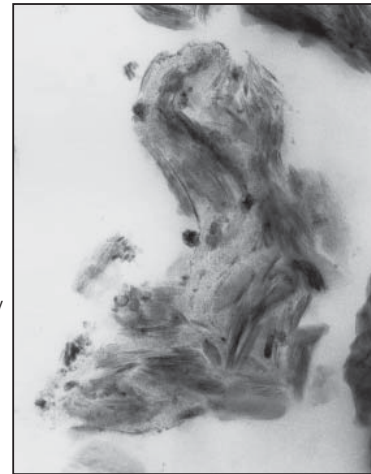
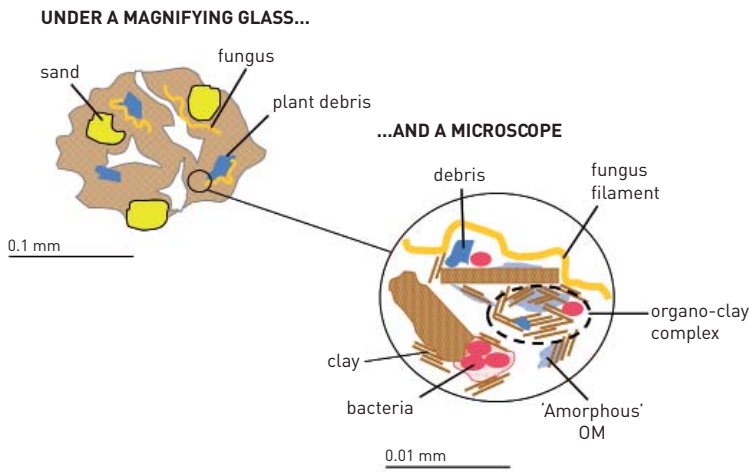
Note that the soil inorganic carbon distribution and content influence the fertility of soils, their erodibility and water holding capacity. Little is known about the impact of the soil management strategy, e.g. cropping or irrigation, on inorganic carbon stocks. Few data are available on the short-term evolution of SIC stocks because of the complex interactions and balances between atmospheric carbon, organic and inorganic soil carbon (*see p. 24*).



◀ Soil inorganic carbon distribution.

Source: FAO-UNESCO, *Soil Map of the World*, digitized by ESRI. *Soil climate map*, USDA-NRCS, *Soil Science Division, World Soil Resources*, Washington D.C.

<http://soils.usda.gov/use/ldsoils/mapindex/sic.html>



◀ The association between organic carbon and clay particles ensures soil aggregate cohesion.

The diagram on the left shows different forms of organic matter associated with soil mineral particles.

The photograph on the right shows clay particles associated with amorphous organic matter.

© Chenu & Planete

ORGANIC MATTER IS ESSENTIAL FOR AGRICULTURAL SOIL FERTILITY...

SOM—and thus soil organic carbon—has many crucial functions for soils and the ecosystems they support. These are provided via their physical, biological and chemical features:

- Storage and provision of nutrients for plants.
- Stabilization of soil aggregates and structure. SOM influences soil aggregates and thus the soil structure, in addition to the formation of pores which are essential for water and air transport. It thus affects many physical soil traits and properties such as the water holding capacity, resistance to compaction, soil aeration, erosion susceptibility, etc.
- Pollution control: SOM has an impact on water and air quality through its pollutant (pesticides, metals, etc.) retention and/or desorption capacity.
- Source of energy for soil organisms.

Loss of SOM and therefore of organic carbon, especially when initial levels are low, as in dryland regions, invariably results in the degradation of soils and their associated functions—especially concerning agricultural production—leading to a vicious circle of degradation: soil degradation, decreased agricultural productivity, increased food insecurity, malnutrition and famine. **Conversely, an SOM increase directly enhances the soil quality and fertility, thus contributing to the agricultural resilience and sustainability, in turn ensuring food security for societies.**

The soil organic carbon content is now generally regarded as the main indicator of soil quality in terms of its agricultural and environmental functions (e.g. water and air quality, *see opposite*).

▼ Roles, actions and benefits of soil organic matter.

Roles	Actions	Benefits
Physical	Structure, porosity	- Water and air penetration - Water storage - Limiting waterlogging - Limiting runoff - Limiting erosion - Limiting compaction - Warming
	Water retention	- Improved water supply
Biological	Stimulation of biological activity (earthworms, microbial biomass)	- Degradation, mineralization, reorganization, humification - Aeration
Chemical	Decomposition, mineralization	- Supplying mineral elements (N, P, K, trace elements, etc.)
	Cation exchange capacity	- Mineral storage and availability
	Trace metal complexation	- Limiting toxicity (e.g. Cu)
	Organic micropollutant and pesticide retention	- Water quality

> FOCUS | Soil organic carbon—an excellent indicator to monitor the soil status and functioning

The European ENVironmental ASsessment of Soil for mOnitoring (ENVIASSO) project* proposed SOC as one of the 16 main indicators (out of 290 potential indicators) to be used in setting up a European soil monitoring system.

Globally, SOC was also put forward by the Global Bioenergy Partnership (GBEP)**. In late December 2011, GBEP proposed a set of 24 indicators to inform decision making processes and facilitate sustainable bioenergy development. SOC is the main variable selected to classify the 'soil quality', i.e. one of the eight indicators of the environmental pillar.

In 2013, during the 11th Conference of the Parties (COP11, Windhoek, Namibia), the 'evolution of soil and surface carbon stocks' became one of the six indicators used to monitor progress achieved in the implementation of the Convention.

However, the soil carbon content varies on multiannual scales. Other indicators that are more sensitive to the soil organic status can be used for earlier detection of change trends.

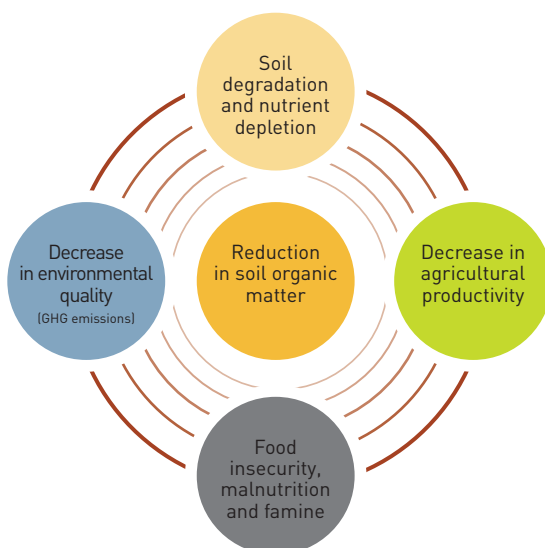
These indicators also provide information on the organic matter quality. This involves, for instance, monitoring particulate organic matter, sugars, enzymes, microbial biomass or mineralizable soil carbon. However, these indicators are more complicated to use.

The SOC indicator generally meets the 'specific, measurable, attainable, realistic, timely and affordable' (SMARTA) criteria:

- **Specific:** the indicator can clearly reveal the OM quantity and can be understood by everyone in the same way.
- **Measurable:** it is quantifiable and objectively verifiable.
- **Attainable:** data required for its measurement are easy to collect (see. p. 26).
- **Realistic:** it is suitable for monitoring the soil status and functioning.
- **Timely:** it can highlight changes over time.
- **Affordable:** it is, however, relatively expensive and requires qualified skilled operators and specialized laboratories (see. p. 26)

* <http://eussoils.jrc.ec.europa.eu/projects/envasso>

** GBEP was launched during the Ministerial Segment of the 14th session of the Commission on Sustainable Development (CSD14) in New York on 11 May 2006. www.globalbioenergy.org



▲ The vicious circle between the decrease in soil organic pools, land degradation and food insecurity.

From Lal, 2004.

...AND ENABLES ATMOSPHERIC CARBON STORAGE IN SOIL...

The relationship between soil and the atmosphere composition, particularly greenhouse gas concentrations, is not immediately obvious! Yet soils are pivotal in the carbon cycle, which includes two important greenhouse gases: CO₂, or carbon dioxide, which is the most important greenhouse gas after water vapour in terms of its atmospheric concentration*, along with methane (CH₄).

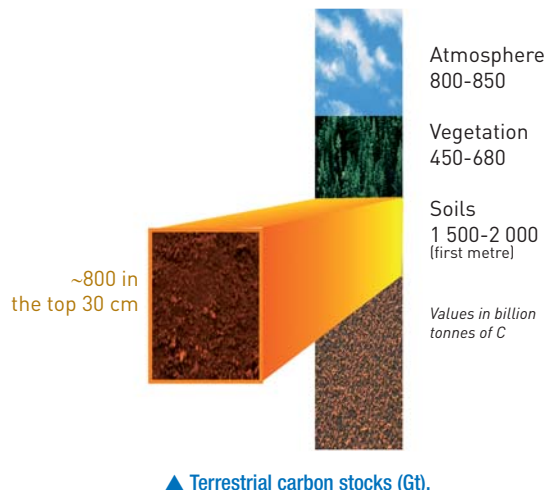
The atmospheric CO₂ concentration (around 0.04%) seems low. Quantitatively, however, atmospheric carbon represents a compartment of roughly 830 Gt of carbon.

But much less carbon is stored in the atmosphere than in vegetation (600 Gt or less) and soil (2 000 to 2 500 Gt) combined. Hence, in the terrestrial carbon cycle, **soil organic carbon is the largest pool in interaction with the atmosphere.**

* The atmospheric CO₂ concentration is 400 ppm (parts per million), or 400 cm³ of CO₂ per m₃ of air. The atmospheric CH₄ concentration is 1.8 ppm (mean values for 2013).

Intense exchanges of carbon occur between soil, vegetation and the atmosphere—soil emits CO₂ (via root respiration and microorganisms) and sequesters organic carbon (via photosynthesis and plant residue transformation into humus). Overall, soils capture more CO₂ than they release, thus generating a carbon sink that increases by 1-3 Gt a year, which in turn participates in mitigating global warming.

Preserving or increasing the SOM quantity can thus have a significant effect on atmospheric CO₂ concentrations by limiting some greenhouse gas emissions, thus helping to mitigate climate change.



> FOCUS | Terrestrial carbon cycle and global climate change

The atmosphere constantly exchanges carbon with the biosphere. Terrestrial ecosystems capture atmospheric CO₂ at a rate of around 1-3 Gt of carbon per year:

- Globally, vegetation extracts around 120 Gt of carbon from the atmosphere via photosynthesis annually, or about 1 atom of atmospheric carbon out of 7.
- At the same time, plants emit CO₂ and thus release about half of the carbon they extract from the atmosphere. Then most of the other half returns to the atmosphere through the so-called ‘soil respiration’ process. The latter includes two main processes: root respiration and that resulting from the activity of microorganisms and soil fauna which decompose organic matter.

Ultimately, in terms of carbon exchange, photosynthesis is slightly superior to plant and soil respiration—part of the atmospheric carbon captured by plants is thus stored in biomass and soil in the form of soil organic matter (SOM, see p. 6). This is called carbon sequestration. Through this process, terrestrial ecosystems serve as a sink which slows down the buildup of atmospheric CO₂. Part of the CO₂ emitted as a result of human activities is therefore absorbed by terrestrial ecosystems but also by the oceans (see figure below).

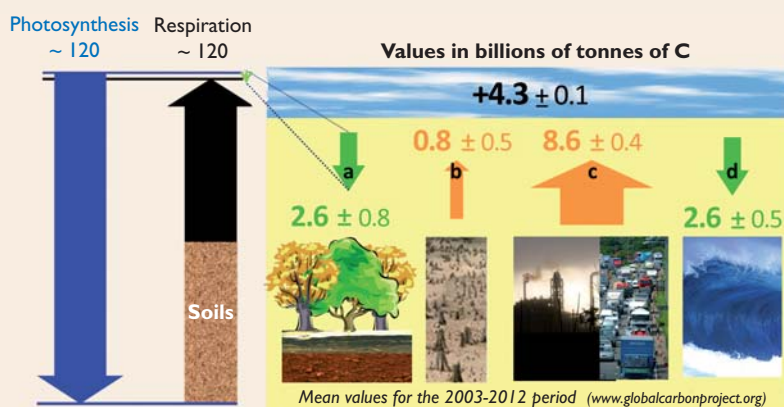
However, only the terrestrial sink could be increased, without risk, by human activities (see p. 15). An increase in CO₂ uptake by the oceans is accompanied by acidification, which has a dramatic impact on ocean ecosystems.

