Chapter 3

# Soil health

*Agriculture must, literally, return to its roots by rediscovering the importance of healthy soil, drawing on natural sources of plant nutrition, and using mineral fertilizer wisely*

Soil is fundamental to crop production. Without soil, no food could be produced on a large scale, nor would livestock be fed. Because it is finite and fragile, soil is a precious resource that requires special care from its users. Many of today's soil and crop management systems are unsustainable. At one extreme, overuse of fertilizer has led, in the European Union, to nitrogen (N) deposition that threatens the sustainability of an estimated 70 percent of nature[1]. At the other extreme, in most parts of sub-Saharan Africa, the under-use of fertilizer means that soil nutrients exported with crops are not being replenished, leading to soil degradation and declining yields.

How did the current situation arise? The main driver was the quadrupling of world population over the past 100 years, which demanded a fundamental change in soil and crop management in order to produce more food. That was achieved thanks partly to the development and massive use of mineral fertilizers, especially of nitrogen, since N availability is the most important determinant of yield in all major crops[2-5].

Before the discovery of mineral N fertilizers, it took centuries to build up nitrogen stocks in the soil[6]. By contrast, the explosion in food production in Asia during the Green Revolution was due largely to the intensive use of mineral fertilization, along with improved germplasm and irrigation. World production of mineral fertilizers increased almost 350 percent between 1961 and 2002, from 33 million tonnes to 146 million tonnes[7]. Over the past 40 years, mineral fertilizers accounted for an estimated 40 percent of the increase in food production[8].

**The contribution of fertilizers to food production** has also carried significant costs to the environment. Today, Asia and Europe have the world's highest rates of mineral fertilizer use per hectare. They also face the greatest problems of environmental pollution resulting from excessive fertilizer use, including soil and water acidification, contamination of surface and groundwater resources, and increased emissions of potent greenhouse gases. The N-uptake efficiency in China is only about 26-28 percent for rice, wheat and maize and less than 20 percent for vegetable crops[9]. The remainder is simply lost to the environment.

The impact of mineral fertilizers on the environment is a question of management – for example, how much is applied compared to the

amount exported with crops, or the method and timing of applications. In other words, it is the *efficiency* of fertilizer use, especially of N and phosphorus (P), which determines if this aspect of soil management is a boon for crops, or a negative for the environment.

The challenge, therefore, is to abandon current unsustainable practices and move to land husbandry that can provide a sound foundation for sustainable crop production intensification. Far-reaching changes in soil management are called for in many countries. The new approaches advocated here build on work undertaken by both FAO[10-12] and many other institutions[13-20], and focus on the management of soil health.

## Principles of soil health management

Soil health has been defined as: "the capacity of soil to function as a living system. Healthy soils maintain a diverse community of soil organisms that help to control plant disease, insect and weed pests, form beneficial symbiotic associations with plant roots, recycle essential plant nutrients, improve soil structure with positive repercussions for soil water and nutrient holding capacity, and ultimately improve crop production"[21]. To that definition, an ecosystem perspective can be added: A healthy soil does not pollute the environment; rather, it contributes to mitigating climate change by maintaining or increasing its carbon content.

Soil contains one of the Earth's most diverse assemblages of living organisms, intimately linked via a complex food web. It can be either sick or healthy, depending on how it is managed. Two crucial characteristics of a healthy soil are the rich diversity of its biota and the high content of non-living soil organic matter. If the organic matter is increased or maintained at a satisfactory level for productive crop growth, it can be reasonably assumed that a soil is healthy. Healthy soil is resilient to outbreaks of soil-borne pests. For example, the parasitic weed, *Striga*, is far less of a problem in healthy soils[22]. Even the damage caused by pests not found in the soil, such as maize stem borers, is reduced in fertile soils[23].

