Chapter 5

Land degradation and climate change

What challenges?

Chapter coordinator

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Abstract

This chapter sets out to present a short review of (i) the general context of land degradation under the framework of UNCCD – the international convention on desertification with a specific focus on Land Degradation Neutrality, and (ii) examples of the main processes responsible for soil degradation (e.g. surface crusting, runoff and water erosion, tillage erosion, wind erosion, and salinization), along with the principles of desertification control and land rehabilitation, in light of the socioeconomic context and ecological conditions and processes. It also focuses on two other key considerations for land restoration: the conservation/increase of soil carbon stocks (see Tunisian example), and the biological restoration of functioning soil through the management of mycorrhizal fungi.

Although there is plentiful scientific evidence for strategies to prevent land degradation and/or restore degraded land, new knowledge is needed to step up the fight against land degradation and allow Mediterranean ecosystems to deliver appropriate sustainable services. This chapter cites examples of these scientific gaps (e.g. sensitivity of soil organic matter to temperature increases, the dynamics of inorganic carbon and deep soil organic, and the most effective Plant-AM in ensuring the success of restoration programmes).

Résumé

L'objectif de ce chapitre est de présenter un bref aperçu i) du contexte général de dégradation des terres dans le cadre de la Convention des Nations unies sur la lutte contre la désertification avec un accent particulier sur la dégradation neutre des terres, et ii) quelques exemples des principaux processus responsables de la dégradation des sols (par exemple, l'encroûtement de surface, les eaux de ruissellement et de l'érosion de l'eau, l'érosion du travail du sol, l'érosion éolienne, salinisation), et les principes de lutte contre la désertification et la réhabilitation des terres, compte tenu des conditions et des processus écologiques, et le contexte socio-économique. De plus, ce chapitre met en lumière deux autres aspects pour la restauration des terres qui sont le maintien/l'augmentation des stocks de carbone du sol (voir l'exemple des stocks des sols en Tunisie) et la restauration biologique du fonctionnement des sols par la manipulation des champignons mycorhiziens.

Bien que les preuves scientifiques sont déjà disponibles pour aider les stratégies visant à prévenir la dégradation des terres et/ou à restaurer les terres dégradées, de nouvelles connaissances sont nécessaire pour intensifier les moyens de lutte contre la dégradation des terres et permettre aux écosystèmes méditerranéens de répondre aux enjeux de développant durable. Ce chapitre aborde quelques exemples de ces fronts de science (sensibilité des matières organiques des sols à l'augmentation de la température, dynamique du carbone inorganique, et du carbone stocké dans les horizons de profondeurs, choix des plantes et de leur hôte mycorhiziens adaptés aux conditions locales, valorisation des ressources végétales locales...).

Introduction: adaptation, resilience, conservation of resources and prevention

Under the framework of UNFCCC, the Paris agreement (December 2015), in place of the almost expired Kyoto Protocol, aims to limit the increase of the global temperature to below 2°C. Article 2.1 stresses the need "to strengthen the global response to the threat of climate change, in the context of sustainable development efforts to eradicate poverty", including actions aimed at "increasing the ability to adapt to adverse impacts of climate change and foster climate resilience and low greenhouse gas emission development, in a manner that does not threaten food production." The need to pursue mitigation and adaptation in tandem is therefore widely acknowledged.

Although humankind has always adapted to diverse weather and climate conditions using a wide range of practices (irrigation, water management, crop diversification, etc.), there is an urgent need to take action to consolidate and accelerate adaptation strategies, particularly in agriculture. This need is borne out by the following factors (Howden et al. 2007):

- A 0.1°C increase in world temperature during the past decade,
- More rapid than expected climate change because of increases in greenhouse gas (GHG)
- Lack of agreement for the reduction of GHG emissions.

Although adaptation has different meanings in ecology, climate policy and evolutionary biology (see Glossary IPPC, 2014), a broad definition would be "an adjustment to actual and expected climate conditions to reduce the risk and vulnerability of ecosystems and society and to seek opportunities to cope with climate change". Adaptation strategies must be formulated in response to well identified risks and vulnerabilities[1]. Two main categories of adaptation can be identified:

- Ecosystem-Based Adaptation (EBA) is the use of biodiversity and ecosystem services as part of an overall strategy to help people adapt to the adverse effects of climate change (SCBD, 2009),
- Community-Based Adaptation (CBD) refers to the participatory identification and implementation of community-based development activities that strengthen the capacity of local people to adapt to climate change (see in Archer et al. 2014).

Africa is the world's second most populous continent after Asia. Most African regions have faced an increase in extreme temperature (Seneviratne et al. 2012). Toward the end of the century, heat waves and extreme temperatures will increase whereas – except in East Africa – projected heavy precipitation will not increase. Observed and projected data lack sufficient scope.

Africa as a whole is the most vulnerable continent due to its high exposure and low adaptive capacity. Because of the lack of observations, the detection and attribution of observed climate change in Africa to anthropogenic emissions is not sufficiently clear-cut (Niang et al. 2014). This therefore reduces the effectiveness of any adaptive strategy, although action is urgently needed. Agriculture – the main economic domain in terms of employment – has witnessed stagnant yields relative to the population growth (FAO, 2002). Recent improvements (2000-2010) have not impacted significantly on the overall pattern, since they have been recorded from the lowest productive countries. Reliance on rainfed crop production (98% of the production relied on rainfed crops un SSA), high intra- and inter-seasonal climate variability, recurrent droughts or floods and persistent poverty limit the capacity to adapt. Africa's food production

1. « The propensity or predisposition to be adversely affected » (IPPC, 2014)

is therefore at risk. Simulations of main crop yields point to the consistently negative effect of climate change on major cereal crops in Africa. A study by Eid et al. (2007) stressed the high vulnerability of wheat production in North Africa. The temperature increases in West Africa are estimated to counteract the positive impact of rainfall increase (Sultan et al. 2013).

Climate uncertainties, lack of real-time and future climate projections, and complex interacting barriers at local, national and international levels need to be addressed to build long term and multi-scale adaptive plans for actions. The National Adaptation Plan for Action (NAPA) and the Comprehensive African Agriculture Development Program (CAADP) highlight the political will to enrich economic growth through agriculture. CAADP focuses on four pillars: land and water management, market access, food supply and hunger and agricultural research (NEPAD, 2010). For Africa, reduced crop productivity has been identified as one of nine key regional risks (Niang et al., 2014).

Research has demonstrated that no single adaptation can meet the needs of all communities in Africa. Moreover, adaptation and mitigation must be integrated in policy. For agriculture, sustainable land management techniques are particularly vital for Africa. This chapter explores the situation with a particular focus on soil functioning. It sets out to present a short review of (i) the general context of land degradation under the framework of UNCCD – the international convention on desertification with a specific focus on Land Degradation Neutrality, and (ii) examples of the main processes responsible for soil degradation (e.g. surface crusting, runoff and water erosion, tillage erosion, wind erosion, and salinization), along with the principles of desertification control and land rehabilitation, in light of the socioeconomic context and ecological conditions and processes. It also focuses on two other key considerations for land restoration: the conservation/increase of soil carbon stocks (see Tunisian example), and the biological restoration of functioning soil through the management of mycorrhizal fungi.

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Sub-chapter 3.5.1

Land degradation neutrality

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Land degradation, desertification and land degradation neutrality: definitions

Land degradation is a threat to sustainable development. The term refers to both:

- The decline in biological and/or economic resilience of land when exposed to stress and/or perturbations and
- The loss of the land's adaptive capacity to support basic ecosystem functions (primary productivity, nutrient recycling) after a stress or a perturbation.

The effects of land degradation extend far beyond local or regional scales, because of: a) the connections within the ecosystem – e.g. loss of biomass through vegetation clearance and soil erosion, produces greenhouse gases that contribute to global warming and climate change; and b) the connection between the ecosystem and the sociosystem, e.g. loss of soil and land (in quality, quantity, accessibility), through soil erosion and/or lack of soil restoration, rehabilitation or reallocation, results in land abandonment that contributes to urban migration and/or international migration.