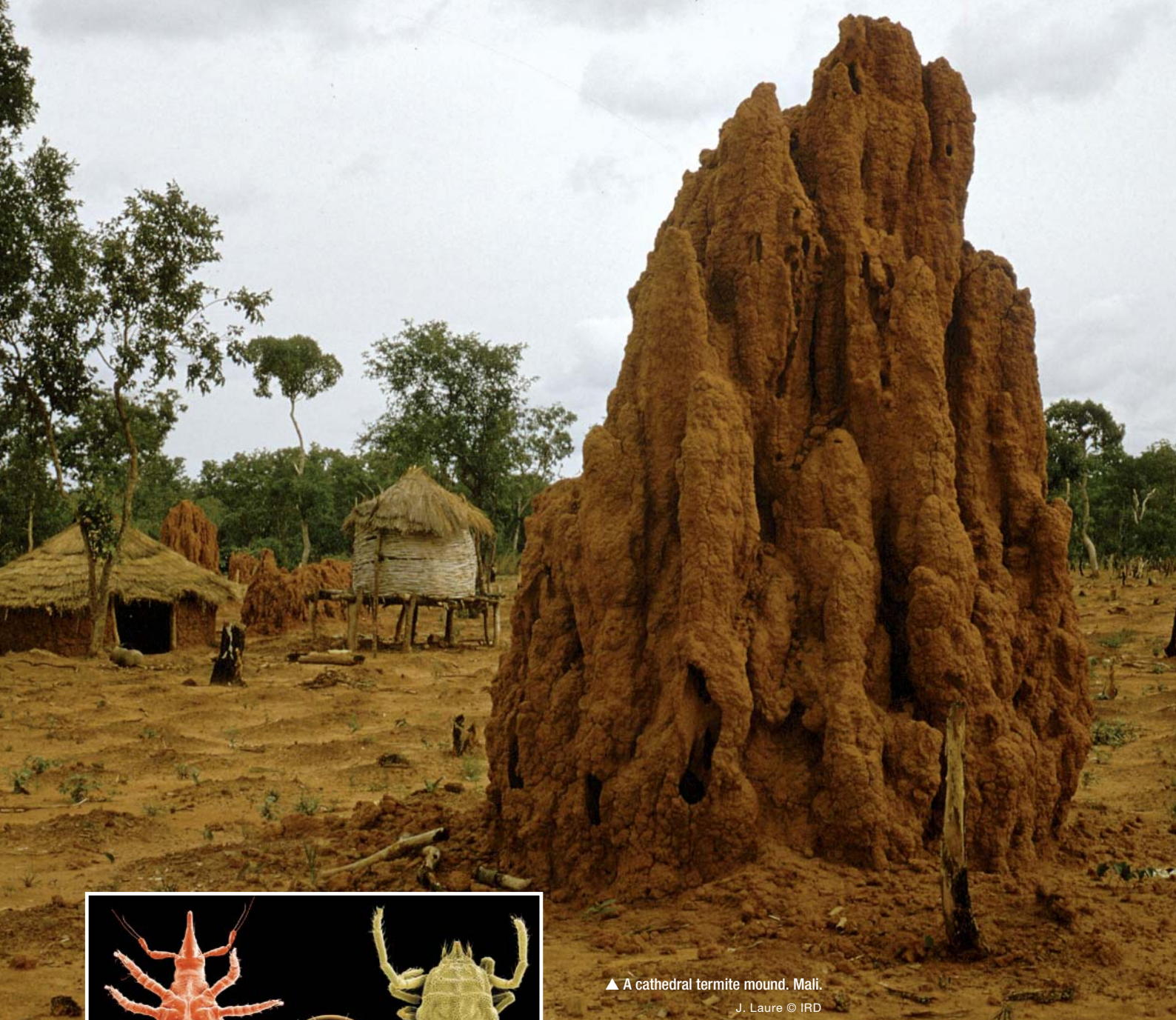
It is already known that global warming will disrupt the carbon cycle, especially soil microorganism respiration. Some studies have estimated that an increase of a few tenths of degrees could eliminate the current biospheric sink. Raich & Schlesinger (1992) estimated that a global annual temperature rise of 0.3°C alone would result in an increase in soil respiration of 2 Gt of carbon per year, thus cancelling out the current biospheric pool.

The sensitivity of organic carbon stocks and respiration to temperature increases is still the focus of heated debate. There is only a consensus on the fact that the decomposition rate determined on the basis of observations and experiments under current conditions are inadequate for predicting the effects of climate change on the global soil carbon pool.

▼ Carbon exchanges between ecosystems and the atmosphere.

- Soil carbon sequestration resulting from gaseous exchanges between photosynthesis and plant respiration and soil organisms and microorganisms.
- Soil carbon fluxes to the atmosphere following deforestation.
- Nonagricultural/nonforest anthropogenic CO₂ emissions.
- Oceanic sink.





▲ A cathedral termite mound. Mali.

J. Laure © IRD



D. Walter © JFC

▲ Mites of the Prostigmata suborder are commonly found in soils. They have a broad range of shapes, sizes (here 0.25 mm) and diets.

...AND HELPS PRESERVE SOIL AND PLANT BIODIVERSITY

Soil organic matter is essential for biological activity in the soil and is the main source of energy and nutrients for soil organisms. SOM also improves the soil structure, increases the nutrient and water holding capacity and protects the soil against erosion. SOM thus generates a diverse range of habitats for soil fauna (earthworms, mites, nematodes, etc.) and microflora (fungi, algae, microorganisms, etc.). Most species live in the top 2-3 cm soil layer, where organic matter and root concentrations are highest. Soils with a high organic matter content can also support more diversified vegetation, which generally enhances soil biodiversity. However, very few studies have focused on quantifying these effects.

Combating desertification, carbon storage and mitigating global warming

Land management strategies that preserve carbon stored in soil are essential for controlling atmospheric carbon concentrations. **They contribute to mitigating climate change by slowing down the rate of CO₂ increase in the atmosphere.** Agricultural and forestry production systems that reduce atmospheric carbon concentrations by trapping this element in biomass and SOM are therefore carbon ‘sinks’—this phenomenon is also called ‘carbon sequestration’.

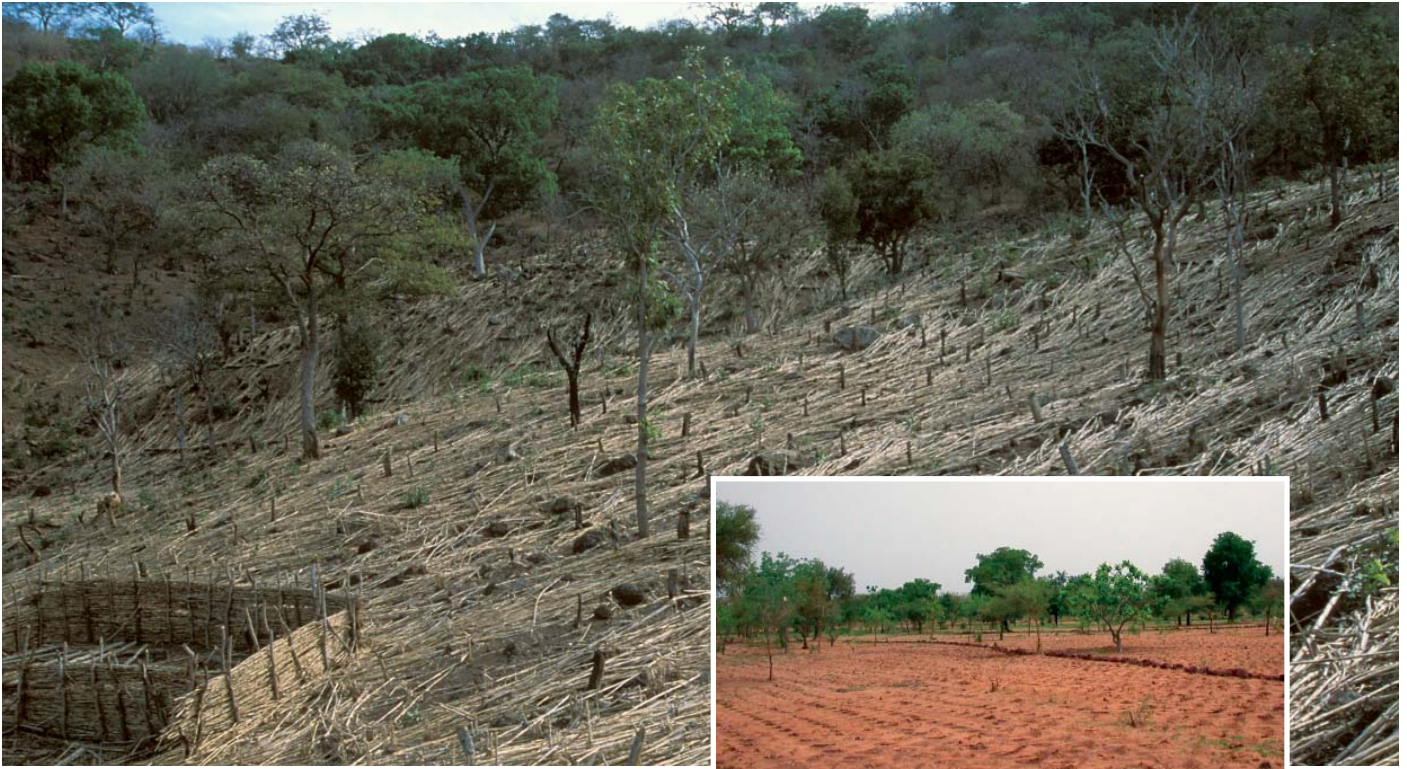
Mechanical, agricultural or biological techniques for combating desertification (CD) contribute to carbon sequestration in soils. However, land-use changes, such as deforestation and some unsuitable agricultural practices such as burning, can lead to a net release of soil carbon into the atmosphere, thus aggravating greenhouse gas related problems.

Soil and land management strategies that preserve soil carbon also contribute to sustainable agricultural management by enhancing agricultural soil fertility. They are usually synonymous with land management rehabilitation and sustainability. Maintaining a suitable soil carbon level often has many other benefits, such as erosion control, maintenance of soil fertility and protection against extreme events. It is thus essential to preserve or even increase organic soil carbon for the prevention of cropland degradation or the recovery of already degraded cropland, ultimately ensuring food security for societies. In dryland regions, this especially involves improving water management while avoiding loss of soil organic matter (and thus carbon). Good water management often requires good organic matter management.

J. Touma © IRD

▼ Traditional half-moon shaped bunds in a hydroagricultural development project.Tunisia.





▲ A sorghum field after harvest. Senegal.

▲ Stone bunds and mulch in Burkina Faso.

© D.Masse

DESERTIFICATION AND SOIL CARBON SEQUESTRATION TECHNIQUES

Many land management techniques have long been advocated by various stakeholders (NGOs, development agencies, governments, scientists, etc.) to preserve or increase soil carbon levels. This primarily requires effective organic matter and water management in order to maintain a sufficient level of fertility for sustainable production. So-called land husbandry (LH) techniques for water and soil conservation management (Roose *et al.*, 2011) are currently almost all recognized as being effective soil carbon management techniques. Many 'traditional' techniques are also efficient for organic matter management (*see p.16*). A recent study conducted by the *Groupe de Travail Désertification* highlighted that many agroecological practices make effective use of local knowledge (GTD, 2013).

Mechanical water and wind erosion control techniques

Mechanical techniques are mainly aimed at reducing the runoff rate and making effective use of this water. The structures proposed capture runoff water and channel it towards plants or crops, thus promoting water infiltration and retention to benefit plants, as well as the sedimentation of fine waterborne soil particles. Water conservation and fertile sediment retention enhances soil fertility and facilitates the growth of natural or replanted vegetation around these structures.

Heavier structures (manually dug trenches, dams, water-spreading weirs, etc.) may also improve water infiltration and thus boost groundwater levels. Some of these techniques serve as windbreaks and provide protection against sand encroachment. Grass and shrub seeds may be trapped by these structures, which promotes spontaneous growth of natural vegetation, in turn restoring biodiversity. These land conservation techniques enable degraded land reclamation, while improving crop production and thus organic carbon contributions in soils.

Such techniques require thorough knowledge of the environment (slope, infiltration rate, rainfall regime) and efficient logistics for sustainable management of the structures. As they require substantial manpower, the extent of work could reduce the cost-effectiveness of these structures. Here are some examples:

- Half-moon shaped bunds (agricultural, pastoral or forestry)
- Nardi trenches
- Agricultural and silvo-pastoral benches
- Manually-dug contour trenches
- Permeable dikes, closing ravines
- Stone contour bunds
- Permeable contour bunds
- Water-spreading weirs (flood control structures)
- Microdams
- Irrigated areas

> FOCUS | Traditional soil rehabilitation techniques

Rural communities can locally develop complex techniques to accelerate rock weathering and rehabilitate soil cover by combining the management of surface water and mixed organic and mineral fertilizer applications, and various biological erosion control structures. However, land issues should not upset these small-scale rural initiatives.

In Mali, with less than 300–450 mm/year of rainfall, Dogon communities have rehabilitated soils on subhorizontal sandstone banks by building honeycomb stone bunds upon which they deposit manure and sandy soil transported from a nearby plain. Each hexagonal 1 m² compartment is planted with sweet onion and watered using a calabash filled with water from a well or a nearby microdam. This irrigation scheme is only developed in lowland areas where water is available in the dry season. Moreover, farmers have developed a variety of water and soil conservation techniques to preserve as much rainwater and soil as possible, such as alignments of stones, stone walls on steep slopes, alignments of faggots of millet and sorghum straw, combined with cultivation techniques (localized fertilization, planting in holes, *zaï*, mounding between planting holes, microcatchment ridging).

In the Mandara Mountains of northern Cameroon (300–600 mm/year of rainfall), in granite chaos, Mofu people accelerate the formation of narrow crop plots on terraces built with stone walls. This physical structure is supplemented with inputs of manure and sand, as well as plants selected for their root systems that wind through the rock fissures. They rear their calves in special pens in order to generate more manure. Finally, they light fires at the base of rocks, which then explode and disintegrate into sand particles. Over time, they have thus been able to reintroduce dozens of local woody species.

In the High Atlas mountains of Morocco, with 350–600 mm/year of rainfall, there is very little available cropland, so farmers develop the floodplains of wadis by enclosing rectangular fields in wide parts of the wadi to trap floodwater and transported sediment behind solid but permeable low walls. First, the system traps gravel, sand and organic matter upon which a natural sward gradually develops, which in turn enhances the trapping of fine particles by slowing down the water flow. Once the sediment layer exceeds 10 cm, farmers apply manure, till it and sow a cereal-legume mixture. The resulting fodder crop is then mowed to protect the soil and further enhance the trapping of fine suspended particles. After a few more floods, this new soil layer can be over 40 cm thick and fruit or forage trees can be planted.

Crops and trees grow rapidly throughout the summer because of the closeness of groundwater, which is fed by snowmelt from the highest mountain peaks. Tree growth has to be fast enough for the trees to survive the next floods. However, these restored lands remain fragile and the soil may be swept away by extreme floods that occur at a rare frequency. When this happens, the owners reconstruct groynes and bunds to capture sediment, and this new land restoration process can take about 10 years.