The diversity of soil biota is greater in the tropics than in temperate zones[24]. Because the rate of agricultural intensification in the future will generally be greater in the tropics, agro-ecosystems there are

under particular threat of soil degradation. Any losses of biodiversity and, ultimately, ecosystem functioning, will affect subsistence farmers in the tropics more than in other regions, because they rely to a larger extent on these processes and their services.

Functional interactions of soil biota with organic and inorganic components, air and water determine a soil's potential to store and release nutrients and water to plants, and to promote and sustain plant growth. Large reserves of stored nutrients are, in themselves, no guarantee of high soil fertility or high crop production. As plants take up most of their nutrients in a water soluble form, nutrient transformation and cycling – through processes that may be biological, chemical or physical in nature – are essential. The nutrients need to be transported to plant roots through free-flowing water. Soil structure is, therefore, another key component of a healthy soil because it determines a soil's water-holding capacity and rooting depth. The rooting depth may be restricted by physical constraints, such as a high water table, bedrock or other impenetrable layers, as well as by chemical problems such as soil acidity, salinity, sodality or toxic substances.

**A shortage of any one of the 15 nutrients** required for plant growth can limit crop yield. To achieve the higher productivity needed to meet current and future food demand, it is imperative to ensure their availability in soils and to apply a balanced amount of nutrients from organic sources and from mineral fertilizers, if required. The timely provision of micronutrients in "fortified" fertilizers is a potential source of enhanced crop nutrition where deficiencies occur.

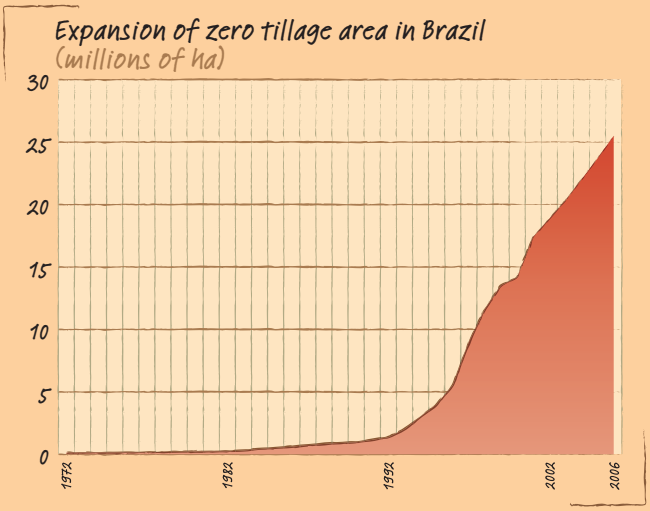
Nitrogen can also be added to soil by integrating N-fixing legumes and trees into cropping systems (see also Chapter 2, *Farming systems*). Because they have deep roots, trees and some soil-improving legumes have the capacity to pump up from the subsoil nutrients that would otherwise never reach crops. Crop nutrition can be enhanced by other biological associations – for example, between crop roots and soil mycorrhizae, which help cassava to capture phosphorus in depleted soils. Where these ecosystem processes fail to supply sufficient nutrients for high yields, intensive production will depend on the judicious and efficient application of mineral fertilizers.

A combination of ecosystem processes and wise use of mineral fertilizers forms the basis of a sustainable soil health management system that has the capacity to produce higher yields while using fewer external inputs.

# Technologies that save and grow

No single technology is likely to address the specific soil health and soil fertility constraints that prevail in different locations. However, the basic principles of good soil health management, outlined above, have been successfully applied in a wide range of agro-ecologies and under diverse socio-economic conditions.

Building on soil health management principles, research in different regions of the world has identified some "best-bet" technologies. The following examples describe crop management systems that have high potential for intensification and sustainable production. They address specific soil fertility problems in different agro-ecological zones and have been widely adopted by farmers. They may serve as templates for national partners in devising policies that encourage farmers to adopt these technologies as part of sustainable intensification.