Land degradation is caused by multiple drivers. The various processes involved (alone or in combination) include those generated by human activities (i.e. water and wind erosion, overcultivation, overgrazing, inappropriate uses of natural resources (uprooting of woody areas and excessive clearing). During the 20th century, land degradation has accelerated as a result of the increasing and combined pressures of agricultural and livestock production, urbanization, deforestation, land grabbing, and extreme weather events such as droughts. Land degradation results in each place from an original combination of biophysical, social, economic and political factors.

Although land degradation can occur in any climatic zone, land degradation in arid, semi-arid and dry sub-humid areas[1] is referred to as "desertification". These drylands represent about 41% of the total surface of worldwide terrestrial ecosystems. It is estimated that 10% to 20% of drylands are affected by land degradation (MA, 2005), with severe and extensive desertification in Africa and in Asia. The 2 million or so people who inhabit the drylands suffer from the lowest human well-being and the highest poverty (Thomas, 2008). Nevertheless, drylands provide a wide range of commodities. For example, cotton provides about 30% of annual incomes from export for Burkina Faso, and for Mali (Reed and Stringer, 2016). However, land productivity relies on natural resources there more than in any other region in the world. In these zones, productivity, largely dependent on precipitation, is strongly affected by climate change. It is thought that up to 50% of the Earth's surface will face frequent droughts by the end of 21st century under a "business as usual" scenario. Drylands in northern Africa and southern Europe are likely to become dryer. A potential increase of 1-3°C in drylands (if CO_2 concentrations reach 700 ppm) would result in an increase in the evapotranspiration by 75-225 mm per year (Burke et al. 2006; D'Odorico et al. 2013)

The following statement: "[there is a] need for urgent action to reverse land degradation. In view of this we will strive to achieve a land degradation neutral world…." (paragraph 206 of "The future We want", Rio+20, 2012) sets the goal for maintaining a world where the total amount of degraded land remains constant. In 2015, UNCCD defines "Land Degradation Neutrality" (in areas affected by desertification) as a "state whereby the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security remain stable or increase within specified temporal and spatial scales and ecosystems". This could be achieved by a) sustainable management of land to reduce the rate of degradation; or b) increasing the rate of restoration of degraded land, so that these two trends converge to a zero net rate of land degradation. Very recent publications (see Chasek et al. 2015; Grainger, 2015) have examined the bottlenecks and assessed the feasibility of the operationalization of LDN.

1. Ratio of annual precipitation to potential evapotranspiration within the range of 0.05 – 0.65.

Box 1
Policy context

The Agenda 21 at the Earth Summit in 1992 at Rio de Janeiro was an opportunity to address the various domains for sustainable development:

• The Convention on Biological Diversity (CBD) targets "the conservation of biological diversity the sustainable use of its components and the fair and equitable sharing of the benefit arising out of the utilization of genetic resources" (for more detail, see https://www.cbd.int/doc/legal/cbd-en.pdf)

• The Convention on Climate Change (UNFCCC) targets the "stabilization of greenhouse concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system…" (for more detail, see http://unfccc.int/files/essential_background/convention/background/application/pdf/convention_text_with_annexes_english_for_posting.pdf)

• The Convention to Combat Desertification (UNCCD) aims "to combat desertification and mitigate the effects of drought in countries experiencing serious drought and/or desertification, particularly in Africa, through effective action at all levels, supported by international cooperation and partnership arrangements, in the framework of an integrated approach which is consistent with Agenda 21" (for more detail, see http://www.unccd.int/en/about-the-convention)

There are obvious links between these 3 Rio Conventions. For example a special report on "Climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems will be drafted for the 6th IPCC assessment report, and in 2015 IPBES launched an assessment of land degradation and restoration (global status and trends in land degradation and state of current knowledge). At the crossroads of these 3 Conventions, soils and organic carbon stocks play a key role in strengthening a triple gain in mitigation, adaptation and food security solutions. The recent adoption of the 17 Sustainable Development Goals (September 2015, https://sustainabledevelopment.un.org) by the United Nations reinforces the "nexus" Food security (SDG 2), Land Degradation (SDG 15) and Climate Change (SDG13).

Box 2
The French Scientific Committee on Desertification (CSFD)
http://www.csf-desertification.eu/

Launched in 1997 by the French Ministry of Foreign Affairs, the Ministry of Ecology and Sustainable Development, and the Ministry for Higher Education and Research, CSFD is an independent multidisciplinary committee (20 members from the main French scientific research institutions) providing policymakers and civil society stakeholders in France and affected countries with updated science-based evidence of causes and impacts of desertification (http://www.csf-desertification.eu/dossier contains examples on "Carbon in dryland soils", and "Ecological engineering for sustainable agriculture in arid and semi-arid West African regions"). CSFD is actively involved in several networks, e.g. "DesertNet International"

Box 3

Operationalization of land degradation neutrality (LDN)

An estimated US$40 billion annually is attributed to land degradation worldwide. Additional costs resulting from, for example, increased fertilizer use and loss of biodiversity must be taken into account. Degraded land is costly to reclaim and, if severely affected, may no longer provide a range of ecosystem functions and services, with a loss of goods and many other potential environmental, social, economic and non-material benefits that are critical for society and development.

Strategies to implement the LDN scheme are organized in five steps (Chasek et al. 2015):

• Step 1: **Scoping scale and domain**: although the ambition of LDN is to address global issues, since local land degradation directly affects land inhabitants, any plan for LDN actions needs to determine the spatial scale and the thematic domain targeted,

• Step 2: **Mapping degradation**: Monitoring the implementation of LDN (Step 5) necessitates the definition of baselines. This means classifying and mapping the lands in the areas where LDN is to be achieved, i.e. the identification of lands already degraded and lands under degradation, but also lands not degrading – the difficulty being to differentiate these states along a continuum.

• Step 3: **Prescribing relevant practices**: Good practices in sustainable land management (SLM), when implemented in a given context, lead to improved land management performance. Several criteria determine whether a practice is a good or relevant one. Several regional or international initiatives focus on guidelines and best practices, but more should be done particularly in terms of:

- Stakeholder knowledge brokering systems to share best practices.
- Economic valuations of the best practices.

Practices which do not degrade the land, or which reduce or fight against degradation are relevant if they are targeted and appropriate to the context and to the state of the land degradation, accepted and fair according to the points of view of all stakeholders. That means:

– They should take into account the specificities of the place and its connexion with its immediate (local) and global environment.

– They should be appropriate to the type and severity of the damage, taking into account the the intrinsic characteristics of the place, the climate and human activities, the temporal dynamics and the spatial diversity of the degradation, the multifunctionality of landscapes and the diversity of stakeholders.

– They should be built with several stakeholders and based on experienced practices (e.g. zaï, cordon pierreux).

– They should promote a judicious combination of practices (e. agroforestry, agroecology, integration of agriculture and livestock practices), and their integration in existing exploitation and territorial systems.

– They should be applied without taking the risk of affecting other areas or systems near or far , and within a legal framework.

• Step 4: **Monitoring**: Earth Observation, Official Statistics, with supported by survey sampling/grounds measurements and citizen sourcing will be used to monitor, detect and validate the changes in the sub indicators. Several international and regional organisations

(FAO, OSS, JRC, NASA, ESA) have developed a methodology (land cover classification system) and databases that could be used. One of the key ways to ensure effective LDN monitoring is to set up baselines on land cover information, land productivity and for carbon stocks to determine the initial status of the sub-indicators. The challenge is therefore to use appropriate indicators. In line with SDG target 15.3 and to monitor progress, the indicator: "the percentage of land that is degraded over total land area", is being considered by international organizations (UNCCD, FAO, CBD) and would be based on the use of three metrics:

- Land cover and land cover change
- Land productivity
- Carbon above (plant biomass) and below (soils) stocks

The resulting indicators will allow countries to focus on the relevance and effectiveness of current land and planning policies and agricultural practices.

This monitoring approach should be accompanied by local and participatory initiatives including a broad range of stakeholders. Countries will also need adequate capacity building in data interpretation and validation and their use to inform national authorities and international reporting.