In southern Benin, on *terres de barre* (desaturated lateritic soils developed on tertiary sandy-clay sediments from the Benin coastal region), in a highly populated region, a unique cropping system was developed which reduces runoff and erosion and increases the SOM content along with the maize grain yield from 0.2 to 2.8 t/ha/year within a few years. This involves a rotation between maize during the first rainy season, followed by a 7-month *Mucuna pruriens* fallow, with maize replanted the next year. Depending on the aridity conditions, the rock mineral content and the extent of land degradation, it takes 10–50 years to rehabilitate the soil productivity through fallowing, but this time can be reduced to less than 3 years by protecting the soil against erosion and livestock.

In Burkina Faso, after 10–15 years of extensive cropping with tillage, the bare exhausted fields are abandoned. They form a thick and almost impermeable erosion crust which hampers spontaneous regeneration via fallows. Nothing grows despite the 400–800 mm of rainfall over a 4–5 month period. These *zipellés** may be recuperated by landless farmers when there is a land shortage. Using the *zaï* technique, in the dry season, landless farmers dig 8 000 to 12 000 shallow 20 cm deep and 40 cm diameter holes per hectare, with the dug-out earth arranged in crescent shapes on the downslope side of the holes. The farmers bury 1–3 t/ha of manure (usually powdered goat dung) or organic residue, followed by the sowing of 10–12 sorghum or millet seeds per hole so that the germinating seeds will lift the sedimentation crust that forms at the bottom of the crescent basins. At the first rains, these basins capture nutrient-rich runoff and store large pockets of water in the soil, which the young plantlets survive on for up to 3 weeks when there is no rainfall. Right from the first year, the field produces as much grain as the regional average (600 kg/ha), but this can be increased to as high as 1 500 kg/ha when a complement of N60 + P30 is applied, i.e. eightfold the productivity without *zaï*. Goat manure was also found to contain viable seeds, leading to the reintroduction of 15 leguminous shrubs and 26 weeds. These techniques are highly labour-intensive, requiring around 350 man-hours/ha for hoe cultivation, transporting 3 t of manure and 10 t of stones to build erosion control bunds.

From Roose *et al.*, 2011.

* Encrusted and bleached soils.

Cultivation technique to boost soil organic matter

These cultivation techniques mainly concern the management of soil organic matter through organic inputs in the form of compost, manure or straw (or mulch):

- Compost is made by mixing crop residue (millet or sorghum straw, etc.) with animal dung. These mixtures are placed in pits and watered regularly to promote decomposition. This compost can be enriched with ashes and/or phosphates. The recommended compost dose is 1.5-2 t/ha/year, applied once or several times depending on the type of soil.
- Application of manure from agroforestry parklands (such as *poudrette*, or dried powdery dung, in West Africa) or livestock pens. This technique is used more regularly than composting because it is less labour intensive.
- In the Sahel, for instance, millet or sorghum straw is laid on the soil at a density of 2-3 stems/m². This straw provides organic matter, reduces water evaporation and blocks wind erosion. However, these techniques compete with many other uses of crop residue (e.g. fodder).
- Direct seeding mulch-based cropping systems (DMC) represent a cropping technique involving no tillage and permanent vegetation cover. Seeds are sown directly in live or dead vegetation cover that remains permanently on the ground. This vegetation cover protects the soil from erosion and enhances its fertility via constant organic inputs and the stimulation of biological activity. This technique requires some technical expertise regarding the choice of crop rotations in association

with cover plants. The cover plants should not compete with the crop. There may also be competition for the use of the cover biomass, i.e. mulch or fodder for livestock.

Applying mineral fertilizers that promote plant growth is another option, but this technique is often too expensive for farmers to implement.

Organic soil fertility enhancement techniques

These techniques involve managing vegetation in areas to be rehabilitated by fallowing plots or protecting them via deferred grazing. Planting hedges (*Acacia* sp., *Euphorbia balsamifera*, *Faidherbia albida*, *Prosopis* sp., etc.) or grass strips along contours fixes the soil and enhances its fertility, water infiltration and the retention of water and aeolian sediments. These hedges also provide refuges for wildlife, thus enhancing biodiversity. Combining grass strips with trees is encouraged. These hedges are also a source of building materials, fodder, etc.

Combining techniques for better results

Combining the different techniques described above is recommended to obtain maximum added value on often major investments in mechanical structures. For example, stone bunds give the best results for their erosion control features when combined with biological measures (vegetation cover, hedges, manure inputs, mulch). In turn, crops are favoured when the structures, such as stone bunds, enhance water retention, therefore generating water supplies for the plants.

▼ Composting pits. Yatenga, Burkina Faso.



▼ A young euphorbia hedge marks the boundary between two fields. Mali.



© D. Masse

H. Maïga © IRD

> FOCUS | The *zaï* technique—better organic matter and water management



▲ Sowing millet in Benin.

P. SILVIE © IRD

Zaï is traditional technique used in the Sudano-Sahelian region of Mali, Niger and Burkina Faso. This technique is efficient in regions with 300-850 mm/year of rainfall. Under 300 mm, the half-moon microcatchment technique is more efficient, while above 850 mm water no longer infiltrates the soil and seeds become waterlogged and die, with a concomitant risk of runoff and erosion.

Zaï is a unique cropping technique whereby seeds are planted in small pits containing manure and water. These pits are around 30-40 cm diameter and 10-15 cm deep. The distance between pits is 70-80 cm, or almost 10 000 pits/ha. The pits are dug manually with a hoe, perpendicular to the slope and staggered. The excavated soil is piled downslope from the pits, forming

a semi-circular ridge to retain water and mitigate wind effects. The concentration of organic fertilizer around the foot of the plants just prior to the first rains helps restore biological activity and improves biological fertility.

The challenges facing this technique concern the need to use a balanced fertilizer for the crop in order to avoid deficiencies and attracting of harmful insects. *Zaï* is a simple technique requiring considerable labour (40-60 man-days/year), substantial community involvement, organization and logistics to apply it on large surface areas.

> EXAMPLE | Various techniques to be used wisely...

In Morocco, a technique that is well known by foresters for restoring degraded soils involves digging a pit or a segment of bench terrace. This depression is filled humus, whereas the excavated mineral soil is used to build a crescent-shaped ridge to capture runoff, transported sediment and available organic matter. Multipurpose trees are then planted. The surface of the catchment area is, depending on the local aridity conditions, four- to seven-fold larger than the projection area of the tree crown. The tenant farmer places highly decomposed manure around the trees while being careful not to burn the surface roots if it is a fruit tree stand. Finally, this method is an adaptation of the *zaï* pits used in Sahelian areas but tailored to the Mediterranean climate and fruit tree cropping.

In Africa, between the Sudano-Sahelian zone and the semiarid Mediterranean zone, there are significant ecological differences regarding climate, soils, slopes and crops and thus techniques to promote:

- In the Sahel, landscapes are often formed with long glacis with gradual 2% slopes. Heavy rains fall for 3-4 months during the hot season, resulting in high potential evapotranspiration (PET) and rapid growth of the vegetation cover. After the rains stop, the crop harvest depends on the extent of soil water reserves to form the seeds. These reserves mainly depend on the physical properties of the soil surface (erosion crust or sedimentation) and upstream runoff, which is why ridging and especially *zaï* are of interest as these techniques concentrate available water and nutrients around the plants.

- In Mediterranean areas, the relief is much more marked and the surface roughness is less efficient, especially when there is a slope of greater than 15%. Moreover, the climate differs substantially because the rains occur in the cold season; the PET is much lower and plant growth is slower. Micro-catchments around trees should thus be considerably larger for watering and manure and mineral fertilizers should be applied to enhance tree growth. As the climatic conditions become more arid, it is necessary to use cropping techniques and mechanical erosion control structures that capture runoff from an area four- to twenty-fold larger than the projection area of the tree crowns so as to ensure multi-year crop growth.

From Roose *et al.*, 2011.



M. Oï © IRD

▲ Irrigated gardens in Niger.

SIX RULES FOR RESTORING THE PRODUCTIVITY OF DEGRADED LAND

It is possible within a few years to restore the production capacity of degraded land to a sufficient depth by planting multipurpose trees and complying with certain rules (Roose *et al.*, 2011), by:

- ❶ capturing runoff with a system that is tailored to the characteristics of the site: hedges, stone bunds, mulching, *zaï*, micro-catchments, etc.
- ❷ recreating the soil macroporosity by deep tillage, at least along the planting line, and stabilizing the soil structure by burying organic matter or lime
- ❸ reviving the topsoil by adding compost, manure, plant litter and growing creeping legumes
- ❹ correcting the soil pH to alleviate aluminium toxicity in very acidic soils (by adding ashes, various residues, mulch) while not reducing the solubility of trace elements in alkaline soils
- ❺ nurturing plants by adding bioavailable nutrients (organic matter, manure, plant litter, or via burning) while adding carefully dosed mineral supplements to meet plant needs
- ❻ choosing plants that are adapted to local users' needs and to the environmental conditions in the area.

The introduction of exotic species (grass, forage, fruit or forest species) should be carefully thought out. For this latter category, seed purchases are essential, but

the seeds should be from many different seed sources. Priority must nevertheless be given to local seeds to benefit from their high genetic diversity, which is generally a better option than planting exotic seeds with a narrow genetic base.

In the absence of seeds, very low cost (layering, suckering induction) or slightly higher cost (root cuttings, stem cuttings, air layering) vegetative propagation techniques are recommended, provided that a high number of genotypes are used (Bellefontaine & Malagnoux, 2008).

Each (re-)introduced species should be carefully chosen according to the preferences of local people and the environmental conditions (soil, climate). In nurseries, modern plant management techniques should be used (grooved rigid small pots placed above ground, optimization of consistent aerated substrates, fertilized irrigation managed and dosed according to the climatic conditions). Plantlets should not be grown in polyethylene bags to avoid the formation of root mats in the nursery, which commonly occurs when using such inadequate and obsolete containers. It is essential to opt for seeding (or herbaceous cuttings under misting, when domesticating a multipurpose tree species, collected from many selected genotypes) in above-ground containers to ensure optimal root development, rapid early growth and earlier application of deferred grazing in the planted area (Bellefontaine *et al.*, 2012).

ALTERNATIVE TECHNIQUES UNDER DEBATE

Biochar, ramial chipped wood and agroforestry are often put forward as alternative solutions for enhancing soil carbon stocks. These techniques are currently being discussed by scientific communities and civil society.

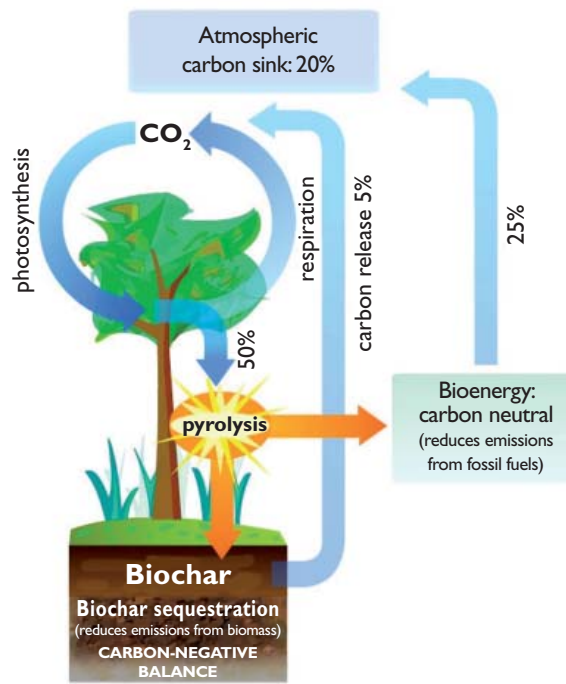
Biochar—a solution for sustainable long-term organic carbon storage in soil*

The production and burying of ‘biochar’ has recently been promoted as an innovative solution for rapid sustainable organic carbon storage in soil. This solution is the result of studies carried out in the central Amazon region in the 1960s on *terra preta* soils which have a high charcoal content. These ‘black soils’ are much more fertile than other generally infertile Amazonian soils, and are the result of the local accumulation of residue via the slow combustion of organic waste from villages along the river.

Biochar (short for biocharcoal) is produced by the pyrolysis of plant biomass to obtain stable carbon—comparable to that found in *terra preta* soils—that can subsequently be ploughed into soils. This combustion is carried out in specifically designed units under very low oxygen conditions. Well controlled pyrolysis can produce a fuel gas as well as a form of plant charcoal, which differs from manufactured charcoal. Biochar is a highly porous stable product that is ploughed into soil to enhance its agronomic properties. Plant residue or even manure is generally pyrolysed to obtain this product. Plantations specifically devoted to carbon sequestration via this technique are considered.

The pyrolysis reaction and energy balance involved are quite clearly delineated from a theoretical perspective, especially as a result of recent research and the development of specific reactors. A number of unknown factors still hamper extrapolation of these results to large surface areas so as to be able to assess the potential impact of the approach on global carbon sequestration. The first challenge is to check whether the beneficial effects noted on some poor Amazonian soils would also improve other types of soil in the world.

From an agricultural standpoint, biochar is a very heterogeneous product due to the nature of the raw material that is pyrolysed, so it is hard to accurately determine the global impacts. There are presently just as many studies that have reported positive, negative or inconclusive results. The observed effects vary markedly depending on the biochar origin. Generally, it initially improves poor soils, but some studies have shown that the hydrophobic properties of some biochars make the soil surface more impermeable, which is conducive to runoff and thus erosion. Others were found to have a negative impact on earthworm populations. Finally, pyrolysis also generates volatile aromatic compounds, some of which are potentially toxic. In the current absence of long-term studies and hindsight, the fate



▲ A carbon-negative ‘bioenergy-biofuel’ system based on biochar sequestration in soil.

A public domain image created by Laurens Rademakers from J. Lehmann, 2007. A handful of carbon. *Nature*, 447: 143-144.

of these residues in soil and their biological impact are unknown. This clearly demonstrates that caution is necessary and that the presumed virtues of biochar should be further tested and verified before proposing its widespread use.