*de Moraes Sá, J.C. 2010.* No-till cropping system in Brazil: Its perspectives and new technologies to improve and develop. *Presentation prepared for the International Conference on Agricultural Engineering, 6-8 September 2010, Clermont-Ferrand, France (http://www.ageng2010.com/files/file-inline/J-C-M-SA.pdf).*

## Increasing soil organic matter in soils in Latin America

Oxisols and ultisols are the dominant soil types in Brazil's Cerrado tropical savanna and Amazon rainforest regions, and they are also widespread in Africa's humid forest zone. Among the oldest on earth, these soils are poor in nutrients and very acidic, owing to their low capacity to hold nutrients – and cations in particular – in their surface and subsoil layers. In addition, being located in regions with high rainfall, they are prone to erosion if the surface is not protected by vegetative cover.

Upon conversion of the land from natural vegetation to agricultural use, special care has to be taken to minimize losses of soil organic matter. Management systems for these soils have been designed to conserve or even increase organic matter by providing permanent soil cover, using a mulching material rich in carbon, and ensuring minimized or zero tillage of the soil surface. These practices are all key components of the SCPI approach.

Such systems are being rapidly adopted by farmers in many parts of Latin America, and particularly in humid and subhumid zones, because they control soil erosion and generate savings by reducing labour inputs. Adoption has been facilitated by close collaboration between government research and extension services, farmer associations and private companies that produce agrochemicals, seed and

machinery. Zero-till farming has spread rapidly and now covers 26 million hectares on oxisols and ultisols in Brazil.

## Biological nitrogen fixation to enrich N-poor soils in African savannas

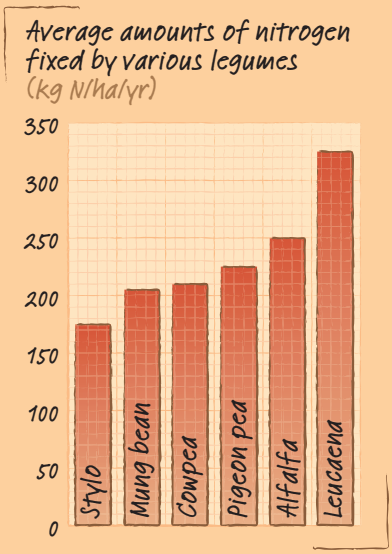
Crop production in the savanna regions of western, eastern and southern Africa is severely constrained by N- and P-deficiency in soils[17, 25], as well as the lack of micronutrients such as zinc and molybdenum. The use of leguminous crops and trees that are able to fix atmospheric nitrogen, in combination with applications of mineral P-fertilizers, has shown very promising results in on-farm evaluations conducted by the Tropical Soil Biology and Fertility Institute, the World Agroforestry Centre and the International Institute of Tropical Agriculture (IITA).

The combination of mineral fertilizer application and a dual-purpose grain legume, such as soybean, intercropped or relay-cropped with maize, increased maize yields in Kenya by 140 to 300 percent[17] and resulted in a positive N-balance in the cropping system. Dual-purpose grain legumes produce a large amount of biomass with their haulms and roots, as well as an acceptable grain yield. Several farming communities in eastern and southern Africa have adopted this system[26]. It has the additional advantage of helping farmers to combat *Striga* – some soybean cultivars act as "trap crops", which force *Striga* seeds to germinate when the weed's usual hosts, maize or sorghum, are not present[10, 27].