Box 4
LDN Fund

In order to achieve Land Degradation Neutrality (LDN) by 2030, an independent fund – the LDN Fund project – was announced during UNFCCC COP 21 in Paris. The LDN Fund intends to raise capital from public and private institutions and to directly or indirectly finance initiatives that promote land rehabilitation and sustainable land management in all countries. The Fund will adopt a collaborative approach, complementing and leveraging existing initiatives. It is expected to partner with other fund managers and financial institutions, including local banks and microcredit agencies to increase scale and impact. Some concerns regarding the Fund's orientation (restoration vs degradation, land status) and structuration (funding platform model, civil society involvement) have been expressed by various partners. Discussions are still on-going during the first semester of 2016 and it is expected that the fund will become operational by the end of 2016

Box 5
LDN Action Plan

Following its initiative "Towards achieving Land Degradation Neutrality: turning the concept into practice" with 15 countries, UNCCD secretariat has launched a LDN Target Setting Programme (LDN TSP), designed to help countries familiarize themselves with the methodological and operational LDN approaches and to support countries (technical guidance and expertise, capacity building) in defining baselines related to the LDN indicator and set LDN targets. More than 80 countries are already involved in this programme. Analysis of LCD National Action Plan of should be also undertaken to identify the key points (legal, scientific, governance) where synergies with LDN could be implemented.

Box 6
Soil carbon stocks:
the Food Security (SGD 2) – Climate Change (SDG 13) – Land degradation and desertification (SDG 13) nexus

At the COP 21 in December 2015 in Paris, Stéphane Le Foll, the French Minister of Agriculture, launched an international initiative called "4 per 1,000, soils for food security and climate change" (see https://youtu.be/JMWpPfhJVzc). This expresses at the global scale the ratio of annual CO_2 increase in the atmosphere (4.3 billion tonnes of C on average over the period 2004-2013) and soil carbon stock up to 30 cm deep (about 800-1,000 billion tons of C). It illustrates the fact that land management practices are key to global GES mitigation (SDG 13). Above and beyond the benefit that storage can represent in the fight against the accumulation of greenhouse gases, soil organic carbon is one of the main indicators of the quality and fertility and hence productivity, which is essential for food security (SDG 2). In family agriculture in LDCs, the management of organic materials (crop residues, crop-livestock integration, recycling organic urban waste, etc.) is at the center of farmer practices to maintain or improve yields and fight against land degradation (SDG 15), particularly soil erosion. Their management also helps overcome the scarcity of mineral fertilizers, which are only partially available and certainly less accessible to farmers.

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Soils and desertification in the Mediterranean region

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Introduction

The Mediterranean region – and more specifically North Africa – have been subject to climate change throughout the period 1860-2005 (Mariotti et al. 2015). Simulations predict an average rise in annual temperatures of more than 2°C with more intense heat waves. Precipitation is projected to decrease compared to 1980–2005 especially in Spain, Morocco, Tunisia and parts of the Middle East region. This is expected to modify soil temperature and soil water content, and consequently pedoclimate. Desertification processes can increase not only due to climate change and population growth but also as a result of ever more pronounced edaphic aridification processes (Floret and Pontanier, 1984).

In the Mediterranean zone, soils are usually much shallower than in the humid tropics and the temperate zone where pedogenesis is faster and erosion less ancient. In some part of the Mediterranean region, accelerated erosion was initiated several thousands of years ago (Butzer, 2005). Shallow soils with low nutrients and water storage capacity are a major constraint to natural vegetation and crop cover, which in turn affords a weak protection to soils from water and wind erosion.

The objective of this paper is to present a short review of (i) the main soil degradation (i.e. desertification) processes in the Mediterranean zone including water, wind and tillage erosion, and salinization; (ii) some soil management principles to combat land degradation and favour soil rehabilitation.

Main processes and factors of desertification: surface crusting, runoff and water erosion

Due to water scarcity, which limits biomass production, the soil organic matter of arid and semi-arid zones remains low, especially in sandy soils. As a result, exposed layers have low structural stability and physical crusts develop rapidly even under low quantity of rainfall (Valentin and Bresson, 1992). These crusts reduce infiltration and favour runoff (Podwojewski et al. 2011) even when these physical crusts are colonized by cyanobacteriae (Malam Issa et al. 2011). They also tend to promote sheet erosion and gully erosion downhill (Valentin et al. 2005). These crusts can be destroyed by trampling and tillage (Bertrand et al. 2014) but form again rapidly under rainfall.

Tillage erosion

Tillage erosion is the downslope displacement of soil through tillage. It mainly affects steep and convex slopes (Kosmas et al. 2001) and is often expressed by lighter-coloured soils than adjacent downhill soils (Photo 1). Due to the often steep cultivated slopes in the Mediterranean region, soil loss rates due to tillage erosion cannot be neglected (Benmansour et al. 2013) especially where tillage started a few thousand years ago (Butzer, 2005). Tillage erosion is therefore one of the major contributors to the variation of soil depth and properties in Mediterranean agricultural landscapes.

Photo 1
Tillage erosion evidenced by light coloured truncated soils, Mateur, northern Tunisia. Tillage erosion is a cumulative process and can have been initiated over on thousand years ago in this region.
C. Valentin.

Wind erosion

Wind erosion is a threat in the arid areas of the Mediterranean region where the wind is often strong and the vegetation sparse. The type of soil also plays a major role since the most sandy soils are also the most prone to wind erosion (Khatteli 1996) whilst, due to low runoff volume and velocity, sheet and gully erosion remain limited. No coarse fragments increase the surface roughness of sandy soils, and the physical crust that develops when it rains does not significantly decrease wind erosion (Rajot et al. 2003), unlike crusts developed on more loamy soils (Belnap and Gillette, 1998). On the other hand, these sandy soils are the most efficient in stocking available water for plant growth (Floret and Pontanier 1984) so that, in undisturbed conditions, the vegetation cover that develops creates effective protection against wind erosion. Wind erosion increases when vegetation cover is decreased. As an example, soil losses reach very high levels when vegetation is removed a part of the year for cereal cropping (Houyou et al. 2014, Abdourhamane Touré et al. 2015). In olive groves, soil is kept bare by regular tillage to stop the vertical connectivity of pores and limit the capillary rise of residual soil moisture of the deeper horizons. Tillage severely depletes soil organic matter content. This favours the formation of microdunes high enough to render ploughing difficult (Photo 2). For the same type of soil, the type of plough used has also a significant effect on soil losses (see Bergametti et al. in this volume). Human activities currently create unsustainable levels of wind erosion on sandy steppe rangelands, which should incite policy makers not to allow their cultivation.

Photo 2
Olive grove on sandy soil, just after rainfall, region of Medenine, South of Tunisia, the dunes, up to 2m height, appeared after ploughing of the sandy soil.
G. Hovhannissian.

Salinization

Salinization develops in time and space due to the gradual accumulation of soluble salts – whatever their nature – in or near the soil surface (saline crusts or efflorescences). Some salts, especially sodium salts, favour clay dispersion, degrade soil structure and hamper water infiltration. The processes of soil salinization and sodication are complex, occurring at all latitudes and in all climates, and are closely linked to the flow processes of surface and ground waters (Ghassemi et al. 1995; Montoroi et al. 2002; Hamdi-Aissa et al. 2004; Ali et al. 2016). Many natural factors generate soluble salts and their concentration (weathering and dissolution of rock and soil minerals, geothermal sources, decomposition of dead organisms, drying wind), transport (rain, rivers, groundwater, sea water, wind) and accumulation in soils (arid climate, temporary droughts), near the sea in coastal and delta areas, near a shallow saltwater table, aeolian deposits (sea spray, aerosols), endoreic zones (sebkhas, chotts). A so-called «secondary» salinization is induced by anthropogenic causes: mismanaged irrigation, old irrigation techniques, irrigation with waters rich in salts, deforestation, fertilizers containing potassium and nitrogen salts, atmospheric deposition near industrial sites. Above a given threshold of soil salinity, plant growth, crop production, water and soil quality are severely affected up leading to accelerated soil erosion and land degradation or ecosystem desertification (Gorji et al. 2015).