From an energy viewpoint, the balance is more clearcut when pyrolysis is conducted in a well-controlled unit—it is ‘carbon-negative’. The fraction of carbon sequestered in soil by the incorporation of biochar is greater than that which would be produced through a natural decomposition process with the same organic matter without pyrolysis. A smaller fraction is therefore released into the atmosphere. This balance is only of real interest if the soils also reap the expected benefits.

Biochar could have more positive impacts in dryland regions, where soils are often infertile, by enhancing the soil properties. In a food crisis setting, however, generating biomass to produce biochar would be in competition with other crops. The use of crop residue also means competition with livestock feed or with ecological intensification techniques. These latter techniques require substantial plant residue, manure and compost inputs to boost the soil organic matter content. There could also be competition regarding the use of residual biomass between pyrolysis to generate stable inert carbon and organic fertilizer application to stimulate biological activity in the soil.

* For further information: Cornet & Escadafal, 2009; Escadafal *et al.*, 2011.



Applying ramial wood chips (▲) on a field and a site where *Piliostigma reticulatum* (common wild shrub) branches are chipped with a machete (►). An experimental site at Gampéla (near Ouagadougou).



Biochar is thus not the panacea that some scientists expected, but rather one of the ways that could contribute to sustainable land and environmental management while also enhancing agricultural production. Further research is still needed to ensure that this technique is disseminated on a solid scientific basis and in line with different local settings.

Ramial chipped wood—for sustainable land management and soil organic matter?

Amending soil with ramial chipped wood (RCW) is a currently debated alternative land management technique which can increase the soil carbon content. The use of ramial wood or tree branches mimicks a natural process in wooded ecosystems. This technique, which was developed 20 years ago in Canada, involves burying chips of branches of less than 7 cm diameter (Lemieux, 1996). Because of the chipping process, ramial chipped wood refers to both the material and the technique.

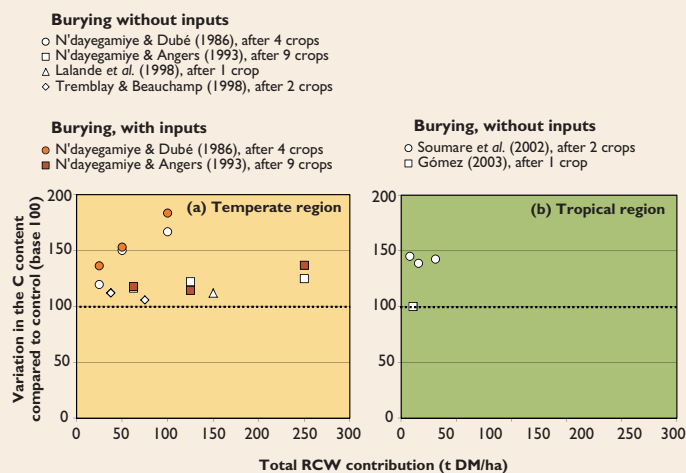
Few scientific studies have assessed the advantages of this technique for enhancing soil organic matter, especially regarding arid and semiarid regions. A literature review carried out in 2010 (Barthes *et al.*, 2010) summarized all available research results concerning temperate and tropical areas (*see next column*).

The RCW technique requires an available biomass supply. This means there may be competition with other conventional uses for this biomass, such as fodder for livestock and fuelwood for households. In addition to the problem of resource availability, the technique is hampered by the fact that the wood chipping process is highly labour intensive.

> FOCUS | Ramial chipped wood—positive results to modulate

Farmers and extension services are showing growing interest in amending soils with branches, especially with ramial chipped wood (RCW), but this practice has not been fully validated from a scientific standpoint. The article of Barthes *et al.* (2010) summarizes statistically significant results concerning the effects of RCW buried chips or mulch on crops and soil in temperate and tropical environments. RCW inputs generally have a positive effect on crop yields except regarding the crop grown immediately following the first burying of chips in sandy soil (this has mostly been tested in temperate environments, with few results documented in the tropics). This negative impact could be mitigated by nitrogen fertilization. RCW inputs, especially mulch, also enhance the physical and hydric properties of the soil (humidity, porosity, structure), boost the soil organic matter, stimulate biological activity, and increase the medium-term nutrient supply. RCW impacts are modulated by several factors, such as the tree species used and the RCW input conditions (dose, frequency, chip size, etc.). However, there are not sufficient confirmed results to draw up precise recommendations. The benefits of RCW as compared to non-wood organic amendments are poorly documented.

From Barthes *et al.*, 2010.



▲ Influence of the RCW contribution on the relative variation in surface soil carbon content relative to control without amendment (base 100).

> FOCUS | A few tips to select good woody green manure

- If possible, choose a woody species which can, via its deep swivelling or oblique rooting patterns, well nutrients up to the soil surface and locally protect land from heavy rains, sun and wind.
- Select hardy species or clones that will fully tolerate repeated cutting of young stump shoots and which produce high quantities of biomass during the cropping season.
- Chose **actinorhizal plants** (some *Casuarina* species) or legumes that fix atmospheric nitrogen.
- Avoid invasive species with overabundant fruiting (*Leucaena*, *Prosopis*, etc., which farmers do not want) and fodder plants when herds wander freely during part of the season.
- In subhumid areas, there is relatively little competition, with a quite broad choice of species. In dryland areas, competition for water can lead to lower crop yields. In the Sudano-Sahelian and even Sahelian zones, green manure inputs and burying of organic matter are carried out locally (*zai*) without substantially disturbing the soil surface layer by tillage.
- Except in exceptional circumstances, in semiarid regions, avoid thorny species that are unsuitable for various burying procedures.
- Inquire whether vegetative propagation (future domestication of the best genotypes) is economically possible (cuttings, root cuttings, air layering, suckering induction, grafting, etc.) in order to preserve them in clone parks.

From Akinnifesi et al., 2007; Bellefontaine et al., 2002; Makumba & Akinnifesi, 2008; Parmentier, 2009; Robin, 2012.

© C. Jourdan



▲ *Faidherbia* parks in December. Burkina Faso.

Agroforestry*—for efficient soil fertility management

In dryland areas, agroforestry systems that combine trees and annual crops (e.g. cereals) offer a solution for boosting soil carbon reserves. The tree shade also reduces the soil temperature and crop evapotranspiration. Agroforestry has prevailed for several centuries in sub-Saharan dryland regions. The selected tree species have a useful value for households or a commercial value on local, regional or (but less often) international markets.

Recent attempts to densify the woody cover in order to promote agroforestry were disappointing because below-ground competition between the crops and trees for water often nullified the soil enrichment and microclimate improvement benefits. Assisted natural regeneration (ANR) of trees and shrubs could overcome these difficulties and even lead to local extension and densification of trees in croplands.

ANR involves protecting and maintaining woody species that grow naturally in a field or a silvopastoral area. Young natural shoots are then selected and left to grow. A density of 60-80 plants/ha (Dorlöchter-Sulser & Nill, 2012) is recommended, while protecting seedlings against livestock grazing (deferred grazing) and trimming them periodically to stimulate growth.

Agroforestry systems are highly diversified depending on the communities, as well as the climate and soil conditions. They can be very complex, with several storeys consisting of many useful species. There are complex agrosilvopastoral systems (combining annual crops, woody plants of various sizes and livestock) as, for instance, in the southern Sahel, with *Faidherbia albida* parks playing a key role in soil fertility management. The systems may also be simpler (agrosilvocultural or silvopastoral). They can be planted in wooded savannas or open woodland forests. In sub-Saharan Africa, forests-parks cover huge areas (*Faidherbia albida*, *Vitellaria paradoxa*, *Parkia biglobosa*, *Adansonia digitata* and *Borassus aethiopum* parks, etc.). Further north, in Sahelian regions, agroforestry parks are mainly composed of *Balanites aegyptiaca*, *Acacia senegal*, *Acacia raddiana*, *Piliostigma* spp., *Hyphaene thebaica* and many other species.

On the northern rim of the Sahara, argan (*Argania spinosa*) trees were a unique example of a balanced agrosilvopastoral system, but overgrazing hampered regeneration and destroyed the undergrowth.

* This section was adapted from the article of Harmand & Seghier, 2012.

Moreover, commercial crops have also reduced the surface area and the density of these centuries-old parks.

Other systems are developed over time from trees growing outside of the forests—these are fallows enhanced with atmospheric nitrogen fixing legume plants, rangelands with a controlled stocking rate around windbreaks (or quickset hedges) whose leaves provide a feed supplement in the dry season, planted shrubs requiring light shade, or plots enriched with precious timber species under which crops and grazings thrive.

In the Sahel, shrubs, such as *Guiera senegalensis*, *Piliostigma thonningii* or *P. reticulatum*, are associated with millet fields in open landscapes. Further south, trees such as shea (*Vitellaria paradoxa*) are typical of the Sudanian region along a belt extending from Senegal to the edge of Sudan and Ethiopia. They produce edible fruits, cooking oil and are part of local people's diet. To an increasing extent, they represent a resource for export to industries in developed countries, such as the famous shea butter. Trees in the sub-Saharan region also have an important function in land ownership. Unfortunately few studies to date have focused on the stakeholders and their decision making level for management of the parks, and the same applies to systematic studies on carbon sequestration on agroforested land.

> FOCUS | Spectacular recent development of *Gliricidia sepium* in Malawi and East Africa

Gliricidia sepium (Jacq.) Walp. is a *Fabaceae* species that is native to dry Central American forests. This pantropical leguminous tree grows on all types of soil (especially acidic) from Senegal to South Africa since it is able to tolerate 4-9 months of dry season (560-3 800 mm/year). Seedlings have a deep root system, but shallow roots can hamper crop growth. This species grows from cuttings and vigorously sprouts from stumps. It has many agroforestry uses, including hedges, windbreaks, fences, shade trees, stakes and especially as mulch.

According to Parmentier *et al.* (2007), 72% of arable land and 31% of African rangelands are degraded. Agroforestry and agroecology techniques could be used to restore soil fertility within 2-4 years. By combining woody plants which well nutrients up to the surface horizons (and even better, legume or actinorhizal plants which also fix atmospheric nitrogen) and provide green manure for crops, yields are at least doubled (Robin, 2012).

Over a 4-year period in Malawi, Akinnifesi *et al.* (2007) compared yields of a maize monoculture with those obtained when maize was intercropped with *G. sepium* from the best Guatemalan source (*G. sepium* planted in furrows between rows of maize, with 90 cm spacing in the row and 150 cm between rows, or 7 400 trees/ha). *G. sepium* seedlings were cut when they were 30-40 cm tall, and the biomass (prunings with leaves and young shoots) was immediately buried to 15 cm depth three times

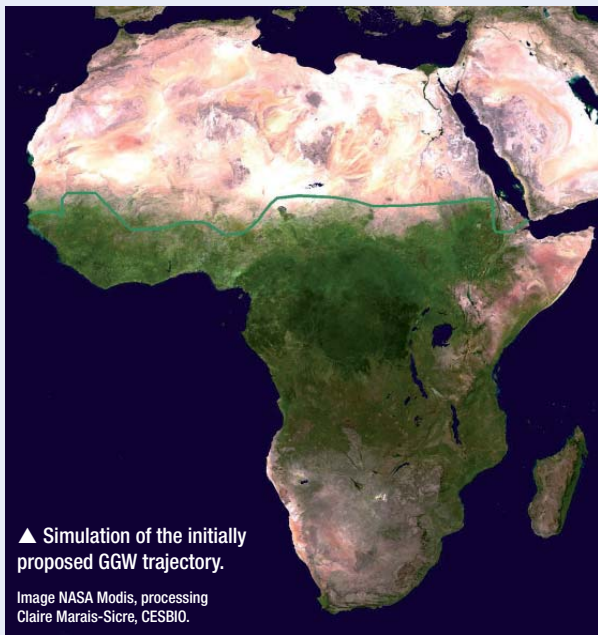
during the crop season (October-April), and then covered with soil. The maize crop was sown 15 days after the first burying operation (30 cm spacing in the row and 75 cm between rows, or 44 000 plants/ha).



These studies revealed that intercropping gave much higher yields than those obtained with a monoculture, but they were variable depending on rainfall conditions and the occurrence of excessive droughts. Soil amendments with small quantities of nitrogen or inorganic phosphorus could have additive effects. Makumba & Akinnifesi (2008) obtained evidence in Malawi that *G. sepium* decomposed better than *Sesbania sesban* or other plants and they concluded that a blend of *G. sepium* prunings with crop residue accelerates the decomposition of low quality crop residue.

In 2006, the Malawian President Mutharika launched the Green Revolution and subsidized fertilizers (before exhausting all the funds). Then in 2007 he launched a national agroforestry programme with *G. sepium* playing a front-stage role. The results showed that, of the two agricultural models, the agroforestry programme was much more efficient and sustainable than the monoculture. Yields were at least twofold higher, reaching 3.7 t/ha on average. Several hundreds of thousands of farmers adopted the intercropping technique and now Malawi no longer suffers from chronic hunger. In addition to *G. sepium*, trees that produce fruit, forage or fuelwood are commonly planted and protected (Robin, 2012).

> EXAMPLE | Public policy in dryland regions—the Great Green Wall



Trajectory from UA, CEN-SAD & Senegal, 2008. *Grande Muraille Verte. Modalités opérationnelles de mise en œuvre*. Conceptual scheme (draft project document). Report. 35 pp.

The African Great Green Wall (GGW) initiative is seen as a major priority project of Saharan-Sahelian States. The 100-400 mm annual rainfall belt chosen for the GMV trajectory spans the northern fringe of the rainfed agriculture areas, which are saturated and densely populated, as well as so-called pastoral areas, which are increasingly affected by crop farming encroachment.