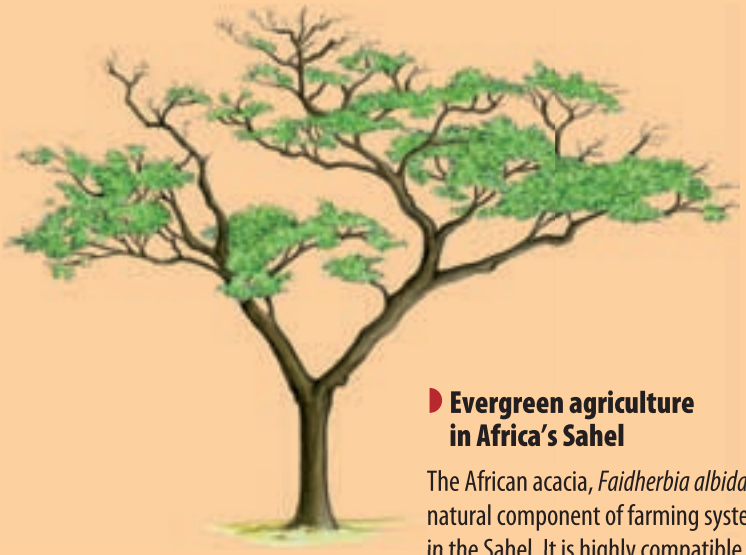
In eastern and southern Africa, N-deficient maize cropping systems have become more productive thanks to improved fallows using leguminous trees and shrubs. Per hectare, species such as *Sesbania sesban, Tephrosia vogelii* and *Crotalaria ochroleuca* accumulate in their leaves and roots around 100 to 200 kg of nitrogen – two-thirds of it from nitrogen fixation – over a period of six months to two years. Along with subsequent applications of mineral fertilizer, these improved fallows provide sufficient N for up to three subsequent maize crops, resulting in yields as much as four times higher than those obtained in non-fallow systems.

Research indicates that a full agroforestry system with crop-fallow rotations and high value trees can triple a farm's carbon stocks in 20 years[28]. The system has been so successful that tens of thousands of farmers in Kenya, Malawi, Mozambique, Uganda, the United Republic of Tanzania, Zambia and Zimbabwe are now adapting the component technologies to their local conditions.

*Sesbania sesban*




*FAO. 1984.* Legume inoculants and their use. *Rome.*

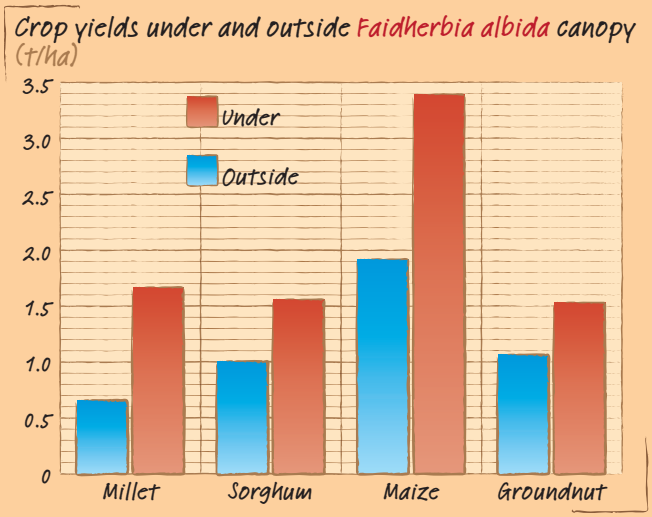


*Faidherbia albida*

## Evergreen agriculture in Africa's Sahel

The African acacia, *Faidherbia albida*, is a natural component of farming systems in the Sahel. It is highly compatible with food crops because it does not compete with them for light, nutrients or water. In fact, the tree loses its nitrogen-rich leaves during the rainy season, thus providing a protective mulch which also serves as natural fertilizer for crops. Zambia's Conservation Farming Unit has reported unfertilized maize yields of 4.1 tonnes per hectare in the vicinity of *Faidherbia* trees, compared to 1.3 tonnes from maize grown nearby, but outside of the tree canopy[29]. Today, more than 160 000 farmers in Zambia are growing food crops on 300 000 ha with *Faidherbia*. Similarly promising results have been observed in Malawi, where maize yields near *Faidherbia* trees are almost three times higher than yields outside their range. In Niger, there are now more than 4.8 million hectares under *Faidherbia*-based agroforesty, resulting in enhanced millet and sorghum production.

Thousands of rainfed smallholdings in Burkina Faso are also shifting to these "evergreen" farming systems.