The soils of Mediterranean countries are particularly affected by salinization (Photo 3) because of the semi-arid to arid climate and the development of intensive irrigation for agriculture by building many storage and irrigation schemes (dams, hillside dams, canals and water distribution pipes). The consequences of climate change (increased rainfall variability and water scarcity, freshwater evaporation increase and higher plant evapotranspiration rates) will result in a concentration of soluble salts in the water bodies and the extension of soil salinization. The predicted sea level rise by the Intergovernmental Panel on Climate Change (IPCC) scenarios will impact coastal areas and wetlands (deltas of major rivers like the Danube, the Ebro, the Mejerdah, the Nile, the Po and the Rhone) and promote the saline contamination of coastal aquifers due to sea water intrusion. The overexploitation of upper fragile fresh water lenses overlaying denser brackish aquifers will intensify with the increased needs for agricultural, industrial, touristic and domestic activities which are mainly located along the coast (Kuper et al. 2009; Ashour and Al-Najar, 2012; Mansour and Hachicha, 2014).

Photo 3
Irrigated pomegranate crop in the clayey and saline soils of the Kairouan alluvial plain (Central Tunisia). The drip system is placed on the ridges for optimal water supply and salt leaching. The white spots (salt efflorescence) correspond to the highest soil salinity, where the trees are dead. The inter-ridges are ploughed to promote rainwater infiltration into the soil and prevent the invasion of weeds.
J.-P. Montoroi.

Main principles of desertification control and land rehabilitation: underlying ecological conditions and processes

A cover must be kept at soil surface to prevent crusting, water and wind erosion. To reduce the risks of tillage erosion, tillage operations and tillage depth should be limited. No-till agriculture associated with permanent cover is only possible where rainfall regimes allow sufficient biomass production. No-till farming can be very effective in reducing water erosion and runoff production at the plot scale. Attention must be paid on the plot length to reduce the risk of gully erosion.

In dry Mediterranean zones (annual rainfall < 300 mm) where vegetation cover cannot be continuous in space and time, the ubiquitous crusts should not be considered as a symptom of desertification because they are essential elements of arid and semi-arid zones. They favour natural water-harvesting through runoff-runon processes (Valentin and d'Herbès, 1999; Assouline et al. 2015). A wide range of water harvesting techniques has been developed for centuries in dry Mediterranean zone to enable crop and fodder production. Many of them, for example Jessour (photo 4) in southern Tunisia or micro-catchments in Israel (Zhang et al. 2013) are still in use and should be encouraged.

Photo 4
Jessour of the Dahars Range, Béni Khedache Road. Mean annual rainfall of 215 mm (period 1949-2001; Kallel, 2001), Average maximal temperature: 35.9°C (August period 1990-1996, Ouessar et al. 2006).
C. Bouet.

Considering the socioeconomic context

The abovementioned biophysical processes interact with many human decisions and constraints, including land users and policy makers. Both levels are crucial to lead to a successful control of desertification processes and soil rehabilitation. The top-down approach of terraces, check dams, deep drilling and reforestation has usually led to failures because the lack of involvement and interest of the land users. More success is expected through participatory and incentive approaches (De Graaf et al. 2013).

Conclusions

Climate change associated with land use changes in the Mediterranean region are expected to induce a major latitudinal shift of the pedoclimatic zones, resulting not only from the changes in climatic averages, but also from the higher frequency of extreme events (rain and wind storms, drought, long dry spells, heat waves...), and higher seasonal and inter-annual variability. These changes should render the already shallow soils even more vulnerable to various degradation processes (tillage, water and wind erosion, salinization) favouring a desertification spiral. To hamper these alarming changes, adaptation and innovative policies should be based on a sound knowledge of the interacting processes and consider the successful practices of soil and water conservation developed in more arid regions, especially those which have been readily adopted by land-users.

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Soil carbon as an indicator of Mediterranean soil quality

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Two forms of carbon in Mediterranean soils

Soils are considered as one of the largest C pools on Earth, after the oceanic and geologic reservoirs. The soil C pool comprises two distinct components: soil organic carbon (SOC) and soil inorganic carbon (SIC), which roughly contribute 2/3 and 1/3, respectively (Batjes, 1996).

Soil organic carbon (SOC) represents about 50% of soil organic matter, by consequence "soil organic matter" and "soil organic carbon" are often confused and used interchangeably. Soil organic matter corresponds to all organic materials in soil, i.e. any material produced originally by living organisms (plant, animal, microorganisms) at various stages of decomposition. Soil organic matter is a

Table 1
Estimated dryland carbon stocks

	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		

Source: Millennium Ecosystem Assessment, 2005 (dryland chapter)

continuum of simple and complex molecules. It constitutes a dynamic soil carbon pool, regularly fed by organic residues and in interaction with the mineral particles of the soil. Soil organic matter influences soil functions and properties. It has a key/role in the overall behaviour of soils and agroecosystems, as it provides energy for soil microorganisms, nutrient storage and supply (nitrogen, phosphorus and potassium) for plant production, improves soil structure and is thus involved in the ability of soil to hold water and resist erosion. Maintaining organic carbon in soil is equivalent to maintaining the soil organic matter and a part of the soil fertility. By consequence soil organic carbon content is often considered to be the prime soil quality indicator, with respect to its agricultural and environmental functions.

Soil inorganic carbon (SIC) represents different C forms involved in a solid-solution-gas phase equilibrium, as carbonate minerals (mainly $CaCO_3$), as aqueous carbonic dioxide, bicarbonate HCO_3^- and carbonate CO_3^{2-} ions in soil solution, and as a gas carbonic dioxide CO_2. In humid regions, SIC tends to get dissolved and fluxes into the groundwater or precipitates deep in the soil or geologic system, whereas in dry regions it precipitates at relatively shallow depths as a result of sparse rainfall and insufficient leaching (Gocke et al. 2011). Because of this, about 90% of the global SIC pool is found in arid and semiarid regions (Eswaran et al. 2000), such as the Mediterranean region. Despite agreement about its large size as a carbon pool (950 Gt), little attention has been paid to the dynamic of the SIC pool, which is considered to be very slow and less influenced by anthropogenic disturbance than the SOC pool. However, there is increasing evidence that the solid-solution-gas phase equilibrium in the SIC system may be shifted in one way or another (to CO_2 emissions or $CaCO_3$ precipitation) by external factors such as management practices, e.g. cropping and irrigation, and human-led environmental changes.

The dynamics of the SIC pool could be impacted by land management. Indeed, irrigation to enhance crop production in the Mediterranean region is often practiced with groundwater 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 and could modify the equilibrium between the different forms of inorganic carbon in soil. The addition of plant residues enhances biological activities (root and microorganism respiration) resulting in an increase in CO_2 partial pressure, which may either lead to an enhanced trapping of CO_2 through carbonate precipitation, or to a decrease in soil pH resulting in the dissolution of carbonates. There are very few studies that try to understand and explain the contradiction between the results of the impact of soil management on SIC dynamics (Monger et al. 2015). More research is needed on that specific issue.

How soil organic carbon benefits soil fertility and the environment

In semi-arid regions, improving water management while avoiding loss of soil organic matter, and thus maintaining the soil organic carbon pool, is essential to preserve soil against degradation and ensure food security for societies. Combating soil desertification requires effective organic matter and water management in order to maintain a sufficient level of fertility for sustainable production. Thus, the techniques for water and soil conservation management are also recognized as effective soil organic carbon management techniques. Water conservation and fertile sediment retention enhances soil fertility and facilitates the growth of natural or replanted vegetation around the structures as half-moon or stone bunds.

Soil carbon is linked to soil organic matter, as 50% of soil organic matter is soil organic carbon. Soil organic matter ensures a part of soil fertility as it allows for storage of nutriments for plant growth, stimulates soil biodiversity and contributes to soil structure stability. Maintaining the soil organic matter pool is essential in sustainable land management and soil productivity (fig 1).