This project is sometimes over-simplistically presented as wall of trees planted to block the advancing desert. Actually, this project currently aims to develop reforestation and development activities and to effectively contribute to the integrated development of rural areas in the vicinity of the GGW, and to initiatives to fight poverty in a sustainable development framework. However, local specificities must also be taken into account due to the biophysical, pedological and cultural differences. CSFD published a Topic Brief (Escadafal *et al.*, 2011) and IRD published a book (Dia & Duponnois, 2012) on the GGW.

For further information: www.grandemurailleverte.org

IMPACT OF DESERTIFICATION CONTROL TECHNIQUES ON INORGANIC CARBON

The organic carbon cycle has been extensively studied and modelled at different spatiotemporal scales, whereas inorganic carbon has been disregarded in studies on the soil carbon cycle. Global inorganic carbon reserves are nevertheless quite substantial (950 Gt) and markedly predominate in soils in arid and semiarid regions (*see p. 8*).

Few studies on soil inorganic carbon

Few studies have been devoted to carbonate content, quality and patterns in the carbon cycle in the medium and short term for two main reasons:

- ① the complexity of the interaction between the atmosphere, different forms of inorganic carbon, soil organic matter and vegetation
- ② the relatively slow dynamics of soil carbonates as compared to organic matter.

Soil carbonate distributions and quantities influence soil fertility, erodibility and water retention capacity. The pH of carbonated soils is basic (often around 8), while they have a high base content and the presence of Ca^{2+} ions stabilizes the soil.

Experimental observations indicate that inorganic carbonate dynamics are not slow and insignificant. As is the case with organic carbon reserves, human activities—including cropping and irrigation—have

a significant impact on inorganic carbon stocks. For instance, Chinese researchers calculated an inorganic carbon loss of 1.6 Gt due to the intensification of human activities on soil (Wu *et al.*, 2009). Conversely, but to a lesser extent, precipitation of atmospheric CO_2 into inorganic carbon in the form of carbonates was observed—Lal & Bruce (1999) studied this formation of pedogenic carbonates and estimated that it occurs at a rate of 0.007-0.266 Gt carbon/year in arid and semiarid regions. These precipitations are promoted by the biological activities of root microorganisms. Moreover, Landi *et al.* (2003) observed inorganic carbon storage in forests and boreal grasslands in Canada. Note that few studies have focused on quantifying carbonate dynamics in dryland regions.

Mixed impact of CD techniques on inorganic carbon

Increasing crop production is often proposed as a way to enhance soil carbon sequestration. This requires sustained crop irrigation in arid and even semiarid regions. However, such irrigation often leads to substantial emissions of CO_2 into the atmosphere. Groundwater in such regions is indeed often laden with dissolved calcium bicarbonate (Ca^{2+} and HCO_3^-). When used for irrigation, this water promotes calcium precipitation in the form of calcium carbonate, in addition to CO_2 emissions. The latter, associated with water with high calcium bicarbonate content in addition to CO_2 directly related to water pumping, tend to eliminate organic carbon sinks created by the increased crop production achieved via irrigation.

For example, annual irrigation (1 m) with calcium-laden water (40 mg/l concentration) releases 12 g of CO₂/m²/year (Schlesinger, 2000). Similarly, some stakeholders have shown that natural relatively acidic precipitation increases CO₂ loss and reduces soil carbonate contents. Conflicting results were obtained in other studies, suggesting that irrigation in semiarid regions can lead to low (yet positive and significant) inorganic soil carbon sequestration.

These often contradictory experimental results could be explained by the different inorganic carbon contributions in the global carbon cycle.

Balances and exchanges between the different carbon forms (secondary carbonates, organic and atmospheric carbon) are dependent on many environmental factors (climate, land-use patterns and forms of inorganic carbon). Hence, it is still very hard to understand and readily predict variations in this system. The only current studies on this issue are located in Arizona. Further studies on inorganic carbon dynamics are needed in other regions and with different inorganic carbon qualities and contents in order to identify general trends in the dynamics of inorganic carbon reserves in the global carbon cycle.

▼ *In situ* measurement (soil sampling) of soil carbon and carbonate contents using infrared spectrometry in Tunisia under the RIME-PAMPA project (www.rime-pampa.net).

© N. Brahim



Conventional accurate but expensive techniques

There are two main soil carbon measurement methods, both of which are destructive:

- wet oxidation (such as the Walkley-Black method, with the Anne method being the French variant)
- combustion methods with determination of the CO₂ produced (IR, titration, conductimetry).

The principle of oxidation methods is the direct determination of organic carbon following organic matter oxidation via excess potassium bichromate in sulphuric acid at 135°C. The quantity of chrome III⁺ formed, proportional to the soil organic carbon content, is determined by colorimetry. However, oxidation may be incomplete, which means that only part of the organic carbon is extracted, which seems to be the case in tropical or carbonate-rich soils. Moreover, handling pollutive and highly allergenic bichromates is a health and safety problem.

Combustion methods have thus been preferred for several years. These elementary analysis methods are used to determine the total soil carbon (organic and inorganic). The most conventional method, as described in the NF ISO 10694 standard, involves micro-weighing (around 25 mg), flash combustion, chromatographic separation of molecular nitrogen and carbon dioxide, and thermal conductivity detection. It is essential to know the inorganic carbon content from the outset in order to determine the organic carbon content, otherwise the sample has to be decarbonated prior to analysis. This method is highly accurate but expensive (around €5-10 for a 25 mg sample) because of the analysis procedure and the time required for soil sample preparation. Moreover, the representativeness of the measured sample is problematic given the low analysed soil sample weights. The samples should thus be finely ground (to less than 250 µm) to avoid some of these representativeness problems, but this will increase the measurement cost.

New faster and less expensive techniques

O'Rourke & Holden (2011) estimate the cost of the Walkley-Black wet oxidation methods at €2.6 per sample and the dry combustion method at €15 per sample. New less expensive soil carbon measurement methods have been developed over the last 10 years. They are based on:

- near-infrared spectroscopy (NIRS), which costs around €0.5-1.2/sample
- laser-induced breakdown spectroscopy (LIBS)
- neutron probes.

Skilled operators are required regardless of the method used.

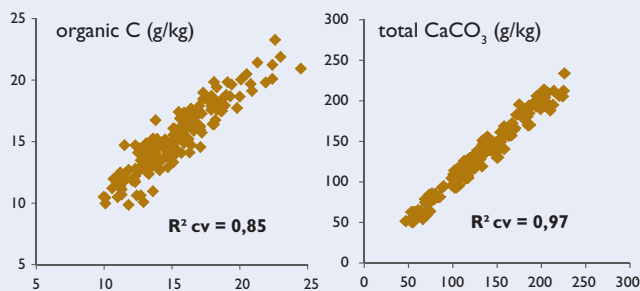
With these three methods, soil samples can be directly analysed without any pre-preparation (grinding, sieving), but they usually require calibration generally via reference (soil) databases.

Current research seems to be focused more intensely on the use of NIRS techniques, which have been used for several years for studying plant materials and litter. Since the 1970s, NIRS has been used in soil studies to characterize soil organic matter. This method has been widely used since the 1990s. These and more recent studies have shown that it is possible to quite adequately calibrate spectra in the near infrared spectrum to determine soil carbon and nitrogen contents. Some studies have focused more specifically on dryland soils. Recent studies have shown that NIRS technology quite accurately differentiates soil organic and inorganic carbon, which is a very tedious process with conventional methods. Finally, studies are currently focused on *in situ* measurements, thus overcoming the need for sample preparation (drying, grinding), which is often long and tedious.



▼ *In situ* measurement (soil sampling) of soil carbon and carbonate contents using infrared spectrometry in Tunisia. The portable spectrometer and contact probe are seen the ground.

> EXAMPLE | Prediction of soil organic and inorganic carbon using infrared spectrometry



▲ Prediction (y-axis = estimated values, x-axis = reference values) based on spectra measured on *in situ* soil samples (Mateur region, Tunisia) without pre-preparation.

From Habimana, 2012. RIME-PAMPA project (www.rime-pampa.net)

The graphs on the left highlight the quality of the spectrometry estimates of organic and inorganic carbon (CaCO₃) contents in a set of Tunisian soil samples.

Values on the x-axis are organic or inorganic carbon levels measured by conventional laboratory techniques, while those on the y-axis are organic and inorganic carbon levels predicted from the sample IR spectrum and via a prediction model. This prediction or calibration model was statistically validated on a set of samples that had been analysed by spectrometry and by conventional laboratory techniques.

On these graphs, when the dots are aligned on the first bisector (1:1 right), this means that the predicted values are equal to the measured values. In this case, the spectrometry prediction is correct. The graphs also show that the soil organic and inorganic carbon content predictions are correct for samples that had not been pre-prepared, i.e. dried and sieved through a 2 mm mesh.

> FOCUS | Specificity in the assessment of carbon contents in soils from arid and semiarid regions



▲ Rocky soil at Siliiana, Tunisia.

Dryland soils often have high coarse element (stones, laterite, etc.) and carbonate contents. This makes it hard to measure the soil density, which is essential for calculating the different element contents.

The first difficulty is encountered during the sampling process, due to the presence of stones in the soils, in addition to the low organic carbon content and its heterogeneous distribution at the sampling scale adopted

for the analysis (a few mg). Hence, it is hard to collect representative samples.

The second difficulty concerns the analysis. Most soil carbon measuring methods estimate the total soil carbon content (organic and inorganic carbon). The soil sample has to be decarbonated when the analysis is focused only on organic carbon. This decarbonation procedure is difficult and expensive.

Carbon at the crossroads of international environmental conventions

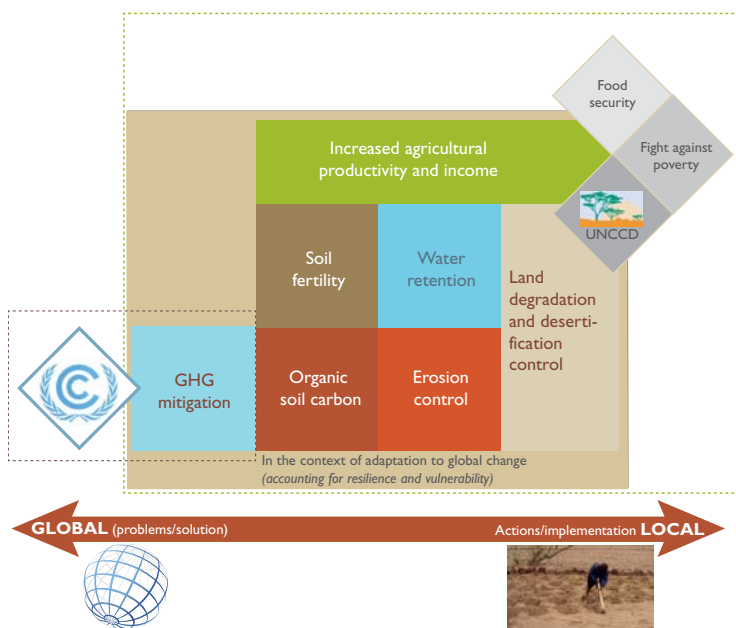
Agriculture and soil carbon have taken a back seat in international negotiations for a long time despite the importance of soil, especially regarding carbon sequestration and food security.

International debates have been focusing on the soil issue since the food price crisis and the food riots in Africa in 2008 and 2009. Because of the multiple functions and services provided by soil carbon—regarding climate control, soil fertility and biodiversity—this element, especially the organic form, is now at the crossroads in many international negotiations. Drylands and soil carbon are now pivotal factors in global environmental issues, especially in the context of the three major multilateral environmental agreements (MEA) in the form of UN conventions:

- United Nations Framework Convention on Climate Change (UNFCCC)
- Convention on Biological Diversity (CBD)
- United Nations Convention to Combat Desertification (UNCCD)

MULTIPLE MULTILATERAL ENVIRONMENTAL AGREEMENTS...

Multilateral environmental agreements (MAEs) were drawn up following the United Nations Conference on the Human Environment (UNCHE, often referred to as the 'Stockholm Conference') in 1972. This laid the foundations for global environmental governance by giving rise to the United Nations Environment Programme (UNEP), with the adoption of a declaration involving 26 founding principles, which are often included in MAEs as principles for the integration of development and environment (principles 13 and 14). Environmental protection and development then evolved into the sustainable development concept.



▲ Soil carbon is at the crossroads in international negotiations, from the United Nations Convention to Combat Desertification (UNCCD) to the United Nations Framework Convention on Climate Change (UNFCCC), and of course in many discussions and negotiation concerning soil fertility preservation and global food security.

> FOCUS | Sustainable development

Sustainable development was defined in the report 'Our Common Future' (also known as the Brundtland Report, after the name of the President of the World Commission on Environment and Development, 1987) as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs".



▲ Sustainable development chart: a global approach to the confluence of three concerns, called 'the three pillars of sustainable development'.

Source: website of the Virtual University Environment and Sustainable Development/Wikipedia.



> FOCUS | United Nations multilateral environmental agreements

Many multilateral treaties are deposited with the Secretary-General of the United Nations* and consolidated in a publication. Environmental issues are covered in the 16 agreements listed below. Other agreements concerning the environment *pro-parte* are also listed, e.g. the United Nations Convention on the Law of the Sea. There are, however, many other MEAs that are registered and supported by other international organizations, e.g. the Convention on Wetlands (Ramsar) is an intergovernmental treaty that is not affiliated with the United Nations (UN) AME system. UNEP lists over 500 AMEs and has also set up a programme to promote consistent governance for the environment, i.e. Programmes for the Development and Periodic Review of Environmental Law ('Montevideo Programme').

- 1979 – Convention on Long-range Transboundary Air Pollution. Geneva, 13 November 1979
- 1985 – Vienna Convention for the Protection of the Ozone Layer. Vienna, 22 March 1985.
- 1989 – Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal. Basel, 22 March 1989
- 1991 – Convention on the Environmental Impact Assessment in a Transboundary Context. Espoo (Finland), 25 February 1991
- 1992 – Convention on the Protection and Use of Transboundary Watercourses and International Lakes. Helsinki, 17 March 1992
- 1992 – Convention on the Transboundary Effects of Industrial Accidents. Helsinki, 17 March 1992
- 1992 – United Nations Framework Convention on Climate Change. New York, 9 May 1992
- 1992 – Convention on Biological Diversity. Rio de Janeiro, 5 June 1992
- 1992 – Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas. New York, 17 March 1992
- 1994 – United Nations Convention to Combat Desertification in those Countries Experiencing Serious Drought and/or Desertification, Particularly in Africa. Paris, 14 October 1994
- 1994 – Lusaka Agreement on Co-operative Enforcement Operations Directed at Illegal Trade in Wild Fauna and Flora. Lusaka, 8 September 1994
- 1997 – Convention on the Law of the Non-Navigational Uses of International Watercourses. New York, 21 May 1997
- 1998 – Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters. Aarhus (Denmark), 25 June 1998
- 1998 – Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade. Rotterdam, 10 September 1998
- 2001 – Stockholm Convention on Persistent Organic Pollutants. Stockholm, 22 May 2001
- 2003 – Protocol on Civil Liability and Compensation for Damage Caused by the Transboundary Effects of Industrial Accidents on Transboundary Waters to the 1992 Convention on the Protection and Use of Transboundary Watercourses and International Lakes and to the 1992 Convention on the Transboundary Effects of Industrial Accidents. Kiev, 21 May 2003.

* <http://treaties.un.org/Pages/Treaties.aspx?id=27&subid=A&lang=fr>

... THREE OF WHICH SPECIFICALLY CONCERN SOIL CARBON IN DRYLAND REGIONS

These three conventions on the global environment have different yet interrelated objectives, especially regarding dryland ecosystems: **desertification, climate change and biodiversity loss interact** (see below). Hence there are relationships and feedback loops between these three conventions. The inner loops especially concern soil erosion while the outer loops highlight the vulnerability of ecosystems to climate change and the importance of biodiversity for mitigation and adaptation (decreased primary production, microbial activities and biodiversity).

Although the UNCCD has laid the foundation for a synergistic relationship between the three MEAs, there is a lag in drawing up concrete policies on drylands and carbon. **One of the obstacles is the lack of a common definition of drylands:**

- UNCCD defines drylands according to an aridity index, which is the mean long-term ratio between the mean annual rainfall in a region and its mean annual potential evapotranspiration. More specifically, the

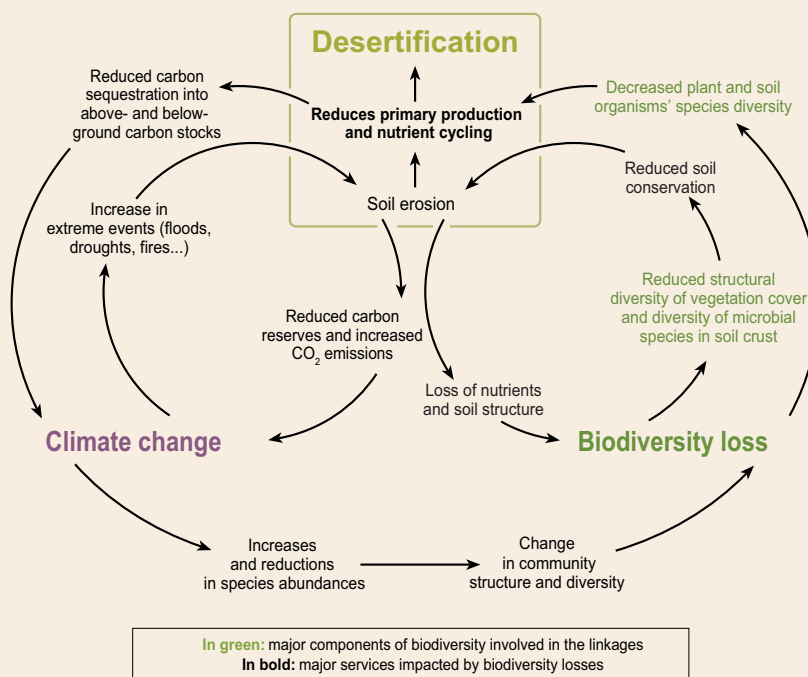
definition encompasses all lands where the climate is classified as dry subhumid, semiarid, arid or hyperarid. The dryland area thus changes with time. This definition also accounts for all uses of these areas, irrespective of whether they concern urban or nonurban, agricultural, forested or other areas.

- The CBD uses the dryland definition derived from its specific programme on the biodiversity of dry and subhumid lands. This definition does not take hyperarid areas into account, i.e. 6.6% of lands.
- The UNFCCC does not set specific categories for arid and semiarid areas. In discussions on mitigating climate change, greenhouse gas emissions and uptake by vegetation and soil are taken into account in six broad 'land use' categories, as outlined in the Intergovernmental Panel on Climate Change (IPCC) guidelines. These categories were selected especially to ensure comprehensive coverage of all areas within a country without duplication. The official names of these categories are as follows: forest land, cropland, grassland (including rangelands, scrubland and pastures), wetlands (mostly bogs and marshes), settlements (everything concerning transportation infrastructure and buildings) and other land (such as rocky areas, glaciers, etc.).

> FOCUS | The three global environment conventions—links and feedbacks

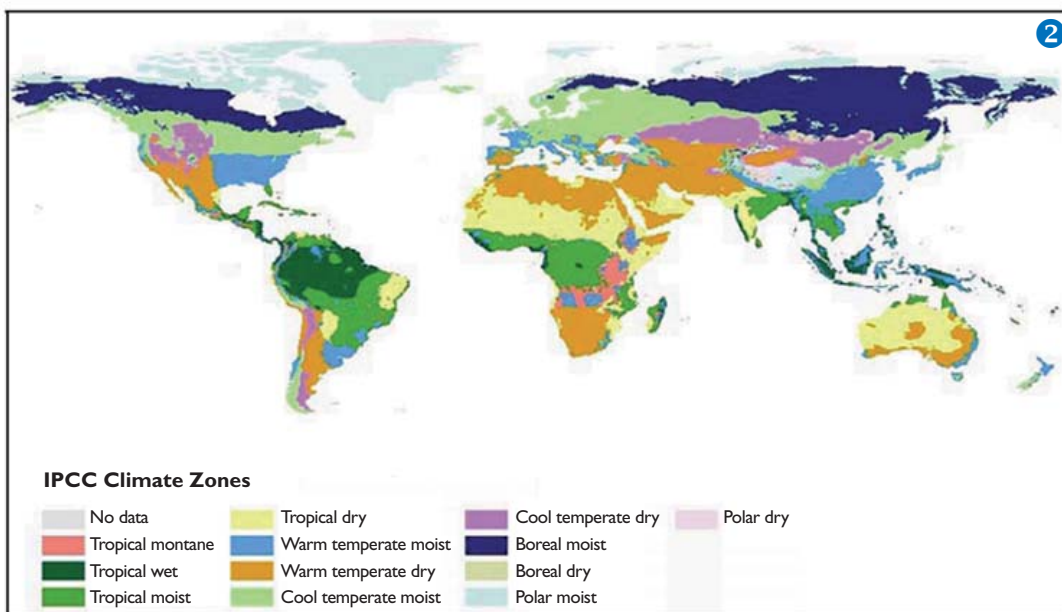
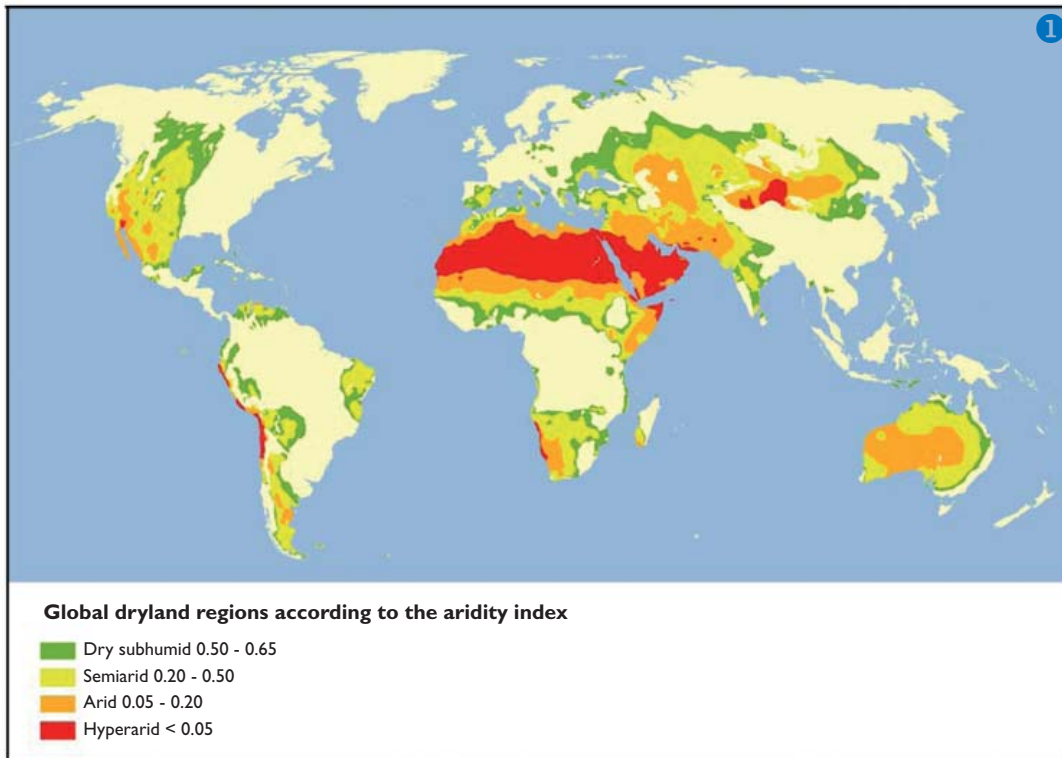
“The major components of biodiversity loss (in green) directly affect major dryland services (in bold). The inner loops connect desertification to biodiversity loss and climate change through soil erosion. The outer loop interrelates biodiversity loss and climate change. On the top section of the outer loop, reduced primary production and microbial activity reduce carbon sequestration and contribute to global warming. On the bottom section of the outer loop, reduced primary production and microbial activity reduce carbon sequestration and contribute to global warming. On the bottom section of the outer loop, global warming increases evapotranspiration, thus adversely affecting biodiversity; changes in community structure and diversity are also expected because different species will react differently to the elevated CO₂ concentrations”.

From the Millennium Ecosystem Assessment Report, 2005.



▲ Linkages and feedback loops among desertification, global climate change and biodiversity loss.

Source: www.millenniumassessment.org/documents/document.797.aspx.pdf



▲ ① Map of dryland regions subdivided according to the aridity index ($P/PET = \text{precipitation/annual evapotranspiration}$).

Source: ESRI, 1993; CRU/UEA; UNEP/GRID, 1991.

● ② IPCC delineation of major climate zones.

Source: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, vol. 4, chap. 3 'Consistent representation of lands'.
www.ipcc-nggip.iges.or.jp/public/2006gl/french/pdf/4_Volume4/V4_03_Ch3_Representation.pdf

Drylands are thus present in these different land use categories. However, for the assessment of GHG sources and sinks, IPCC proposes a simple climate zone classification that includes 12 categories ranging from dry to moist.

The default emission factors proposed by IPCC (e.g. GHG emissions by soil due to the conversion of a forest

into cropland) differ according to these climate zones.

Arid and semiarid areas are also of concern in discussions on climate change adaptation. These discussions—although they may not differentiate climate zones and ecosystems—are sometimes focused on more specific issues, particularly from a technical and scientific standpoint.

> FOCUS | United Nations Convention to Combat Desertification

The origins of the UNCCD date back to the 1970s and are associated with the impacts of the large-scale droughts that took place in the Sahel and to the founding of specialized international and regional organizations such as the UNEP in 1972 and the Permanent Inter-State Committee for Drought Control in the Sahel (CILSS) in 1973. It was not until the late 1980s when the sustainable development concept began to take root, with the preparation of the Rio Earth Summit, and then the adoption of Agenda 21 in 1992 that a draft international agreement to combat desertification was finally adopted and gradually implemented. The UNCCD was ratified in Paris in 1994 and came into force in 1996, and it now includes 195 country Parties.

This treaty aims to halt the decline in the productive, biological and economic potential of cropland, rangeland and forest land in arid, semiarid and dry subhumid regions. These regions are subject to specific climatic constraints and also, as noted with respect to Africa, particularly vulnerable from social and economic standpoints.

The UNCCD is an environmental agreement that targets development objectives, which complicates the definition, implementation, monitoring and assessment of resulting initiatives. The convention was soon criticized because of the weakness of current measures for streamlined assessment of degradation processes and the impacts of control activities on different scales, including global, national and regional.

During the 8th Conference of the Parties (COP8, Madrid 2007), a 10-year strategic plan and framework to enhance the implementation of the Convention (2008-2018) was adopted based on a management plan focused on results. The Treaty includes four strategic objectives:

- ① To improve the living conditions of affected populations
- ② To improve the condition of affected ecosystems

③ To generate global benefits through effective implementation of the UNCCD

- ④ To mobilize resources to support implementation of the Convention through building effective partnerships between national and international actors

Strategic objective 3 is focused on the contribution of the Treaty to the production of global public goods, while specifically **emphasizing links between the UNCCD, CBD and UNFCCC objectives**: *“Sustainable land management and combating desertification/land degradation contribute to the conservation and sustainable use of biodiversity and the mitigation of climate change.”*

This 10-year strategic plan enables the progressive development of a specific framework for setting up a system to monitor the impacts of the Convention on different scales. **One of the indicators designed to measure the extent of fulfilment of this objective concerns carbon sequestration.**

This ‘carbon’ indicator proposed for the national scale in the preparation of reports of affected country Parties is **currently facultative**. In fact, only poverty rate and vegetation cover rate measures regarding strategic objectives 1 and 2 have been mandatory since COP9 (Buenos Aires, 2009).