Besides soil fertility, soil organic matter is also seen as the biggest C reservoir of terrestrial ecosystems after carbon fossil stock (see fig 2). Storing C in soil is seen as a means to mitigate atmospheric CO_2 concentration and Green House Gas emissions (GHG emissions, fig. 1). Thus C balance from soil to the atmosphere is a local issue for soil conservation, agricultural production and food security and at the same time a global issue to limit climatic change. Soil carbon is recognized as an indicator of soil quality in terms of its agricultural and environmental functions.

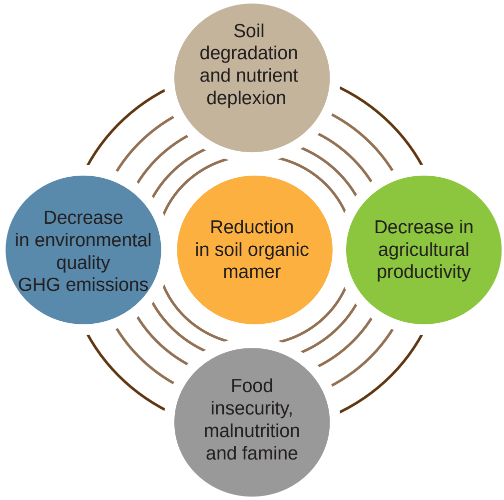

Figure 1
The vicious circle between the decrease in soil organic pools, land degradation and food insecurity (from Lal, 2004 : Soil carbon sequestration impacts on global climate change and food security. Nature 304(5677): 1623-1627).

Measuring or evaluating SOC after changes in management practices

Most Mediterranean soils exhibit low (≤2%) or very low (≤1%) SOC content especially in the southern side of the Mediterranean sea, with a mean SOC content of about 1.1% in the top 0-30 cm for the North Africa region and national means of SOC ranging from 0.67 to 0.79% for Morocco, Tunisia, Algeria and Egypt (Henry et al. 2009). Limited SOC content in the Mediterranean soils is mainly the result of a limited net primary productivity. These low C inputs driven by limited soil moisture availability could be exacerbated by crop residue competition for livestock feeding or the introduction of long fallowing in the crop rotation. Besides low C inputs to the soil, some agricultural management, such as intensive deep-tillage (e.g. moldboard ploughing) may also boost SOC losses. Deep-tillage enhances microbial activity by homogenization of soil moisture and oxygenation and incorporation of crop residues into deep soil, and thus speeds up soil organic matter mineralization and loss. Farming practices that enhance carbon storage are needed for sustainable land management, soil productivity and protection of the environment.

Many soil and management techniques have long been known to maintain or enhance the soil organic matter content: use of compost, manure, cropping residues to “feed” the soil: soil cover techniques, grassed strip, trees, or any

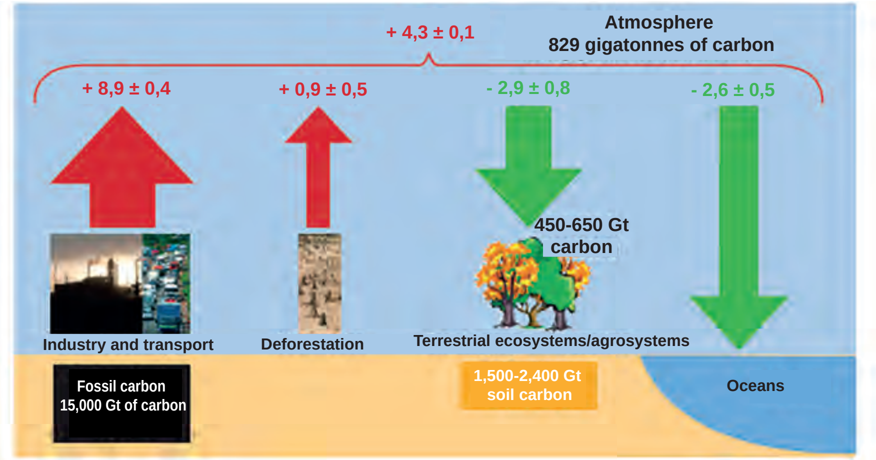

Figure 2
Human activity CO_2 emissions against C stocks, expressed in Gt C or in billions of tonnes of C, and fluxes, expressed in Gt C yr^{-1}, between ecosystems and atmosphere (mean values for 2004-2013, Le Quéré et al. 2014, Earth Syst. Sci. Data Discuss., 6, 1–90, 2014).

land management that preserves soil from erosion, improves water infiltration and enhances soil fertility. To evaluate the efficiency of these techniques to restore, maintain or enhance the soil organic carbon stock, scientists and stakeholders need to quantify soil carbon stocks.

Countries should regularly provide national inventories of greenhouse gas emissions and potential sinks of C for the agriculture and forestry sectors. This comprises national estimates of soil organic carbon (C) stocks (Box 1). These inventories require quantifying the soil carbon stocks on large territories where variability can be large. The development of new measurement techniques for C stock monitoring, that are faster and cheaper than classical techniques are needed (e.g. infrared-spectrometry). Models are also being developed to predict the impact of agriculture and forestry changes on C balances at large scale (region to country) (Box 2).

Carbon stock within the soil profile: the importance of deep carbon

Most of soil carbon surveys focused on the first 30 centimeters of soil (0-30 cm). However, if measured only on the topsoil (0-30 cm), SOC stocks are not representative of the real stock of C stored in the soil, especially in the deep soils of the alluvial cultivated plains. The total carbon stock could be underestimated from 30 to 65 % in Tunisia (Box 1) or on a toposequence in North Algeria (Bounouara et al. 2016) or up to 80% in Cardinael et al. 2015 (Box 3).

Box 1
A specific study "national soil carbon stocks, a case study in Tunisia"

Assessment of carbon contents and carbon stocks in Mediterranean soils is often difficult. 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, sampling representative samples could be hard. The second difficulty concerns the analysis. Most soil carbon measuring methods estimate the total soil carbon content (organic and inorganic carbon). The soil sample must be decarbonated when the analysis is focused only on organic carbon. This decarbonation procedure is difficult and expensive.

In addition, estimation of soil C stocks requires soil bulk density values to convert C content (g C kg^{-1} soil) to a mass of C per unit area (tC ha^{-1}). However, because it is labour-intensive, costly and tedious especially in rocky soil with a high coarse-element content, direct measurement of bulk density is often lacking for soils in arid and semi-arid conditions. Using a pedotransfert equation is an easy option to predict soil bulk density using data from soil surveys, e.g. soil texture or data easier to measure in the field. These predictive functions are specific to regional conditions and need to be built especially for the Mediterranean context (Brahim et al. 2012).

Estimation of national SOC stocks could be conducted after predictive functions using different databases, e.g. soil maps or soil types. Globally the different estimations of SOC stocks for large areas gave similar results and identified the same regions with high SOC stocks. However, the local SOC variability was not precise enough and depends on the predictive function use (Brahim et al. 11). Brahim et al. (2011) organized a soil database with 238 soil profiles corresponding to 707 soil horizons. The mean and median SOC contents of top-soil were 1.17% and 0.86% respectively. The spatial variation of SOC contents are mainly explained by the climatic zones and the soil texture. The global SOC stocks in Tunisian soils are about 0.42-0.46 PgC (0-30 cm) and 1.03-1.13 PgC (0-1m) (Brahim et al. 2011).

Box 2
EX-Ante Carbon blance Tool (EX-ACT)

Ex-Act is a tool developed by FAO in collaboration with IRD to perform ex-ante estimates of the impact of agriculture and forestry development projects on GHG emissions and carbon sequestration in soil and biomass. This tool is especially useful to evaluate the carbon impact of agricultural policies such as land use change incitation (i.e. deforestation, forestation, forest degradation, annual/perennial crops, irrigated rice, grasslands, livestock, inputs, energy, or other investments such as road or warehouse construction). Estimation of C balance is based on IPCC default values (Tier 1), region specific coefficients (Tier 2) are therefore needed to get more accurate C balance results.