Despite the Convention’s efforts to establish means to assess its action, the lack of quantified objectives regarding work carried out on the impact indicators currently limit the analysis and scope of the collected information. **In a unique way, however, the UNCCD, via its 10-year strategy, has laid a concrete foundation for a synergistic relationship between the three multilateral environmental agreements.**

From Cornet, 2012 and the 10-year Strategic Plan and Framework to Enhance the Implementation of the Convention (2008-2018): www.unccd.int/Documents/18%20COP8.pdf

STRATEGIC OBJECTIVE 3 – TO GENERATE GLOBAL BENEFITS THROUGH EFFECTIVE IMPLEMENTATION OF THE UNCCD		
Basic indicators	National level	Global level
S6 – Increase in carbon stocks (soil and plant biomass) in affected areas S7 – Areas of forest, agricultural and aquaculture ecosystems under sustainable management	VII – Animal and plant biodiversity	III – Proportion of the population in affected areas living above the poverty level
	II – Proportion of the population in affected areas living above the poverty level	XI – Areas under sustainable land management
	X – Carbon stocks in above-ground biomass and in soils XI – Areas under sustainable land management	

> FOCUS | United Nations Framework Convention on Climate Change

The international political response to climate change began with the implementation of the UNFCCC in 1992. This set the framework for action aimed at stabilizing atmospheric greenhouse gas concentrations at a level that would prevent 'dangerous anthropogenic interference' with the climate system (Convention objective defined in Article 2). **This objective specifies that this level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.** This objective is essential especially for drylands that are fragile due to climatic constraints and vulnerable from a socioeconomic standpoint. The UNFCCC entered into force on 21 March 1994 and now includes 195 country Parties.

However, UNFCCC did not initially specify any quantitative objectives. Quantified binding objectives were defined when the Kyoto Protocol was signed in 1997. The text entered into force on 16 February 2005 and it has now been ratified by 192 Parties (191 countries + EU). For developed countries, it recommended a global reduction of 5.2% in emissions relative to their levels in 1990 for the 2008-2012 period (first commitment period). This objective was weakened from the outset because of the fact that the United States, a signatory to the 1997 Protocol, did not ratify it and therefore made no commitments. The scope of the objective was further weakened by Canada's decision in 2011 to withdraw from the Protocol. The agreement for the second commitment period was signed at Doha (2012). All eyes are now turned towards the stated intention in 2011 to reach a global agreement by 2015, including all countries (not only developed countries), which would come into force after 2020.

DECISION SUPPORT TOOLS— THE CARBON BALANCE

The 'carbon' indicator has become essential for decision making in most sectors of society. Development agencies are no exception and have also incorporated a component focused on the impact of their activities on the carbon balance. This could result in the definition or implementation of new agricultural policies or development projects. The 2012 edition of the UNEP Year Book concerning emerging issues* thus clearly only focuses on two out of the many environmental issues: 'the advantages of soil carbon' and 'the closure and dismantling of nuclear reactors'.

Various tools are now available to enable decision makers and project developers to incorporate the 'carbon' dimension in their initiatives, e.g. lifecycle analyses used in sector analyses.

These tools must be easy to use and inexpensive. They provide information for project managers funders and stakeholders, with the aim of enhancing project designs from a 'carbon' perspective.

The spatial dimension is currently at the forefront—an activity carried out in a region of the world can actually have direct or indirect impacts on land-use change dynamics, sometimes even well beyond the concerned region. For instance, the European policy aimed at promoting bioenergy, especially biofuels

for road transport, may result in an increase in the production and import of agricultural products. This could lead to the introduction of new farming systems or place pressure on food prices. Carbon balances that currently concern the impact of biofuels often only consider direct carbon emissions without seriously accounting for land-use changes directly induced in producing countries, or even indirectly in other regions. Carbon balances, which are limited to direct emissions, are thus often more favourable for biofuels than for fossil fuels. However, this result is less clearcut when indirect land-use changes are taken into account. Only a few tools currently take this spatial dimension into account regarding the carbon balance in agricultural and forestry sectors.

A review of regional decision-support tools was very recently published**. These tools are online calculators or spreadsheets that may, for instance, be used to assess carbon emissions of agricultural and forestry sectors. These calculators are 'user friendly' decision support tools for field operators, as opposed to more complex models designed for the research community (*see table on next page*). This study shows that current tools can be classified in four categories according to their end use: awareness, accounting, project analysis or sector analysis.

* www.unep.org/yearbook/2012/

** www.fao.org/fileadmin/templates/ex_act/pdf/ADEME/Review_existingGHGtool_VF_UK4.pdf

▼ Time and knowledge required to calculate the carbon impacts of projects.

From + to ++++: from the slowest (>1 month) and the most difficult (training required) to the fastest (<1 day) and easiest to use.

From Colomb *et al.*, 2013.

Calculator	Assessment time	Ease of use
AFD calculator	+++	++++
ALU	+	+
CALM	+++	+++
Carbon benefit project CPB	++	++
Carbon Calculator for NZ Agriculture and Horticulture	++++	++++
Carbon Farming Group Calculator	++++	++++
CFF Carbon Calculator	+++	++
Climagri®	+	+
Cool Farm Tool	+++	+++
CPLAN v2	+++	+++
Dia'terre®	+++	+
EX-ACT	++++	+++
FarmGAS	++	++
Farming Enterprise Calculator	++++	++++
FullCAM	+	+
Holos	++	+++
IFSC	++++	++
USAID FCC	++++	+++

Drylands have been taken into account in three project assessment tools: those developed by FAO (EX-ACT, Ex-Ante Carbon-balance Tool, *see left column*) and by the Global Environment Facility (CBP, Carbon Benefits Project), with global applications, and the tool (Carbon Calculator) proposed by the United States Agency for International Development for developing countries.

Such tools can show that agricultural and forestry carried out to ensure food security, control land degradation and efficiently manage catchments can also be useful in mitigating climate change. It is even more important to show that synergy is possible regarding arid and semiarid regions where natural constraints, especially water shortages, make it hard to obtain a sufficiently high per-hectare carbon sequestration rate to make a strictly agricultural project attractive for the carbon market.

The carbon balance has become a decision support tool, but it is important not to go to the extreme of only using it for decision support. It is actually a supplementary indicator, like economic and social indicators, which are often the main indicators used in dryland assessments. Ultimately, the best trade-offs should be found when implementing agricultural policies, as well as desertification and land degradation control policies.

> EXAMPLE | Mitigation potential of the cashew sector in Burkina Faso



▲ A fruit of the cashew tree (*Anacardium occidentale* L.).

The cashew tree—which is considered as a useful forest species in combating erosion and desertification—is now also recognized for the economic opportunities it provides for different rural stakeholders. The cashew nut sector is developing in Burkina Faso and is supported by several development institutes.

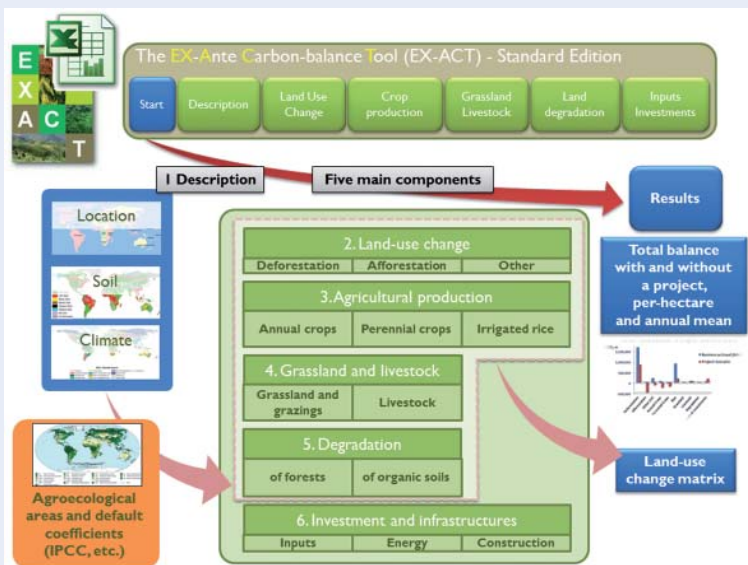
A carbon analysis of white cashew kernels performed using the EX-ACT calculator revealed a good carbon balance due to the fact that the production process represents a GHG sink. However, differences in carbon footprint were noted depending on the location and the processing system. The carbon footprint of cashew kernels processed in a semi-industrial way in Burkina Faso was found to be better than that calculated for white kernels processed on a small-scale in Burkina Faso, which already has a better footprint than that of raw Burkinabé cashews processed in India.

The study carried out thus highlighted the impacts of this sector regarding climate change mitigation. The carbon balance projections representing patterns of the sector over the next 5 years were also calculated. Supporting the sector could thus enable a rapid return of this forest species, which could help combat desertification while also mitigating climate change.

From Tinlot, 2010.

For further information: www.fao.org/fileadmin/templates/ex_act/pdf/master_thesis/MFE_TINLOT_M_210610.pdf

> EXAMPLE | EX-ACT: a tool for calculating the carbon impact of development projects



▲ How the EX-ACT tool functions.

EX-ACT is a tool developed by FAO to perform *ex-ante* estimates of the impact of agriculture and forestry development projects on GHG emissions and carbon sequestration. This tool is currently widely used by FAO and the World Bank, as well as by ministries responsible for agricultural policies in many countries. Case studies using this tool have been focused on dryland areas, especially a study on the cashew production sector in Burkina Faso (see earlier), an agricultural development project in Ethiopia, etc.

EX-ACT consists of spreadsheets developed mainly based on the IPCC Guidelines for National Greenhouse Gas Inventories. EX-ACT consists of a set of worksheets in which project managers insert basic data on land use and management practices foreseen in the project. EX-ACT adopts a modular approach—each ‘module’ describes a specific land use—following a three-step logical framework:

- 1 a general description of the project (geographical area, climate and soil characteristics, project duration)
- 2 identification of changes in land use and technologies foreseen by project components using specific ‘modules’ (deforestation, forestation, forest degradation, annual/perennial crops, irrigated rice, grasslands, livestock, inputs, energy, other investments such as road or warehouse construction)
- 3 calculation of gas emissions and the carbon balance.

EX-ACT is available in English, French, Spanish and Portuguese.

For further information: www.fao.org/tc/exact/ex-act-home/en

CARBON MARKETS— WHAT ARE THE BENEFITS FOR DRYLAND AREAS?

Carbon markets come in various forms. They can be regulated (international market related to the Kyoto Protocol, carbon emissions trading systems in some countries or regions, such as the European Union) or voluntary.

Carbon currently has a very low value. Moreover, rural, agricultural and forestry sectors have a very small share, representing less than 1% of the global carbon trade! The market ‘carbon volume’ mainly comes from energy, industrial, residue and waste treatment sectors, etc. Policies and techniques are the main obstacles to better integration of agricultural and forestry activities into the soil carbon sequestration accounting system:

- Political factors that give priority to high-emission energy and industrial sectors, which limit clean forestry development mechanisms to afforestation

and reforestation activities and the use of forestry credits under the Kyoto protocol, and finally which prohibit the use of forestry credits in the European carbon market.

- Technical factors (field verification of carbon sequestration).

Moreover, under the Kyoto Protocol, the Clean Development Mechanism (CDM) does not recognize activities geared towards promoting carbon sequestration in agricultural soil. Carbon markets therefore cannot currently serve as a lever for changing practices. A global land management policy regarding this soil carbon sequestration function has yet to be drawn up.

At first glance, carbon markets do not seem to markedly concern dryland regions. However, due to the complexity of formal markets (CDM and JI), voluntary markets have quickly taken over in terms of trading volume and recognition of more diversified activities related to cropland and grassland management.

This trend towards increased consideration of agricultural and pastoral activities is the result of a combination of several factors:

- The fact that it is essential to reconcile food security, sustainable development, adaptation and mitigation.
- The importance of agricultural and pastoral sectors in terms of emissions: global GHG emissions related agriculture represent 13.5% of the total, followed by transportation (13.1%). This agricultural sector is inseparable from land use and forestry, which represent 17.4% of global emissions. This proportion is often greater in non-industrialized countries.
- The recognition that policy actions regarding the forestry sector—such as deforestation and forest degradation control—are inseparable from agricultural policies.

Under the Kyoto Protocol, some countries (including Spain and Portugal, which have substantial drylands) have already decided to quantify their emissions regarding cropland and rangeland management in their national inventories.