Box 3
A specific study "Agroforestry in South of France"

Agroforestry is a land use type where trees are associated with crops or pastures within the same field. In Southern France, a sub-humid Mediterranean region, a study evaluated the potential of organic carbon storage in soil and biomass under an 18 year-old agroforestry system with hybrid walnut trees at 110 trees ha^{-1} + durum wheat. The accumulation rates were 0.35 t C ha^{-1} yr^{-1} in the first meter of soil, and 0.75 tC ha^{-1} yr^{-1} in the above-ground tree biomass. The stored soil organic carbon was mostly coarse organic plant residues (particulate organic matter) which may be rather labile SOC fractions. This study demonstrated the potential of alley cropping systems to store SOC under Mediterranean conditions, but suggested that the additional SOC is vulnerable to any future land use change (Cardinael et al. 2015).

Different types of land uses or soil managements affect the stocks, dynamics and forms of SOC in topsoils but their effect on deep C is still unclear. Because SOC is considered to be less dynamic in subsoils than in topsoils, SOC in subsoils were not studied a lot. However, the SOC in deep soil can contribute to SOC stocks and also be a potential source of CO_2. Indeed, some studies in Mediterranean regions showed that SOM could have high C and N mineralization rates even in subsoil. This surprising result was attributed to specific pedoclimatic constraints under Mediterranean soils (Rovira and Vallejo, 1997, 2002). Therefore, SOM characterization and dynamics in deep soil horizons under the Mediterranean pedoclimate was still unclear because of few available data. Its distribution in the landscape and its forms must be characterized in order to understand its dynamics.

The vulnerability of soil carbon

Terrestrial ecosystems play a major role in regulating atmospheric CO_2 concentrations, as the net balance of photosynthesis and respiration corresponds to a current terrestrial sink of about 2.6 Gt C yr^{-1}. Soil respiration, including autotrophic respiration by roots and heterotrophic respiration by microorganisms, has been estimated to be approximately 100 GtC yr^{-1} (IPCC, 2007) with the half being produced by heterotrophic respiration. Thus it is essential to estimate and predict the impact of soil management and climate change on the microbial activities involved in SOC decomposition to predict the vulnerability or sensitivity of SOC stocks to climate change, *i.e.* increasing temperature, dry-wet cycles, and extreme events. Particular attention is currently paid to the effect of climate changes on Mediterranean region, where increased temperature, decreased and more concentrated rainfall, and an increased frequency of extreme events are forecast.

Understanding soil carbon dynamics is especially critical in semi-arid regions, such as North-West Tunisia, where SOC stocks are low and agricultural productivity is already limited by climatic conditions. A study for North West Tunisian soils indicated a moderate and positive response of soil respiration to temperature; Q_{10} of soil respiration was evaluated to 1.7 (Hamdi et al. 2011). Q_{10} is the proportional change in respiration with a 10 °C increase in temperature. This value of Q_{10} was in the current Q_{10} range values given in the literature, 2.6±1.2 (Hamdi et al. 2013). It seems that these Mediterranean soils have no specific behavior when temperature increases. However, maintaining soil at high temperature up to 40°C for one month, which could be possible in Tunisian semi-arid topsoils, decreases microbial biomass and substrate availability and consequently affects the temperature sensitivity of soil respiration.

In addition, it is not yet clear how and under what conditions the large inorganic carbon pool of Mediterranean soils may be affected by changing climatic conditions. Studies of the positive or negative effects of irrigation or rain events on the contribution of carbonates to the CO_2 emissions from dryland soils are conflicting (Emmerich, 2003; Serrano-Ortiz et al. 2010). In addition, no study has considered the impact of soil temperature on CO_2 emission from calcareous soils in drylands soil, where heat waves are expected to become more frequent and extreme within the 21st Century (IPCC, 2007). A better understanding of SIC dynamics and their role in ongoing global change is particularly critical for arid and semiarid areas, where SIC is the most important C form. In addition, certain methodological issues persist which add uncertainty to the investigation of CO_2 fluxes from calcareous soils to the atmosphere (Chevallier et al. 2016).

Conclusion

As the soil carbon content varies on multiannual scales, other indicators which are more sensitive to the soil organic status can be used for earlier detection of change trends. These indicators involve enzymes, microbial biomass or soil organism biodiversity. They are more sensitive to soil functioning changes but also more complicated to obtain and to use. Soil organic carbon content is thus recognized as one of the main indicators to monitor soil quality, for its agricultural and environmental functions by many national and international institutions, initiatives and partnerships (see sub-chapter 3.5.4). As soil C dynamics is poorly studied in Mediterranean context, more research is needed in order to evaluate the content and quality of soil carbon in relation to the quality of Mediterranean soils.

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Sub-chapter 3.5.4

Rethinking the management of mycorrhizal soil infectivity to restore Mediterranean and tropical forest ecosystems

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Introduction

Desertification, one of the main causes of climate change, generally results from a variety of factors, including climatic variations and human activities. Among the man-mediated degradative activities, deforestation is considered to have a major impact by causing extinction, changes to climatic condition, desertification and the displacement of local populations (Defries et al. 2007).

Forest cover is an important source of protection from soil degradation and deforestation which impacts population structure, successional patterns and species diversity, generally inducing degradations in the physico-chemical and biological soil properties (Requena et al. 2001). These changes can be recorded in microbial functional capacity (microbial metabolism, biomass and composition, enzymatic activities and soil organic matter flux) which is mainly involved in soil quality and function (Chaer et al. 2009). Many studies have also shown that deforestation and soil cultivation alter soil microbial community structure (Bossio et al. 2005) and may lead to reduction in microbial biodiversity (Chaer et al. 2009).

Among components of soil microbiota, mycorrhizal fungi are known to be essential key components of sustainable soil-plant systems, especially in arid ecosystems (Duponnois et al. 2011). The mycorrhizal symbiosis mobilizes and transports nutrients to roots (Smith & Read, 2008), reduces water stress (Augé, 2001) and improves soil aggregation in eroded soils (Caravaca et al. 2002). It has also been reported that arbuscular mycorrhizal (AM) fungi affect the diversity of plant communities (van der Heijden et al. 1998)) and influence relationships between plants (van der Heijden et al. 1998).

Since trees are a primary source of protection from soil degradation, many afforestation programs have been undertaken but with generally low performance in terms of productivity and seedling survival after outplanting (Duponnois et al. 2005a). These deficiencies have usually been recorded in Mediterranean semi-arid areas known to have low bioavailable phosphate content and high phosphate retention capacities (Duponnois et al. 2011). This environmental context represents the most favourable conditions for AMF's potential to increase plant growth without any mineral fertilizers (Rodriguez & Sanders, 2015). Unfortunately, this microbial resource has been largely neglected despite numerous studies focused on this symbiosis.

The native inoculum potential of AM fungi in arid and semi-arid Mediterranean ecosystems is generally limited which, in turn, prevents plant establishment and growth (Smith& Read 2008). It is necessary to apply mycorrhizal inoculation technologies or to manage native AM fungus communities to replace or reinforce the mycorrhizal potential in these degraded areas (Duponnois et al. 2011).

Approaches to AM application in forestry practices

This chapter aims to describe different practical approaches to integrate the AM symbiosis in forestry practices through a "reductionist" approach (also named Controlled mycorrhization) (Inoculation of optimized AM fungal strains to improve the plant growth in unfriendly conditions) or a "holistic" approach (Suitable management of AM fungal diversity for ensuring AM fungi – dependent ecosystem services) (Rodriguez & Sanders, 2015). Each of these cultural practices will be illustrated by results from field experiments performed in Mediterranean and tropical areas.

The "reductionist" approach (controlled mycorrhization)

In recent decades, considerable research has been made by using specific mycorrhizal fungal strains to enhance outplanting performances with forest tree species (Caravaca et al. 2002). Hence, numerous studies have reported the beneficial effects on plant growth resulting from AM fungal inoculation during the nursery plantation. Among all the AM fungal strains tested in these experiments, *Rhizophagus irregularis* has attracted great interest because of (1) its world-wide distribution, (2) its high genetic variability and variation in effects on plant growth and (3) its ability to be produced in an *in vitro* system.