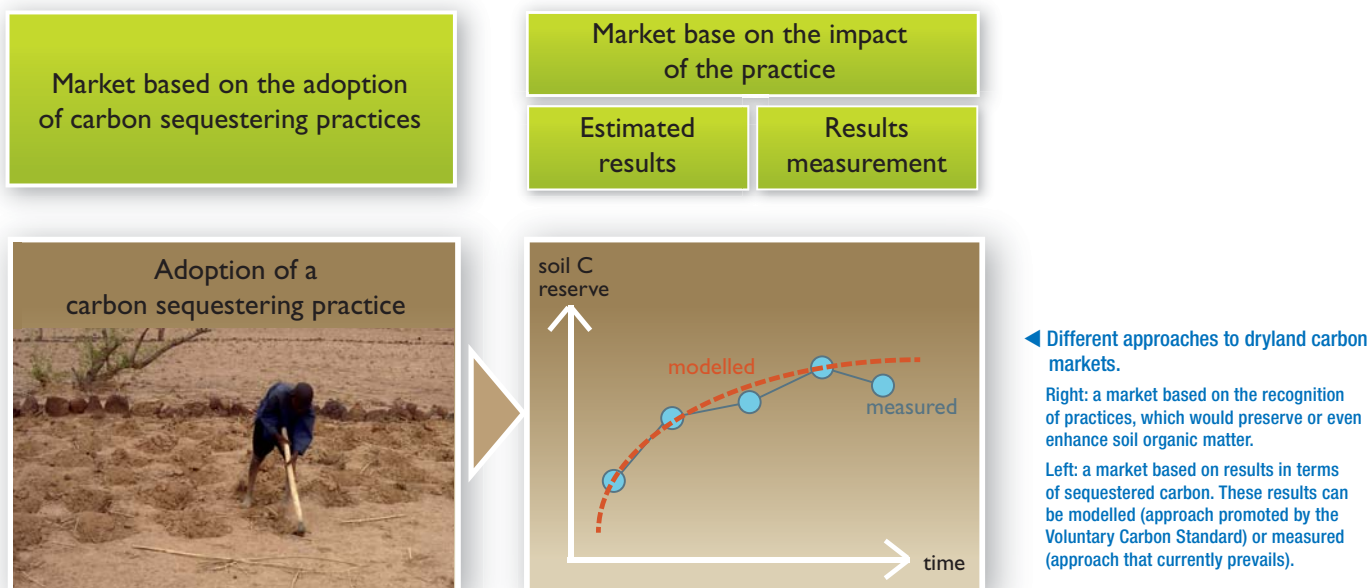
More importantly, it is increasingly clear that carbon should also be recognized for its multiple functions.

Markets have so far focused on verifying the quantity of carbon sequestered, whereas it would be much simpler, and verifiable, to directly promote proven ‘carbon sequestering’ practices. In dryland areas, it would be easier (and necessary) to set up

a carbon market based on the adoption of these sequestering practices. These indeed are more readily, and inexpensively, verifiable than the results of practices, in terms of quantities of carbon actually sequestered. This is in line with the current promotion of alternative production systems focused on optimal management of organic matter, and thus soil carbon. These agricultural practices, and the necessary changes in agriculture, represent “an agriculture that sustainably increases productivity, resilience (adaptation), reduces/removes GHGs (mitigation), and enhances the achievement of national food security and development goals” (FAO, 2010). Many international organizations have adopted this so-called Climate-Smart Agriculture concept, such as the World Bank and the Global Environment Facility (FAO, 2013). These systems are also advocated in strategic agricultural development plans in Africa, such as the Comprehensive Africa Agriculture Development Programme* adopted by the African Union’s New Partnership for Africa’s Development.

A carbon market could provide a much more effective operational lever for modifying agricultural practices and implementing soil conservation initiatives in dryland regions. Setting up a market focused on practices would further recognize the pivotal role of land degradation control.

* For further information: www.nepad-caadp.net



> FOCUS | Carbon markets—how do they work?

The current carbon market system gives an economic value to the quantity of sequestered carbon via application of the Kyoto Protocol, the Clean Development Mechanism (CDM) or the joint implementation (JI) mechanism.

Via CDM, industrialized countries pay for projects that reduce or avoid carbon emissions in poorer nations in return for credits that can be used to meet their own emission targets. JI projects are carried out in other industrialized countries or in countries in transition.

Moreover, every country can also voluntarily offset its own emissions.

Under the Kyoto Protocol or voluntarily, these markets do not fully recognize activities that favour carbon sequestration in agricultural soil. Note, however, that JI only recognize these activities in countries that have opted to account for them (e.g. Ukraine).

For further information: www.cdclimat.com

> FOCUS | Dryland forests and the 'climate' convention

Dryland forests contribute to biodiversity conservation and food security. They ensure sustainable livelihoods and help combat desertification. These forests participate in the livelihoods of local communities while also mitigating the impacts of global climate change. In addition to their roles in preserving the environment and providing goods and services, forests play four major roles in climate change (FAO, 2010) in dryland regions and elsewhere in the world:

- They sequester high volumes of carbon in their woody biomass and roots.
- Deforestation and forest degradation increase global carbon emissions (as CO₂).
- Forests offset the use of fossil fuels by providing carbon neutral products and wood as fuel.
- Forests can help other sectors, such as the agricultural and water resources sectors, to cope with climate change.

As forests represent a substantial climate change mitigation opportunity, the forest sector is a front line element in UNFCCC documents. It was, however, essential to agree on a common definition of forests before being able to take them and their key roles into account—there are in fact over 650 different forest definitions!

UNFCCC introduced area, height and canopy cover criteria in the forest definition, i.e. land spanning at least 0.05-1 ha with trees with a minimum height of 2-5 m and a canopy cover of 10-30% of the area at maturity (or with an equivalent stand density).

Each country then sets three forest definition parameters within this interval. However, the roles of forests and the

G. Michon © IRD



▲ Forest beekeeping in Ethiopia.

Dry acacia forest. Forest beekeeping serves as a climate change observatory: a 'honey tree' (acacia), Shashemene region.

services they provide are not taken into account in this definition, e.g. non-woody forest products (gum, resin, etc.) and fuelwood in dryland regions.

Wood resources are generally found outside of forests in dryland regions. These so-called 'trees outside forests' according to FAO (De Foresta *et al.*, 2013) are scattered over large areas (e.g. 10 million km² of farmland worldwide), but are not yet taken into full account despite the major role these resources play in dryland regions.

For further information: www.fao.org/docrep/017/aq071e/aq071e00.pdf

For further information...

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United Nations Framework Convention on Climate Change (UNFCCC)

www.unfccc.int

Convention on Biological Diversity (CBD)

www.cbd.int

United Nations Convention to Combat Desertification (UNCCD)

www.unccd.int

DesertNet International (DNI)

www.desertnet-international.org

Ex ante Carbon-balance Tool (EX-ACT)

www.fao.org/tc/exact/ex-act-home/en

Forest Trends (Forest Carbon Markets)

www.forest-trends.org/fcm2013.php

Global Carbon Project (GCP)

www.globalcarbonproject.org

Intergovernmental Panel on Climate Change (IPCC)

www.ipcc.ch

Institute for Sustainable Development and International Relations (IDDRI)

www.iddri.org

Land Degradation Assessment in Drylands (LADA)

www.fao.org/nr/lada

Mitigation of Climate Change in Agriculture (MICCA)

www.fao.org/climatechange/micca

RIME PAMPA Project—Sustainable rural development based on soil conservation practices

www.rime-pampa.net

Soil Carbon Network for Sustainable Agriculture in Africa

<http://reseau-carbone-sol-afrique.org/en>

SCOPE - Benefits of Soil Carbon

www.soilcarbon.org.uk

Task Force on National Greenhouse Gas Inventories

www.ipcc-nggip.iges.or.jp

World Overview of Conservation Approaches and Technologies (WOCAT)

www.wocat.net

Glossary

Actinorhizal plant. A nonlegume plant whose roots symbiotically interact with an actinobacterial species, leading to the formation of atmospheric nitrogen-fixing root nodules. Some common actinorhizal plants are: *Alnus*, *Eleagnus*, *Myrica*, *Shepherdia*, etc.

Agroecosystem. An ecosystem in which agricultural activities occur.

Aridisol. A dryland mineral soil that typically has a low organic matter and high salt concentration and is always dry.

Carbon sequestration. A process involving the capture and storage of atmospheric carbon in carbon sinks, e.g. in oceans, biomass and soil.

Carbon sink. A natural or artificial reservoir that captures and stores atmospheric carbon dioxide.

Ecological resilience. The extent to which a system can cope with disturbances without undergoing a shift from one state to another. Stability, an associated concept, is defined as the tendency of a system to return to a balanced state following a disturbance. (Soussana, 2013)

Ecosystem services. The benefits that human societies reap from ecosystems. Four ecosystem service categories were defined in the Millennium Ecosystem Assessment: provisioning (e.g. food), supporting (e.g. habitat), regulating (e.g. pollination) and cultural (e.g. education) services. (Soussana, 2013)

Entisol. A mineral soil without any diagnostic horizons.

Greenhouse gas. Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds (World Meteorological Organization, 2011).

Soil horizon. A soil layer that is roughly parallel to the soil surface and differs from the neighbouring layers to which it is generally linked via its morphological, physical, chemical or biological features (e.g. colour, number and type of organisms present, structure, texture, consistency, etc.).

Soil profile. A vertical section of soil from the surface through all the horizons to the parent rock.

Vulnerability. The extent to which a system is susceptible to, unable to withstand or cope with the negative effects of climate change, particularly climatic variations and extreme climatic conditions. Vulnerability depends on the nature, extent and rate of climatic variation to which a system is exposed, along with its sensitivity and adaptation capacity. (Soussana, 2013)

LIST OF ACRONYMS AND ABBREVIATIONS

AFES	<i>Association Française pour l'Étude du Sol</i> , France
ANR	Assisted natural regeneration
ATSS	<i>Association tunisienne de science du sol</i> , Tunisia
CBD	Convention on Biological Diversity
CBP	Carbon Benefits Project
CD	Combating desertification
CDM	Clean Development Mechanism
CESBIO	Center for the Study of the Biosphere from Space, France
CILSS	Permanent Inter-State Committee for Drought Control in the Sahel
CIRAD	Agricultural Research for Development, France
CNES	<i>Centre National d'Études Spatiales</i> , France
COP	Conference of the Parties
CSFD	French Scientific Committee on Desertification
DMC	Direct seeding mulch-based cropping system
ENVASSO	Environmental Assessment of Soil for Monitoring
EOM	Exogenous organic matter
EX-ACT	Ex-Ante Carbon-balance Tool
FAO	Food and Agriculture Organization of the United Nations
GBEP	Global Bioenergy Partnership
GGW	Great Green Wall
GHG	Greenhouse gas
IAMM	<i>Institut Agronomique Méditerranéen de Montpellier</i> , France

IPCC	Intergovernmental Panel on Climate Change
IRAM	<i>Institut de recherches et d'applications des méthodes de développement</i> , France
IRD	<i>Institut de recherche pour le développement</i> , France
IUSS	International Union of Soil Sciences
JI	Joint implementation
LH	Land husbandry
LIBS	Laser-induced breakdown spectroscopy
MEA	Multilateral environmental agreement
MEDDE	Ministry of Ecology, Sustainable Development and Energy, France
NGO	Non-governmental organization
NIRS	Near-infrared reflectance spectroscopy
PET	Potential evapotranspiration
RCW	Ramial chipped wood
SIC	Soil inorganic carbon
SOC	Soil organic carbon
SOM	Soil organic matter
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNCHE	United Nations Conference on the Human Environment
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change

Abstract

Soil organic carbon (SOC) has a key role in the overall behaviour of soils and agroecosystems. Increasing its content enhances soil quality and fertility, thus improving agricultural resilience and sustainability and, in turn, food security of societies. Soils also contain the largest pool of carbon interacting with the atmosphere. Agricultural and forestry systems that reduce atmospheric carbon concentrations by sequestering this carbon in biomass and in soil organic matter are carbon sinks. Combating desertification contributes to soil carbon sequestration, thus mitigating global warming, while contributing to sustainable agricultural management.

Soils have only recently become a global environmental issue, especially in the framework of three international environmental conventions. These conventions have interrelated issues, especially with respect to dryland regions—desertification, climate change and biodiversity loss. Few tangible policies have, however, been drawn up concerning carbon in dryland regions. The impact of agricultural, pastoral and forestry activities on the carbon cycle need especially to be taken into greater account.

In the current carbon market system, carbon volumes of agricultural and forestry sectors are low as compared to those of other sectors (industry, etc.). Moreover, these markets do not fully recognize all activities that are conducive to carbon sequestration in agricultural soils, particularly in drylands. Carbon markets have so far been focused on checking amounts of carbon sequestered, whereas it would be much easier, and verifiable, to directly promote recognized 'carbon sequestering' practices. Such a market could provide much more efficient operational leverage for modifying agricultural practices and setting up systems to protect soils in dryland regions.

Keywords: Soil, carbon, organic matter, international environmental conventions, combating desertification, carbon market

Résumé

Le carbone organique des sols (COS) joue un rôle fondamental dans le comportement des sols et des agroécosystèmes. Augmenter sa teneur améliore la qualité et la fertilité des sols contribuant à la résilience et à la durabilité de l'agriculture et, donc, à la sécurité alimentaire des sociétés. De plus, les sols représentent le plus grand réservoir de carbone en interaction avec l'atmosphère. Les systèmes agricoles et forestiers qui réduisent les concentrations en carbone atmosphérique en le piégeant dans les biomasses et dans la matière organique du sol, sont des puits de carbone. La lutte contre la désertification permet de séquestrer du carbone dans les sols et donc d'atténuer le changement climatique, en plus de contribuer à une gestion agronomique durable.

Depuis peu, les sols sont au cœur des débats internationaux, notamment dans le cadre des trois conventions internationales sur l'environnement. Elles ont des préoccupations liées entre elles, notamment dans les régions sèches : désertification, changement climatique et perte de biodiversité. Pourtant, des politiques concrètes concernant le carbone dans ces régions peinent à se mettre en place. Il manque notamment une meilleure prise en compte de l'impact des activités agricoles, pastorales et forestières sur le cycle du carbone.

Dans l'actuel système des marchés du carbone, les secteurs agricoles et forestiers restent faibles face aux autres secteurs (industrie, etc.). De plus, ces marchés ne reconnaissent pas pleinement les activités qui favorisent la séquestration de carbone dans les sols agricoles, notamment dans les zones sèches. Les marchés se sont jusqu'à présent focalisés sur la vérification de la quantité de carbone séquestrée, alors qu'il serait beaucoup plus simple et vérifiable de promouvoir directement des pratiques reconnues comme « séquestrantes ». Un tel marché pourrait constituer un levier opérationnel beaucoup plus efficace pour modifier les pratiques agricoles et mettre en place une protection des sols des régions sèches.

Mots clés : Sol, carbone, matière organique, conventions internationales sur l'environnement, lutte contre la désertification, marché carbone

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