Some of its impacts on the growth of different tree species in controlled conditions are reported in table 1. Most of these experiments have been performed in controlled conditions and few studies have clearly demonstrated the benefits

Table 1
Impact of R. irregularis on the growth of tree species in controlled conditions after different times of cultivation

Tree species	Time (months)	Impact of R. irregularis on plant growth		References
		On shoot biomass	On root biomass	
Acacia holosericea	4	+ 77.5% (1)	+ 122.7% (2)	Duponnois et al. (2005b)
Fraxinus uhdei	3	+ 250%	+ 180%	Ambriz et al. (2010)
Cupressus atlantica	3	+ 48.7%	+ 155.2%	Ouahmane et al. (2007)
Acacia mangium	3	+ 20.2%	+ 50%	Weber et al. (2005)
Citrus aurantium	5	+ 273.3%	+ 66.3%	Nemec & Vu (1990)
Acacia tortilis	4	+ 499.2%	+ 78.3%	André et al. (2003)
Parkia biglobosa	2	+7.1%	+ 25.5%	Guissou et al. (1998)
Tamarindus indica	2	+6.7%	+ 36%	Guissou et al. (1998)
Zizyphus mauritiana	2	+ 130.3%	+ 152%	Guissou et al. (1998)
Alnus cordata	2	+ 441%	+ 1407%	Monzon & Azcon (2001)
Alnus incana	2	+ 644%	+ 1041.2%	Monzon & Azcon (2001)
Alnus glutinosa	2	+ 996.7 %	+ 1194%	Monzon & Azcon (2001)
Acacia senegal	3	+ 171.4%	+ 127.3%	Ndoye et al. (2013)
Phoenix dactylifera	5	+ 140.4%	+ 165.4%	Baslam et al. (2014)

(1) (Shoot biomass of mycorrhizal plants / Shoot biomass of non mycorrhizal plants) x 100. (2) (Root biomass of mycorrhizal plants / Root biomass of non mycorrhizal plants) x 100.

of fungal inoculation in the field. The degree of mycorrhizal responses on a reafforestation site depends on the status of fungal colonization at planting, and the persistence of introduced fungi and other biotic and abiotic factors at the planting site (Duponnois et al. 2011).

Hence, the use of AM fungi and plants adapted to the local environmental conditions may be a prerequisite for the success of reafforestation programmes (Duponnois et al. 2005a). The potential effect of mycorrhizal inoculation with native AM fungi on the survival rates and early growth performance in the field of Mediterranean tree species (i.e. cypress, carob) has been assessed in a few studies (Manaut et al. 2015). The results showed the high potential of this approach by sustainably improving the growth and nutrient status of both tree species and also by inducing a positive soil microbial environment for nutrient cycling and environmental stress resistance (figs. 1 & 2).

The "holistic" approach

It has been reported that certain shrubs react positively to the survival and growth of other neighboring plant species by creating a better environmental habitat with low stresses from high radiation and temperature as well as from soil nutrient and moisture deficiencies (Callaway & Walker, 1997) named "the nurse-plant syndrome" (Niering et al. 1963). The ecological facilitation between plant species results in the patchy distribution of the vegetation commonly observed in Mediterranean areas, especially in degraded ecosystems (Callaway & Walker, 1997).

Hence it has been suggested that the use of nurse plants as planting microhabitats in Mediterranean degraded ecosystems could promote the survival and development of native tree species and constitute an alternative reforestation technique compared to the standard practices (Duponnois et al. 2011). The "fertility islands" or "resource islands" (Schlesinger et al. 1996) resulting from the establishment of these nurse plants show a higher arbuscular mycorrhizal (AM) soil infectivity compared to the adjacent soil away from plant influence (Duponnois et al. 2011), which can improve plant growth and survival in arid conditions, by increasing the supply of nutrients to the plants (especially for soil P uptake) (Smith & Read, 2008), enhancing soil aggregation in eroded soils (Caravaca et al. 2002) and reducing water stress (Augé, 2001).

After three years' plantation, it was reported that the association between *C. atlantica* and a nurse plant, *L. stoechas*, enhanced the growth of *C. atlantica* and provided better soil microbial characteristics compared to the control treatment (fig. 3) (Duponnois et al. 2011). AM mycelium network, total microbial activity, dehydrogenase activity, phosphate-solubilizing fluorescent pseudomonads and N, P nutrient uptake by *C. atlantica*, were significantly higher in the presence of *L. stoechas*. This pioneer shrub facilitated the early establishment of Cypress seedlings by improving soil microbial characteristics and AM fungus community development. Since the facilitative effect of one

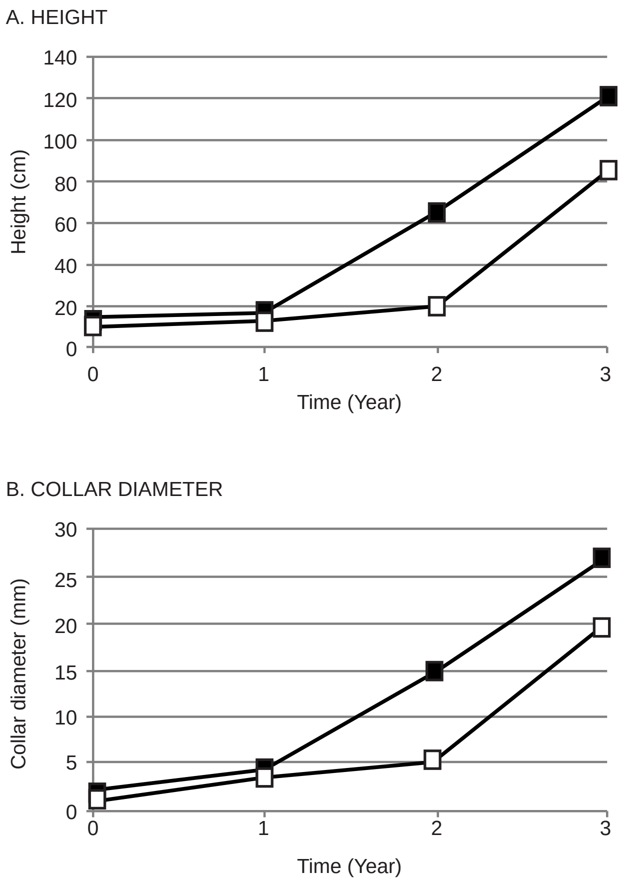


Figure 1

Height and collar diameter of carob outplants in the field, either inoculated with AM fungi (■) or non-inoculated (control □). An asterisk indicates a significant ($P < 0.05$) difference between the two treatments for a given year (From Manaut et al. 2015).

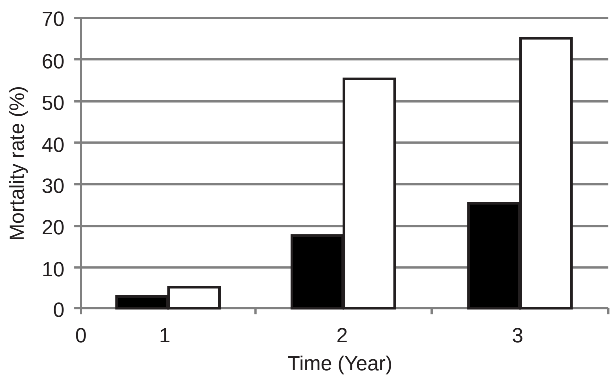


Figure 2

Cumulative mortality of carob outplants in the field, either inoculated with AM fungi (■) or non-inoculated (control □) during the three years of plantation (From Manaut et al. 2015).

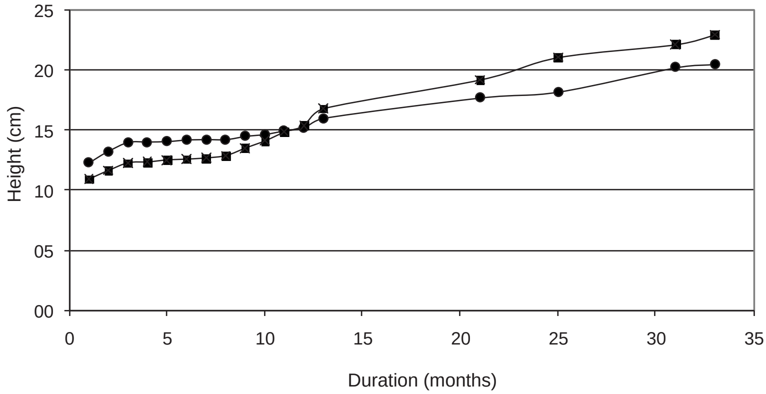


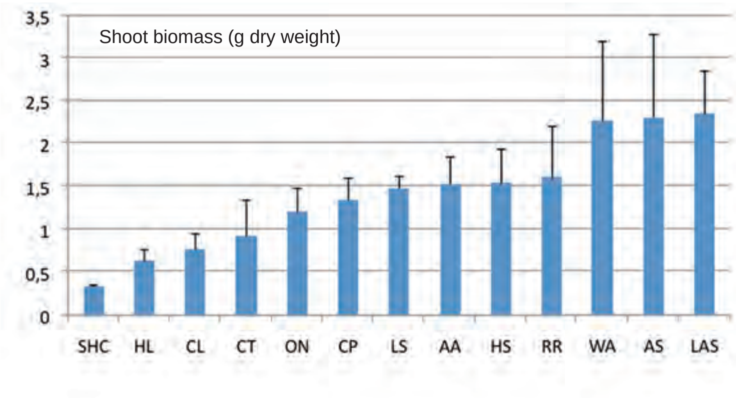
Figure 3

Time course changes in plant height (expressed in cm) of C. atlantica *outplants growing under natural conditions in the High Atlas Mountains (Morocco), either non-inoculated (Control) (●) or associated with* L. stoechas *plants (■). Symbols represent means (± standard error of the mean). An asterisk indicates that the difference between the height of uninoculated* C. atlantica *and* C. atlantica *associated with* L. stoechas *is significant in the corresponding month according to the Newman Keul's test ($p < 0.05$).*

plant species on another increases with abiotic stress (Callaway, 1995), the benefits of this technique would be useful in reforestation programs undertaken to rehabilitate degraded areas in the Mediterranean region (Duponnois et al. 2011). Other shrub species have been identified for their potential nursing effects on Mediterranean tree species (fig. 4).

Conclusion

These data show that the management of the mycorrhizal soil infectivity through different cultural approaches (reductionist or holistic approaches) has large potentialities to improve the performances of afforestation programmes, especially in Mediterranean and Tropical areas. This biological tool must be used according to the biological characteristics of the targeted areas (physic-chemical characteristics, biological characteristics) in order to reach sustainable objectives in forest ecosystem productivity and resistance. Hence ecological approaches at community and population scalesmust be encouraged with a view to better informed management of AM fungi in order to propose practical solutions to manage forest ecosystems in a sustainable manner.



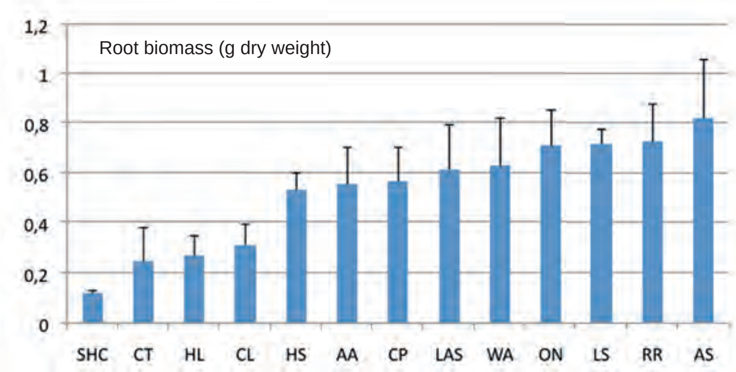


Figure 4
Growth responses of Acacia raddiana *seedlings to the soil origins collected under shrub species native from Morrocan arid areas after 4 months' culture in glasshouse conditions (Unpublished data). HL:* Helianthemum lupii*; ON:* Ononis natrix*; HS:* Haloxylon scoparium*; RR:* Retama retama*; WA:* Withania adpressa*; LS:* Lavandula *sp.: LAS:* Launea *sp.; CL:* Cleome *sp.; CT:* Convolvulus trabutianus*; AA:* Artemisia herba alba*; AS:* Astericus *sp.; SHC: Soil non influenced by plants.*

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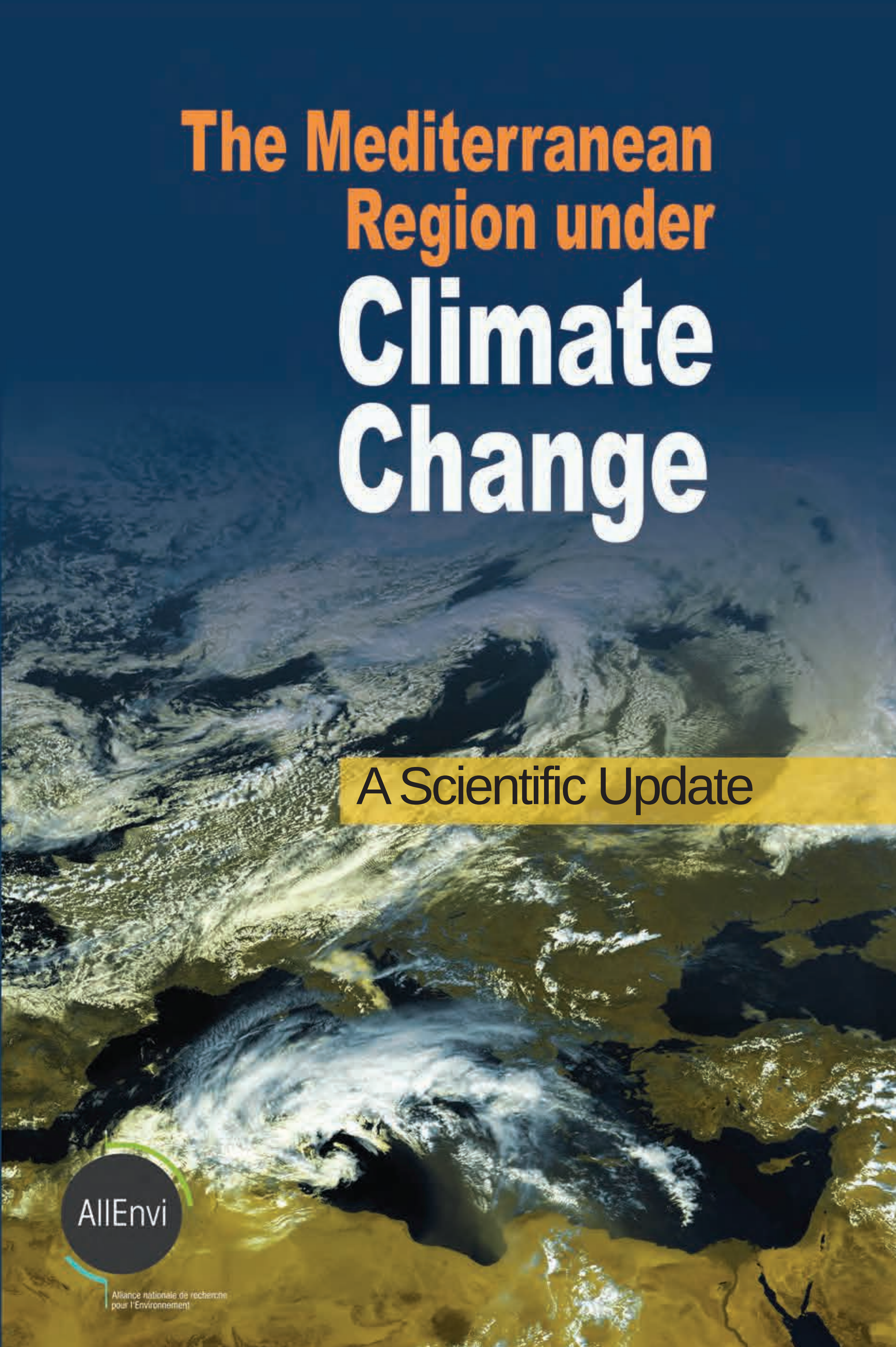

The Mediterranean Region under Climate Change

A Scientific Update

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