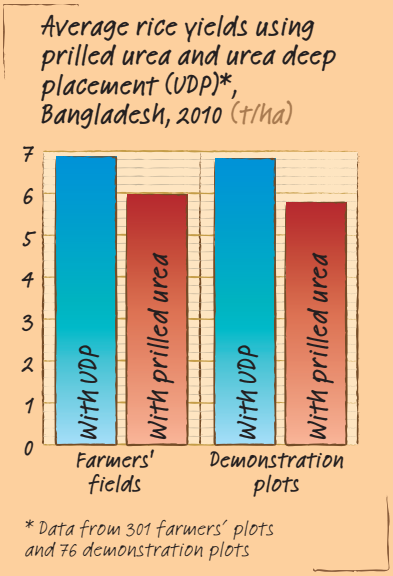



*FAO. 1999.* Agroforestry parklands in sub-Saharan Africa, *by J.-M. Boffa. Rome.*

## "Urea deep placement" for rice in Bangladesh

Throughout Asia, farmers apply nitrogen fertilizer to rice before transplanting by broadcasting a basal application of urea onto wet soil, or into standing water, and then broadcasting one or more top-dressings of urea in the weeks after transplanting up to the flowering stage. Such practices are agronomically and economically inefficient and environmentally harmful. The rice plants use only about a third of the fertilizer applied[30], while much of the remainder is lost to the air through volatilization and surface water run-off. Only a small amount remains in the soil and is available to subsequent crops.

One way of reducing N losses is to compress prilled urea to form urea super granules (USG) which are inserted 7 to 10 cm deep in the soil between plants. This "urea deep placement" (UDP) doubles the percentage of nitrogen taken up by plants[31-35], reduces N lost to the air and to




*IFDC. 2010.* Improved livelihood for Sidr-affected rice farmers (ILSAFARM). *Quarterly report submitted to USAID-Bangladesh, No. 388-A-00-09-00004-00. Muscle Shoals, USA.*

surface water run-off, and has produced average yield increases of 18 percent in farmers' fields. The International Fertilizer Development Center and the United States Agency for International Development are helping smallholder farmers to upscale UDP technology throughout Bangladesh. The goal is to reach two million farmers in five years[36]. The technology is spreading fast in Bangladesh and is being investigated by 15 other countries, most of them in sub-Saharan Africa. The machines used to produce USG in Bangladesh are manufactured locally and cost between US$1 500 and US$2 000.

## Site-specific nutrient management in intensive rice

The International Rice Research Institute (IRRI) and its national partners have developed the site-specific nutrient management (SSNM) system for highly intensive rice production. SSNM is a sophisticated knowledge system focused on double and triple rice mono-cropping. Tests at 180 sites in eight key irrigated rice domains of Asia found that the system led to a 30 to 40 percent increase in N-use efficiency, mainly thanks to improved N management. Across all sites and four successive rice crops, profitability increased by an average of 12 percent.

In several provinces of China, SSNM reduced farmers' use of N-fertilizer by one third, while increasing yields by 5 percent[37]. A site-specific N-management strategy was able to increase uptake efficiency by almost 370 percent on the North China Plain[9]. Since the average plant recovery efficiency of nitrogen fertilizer in intensive rice systems is only about 30 percent, those are remarkable achievements that contribute substantially to reducing the negative environmental effects of rice production. The complex SSNM technology is being simplified in order to facilitate its wider adoption by farmers.

*rice*

## The way forward

The following actions are required to improve current land husbandry practices and provide a sound basis for the successful adoption of sustainable crop production intensification. Responsibility for implementation rests with national partners, assisted by FAO and other international agencies.

*Establish national regulations for sound land husbandry.* A supportive policy framework should aim at encouraging farmers to adopt sustainable farming systems based on healthy soils. Leadership is required to establish and monitor best practices, with the active participation of smallholder farmers and their communities. Governments must be prepared to regulate farming practices that cause soil degradation or pose serious threats to the environment.

*Monitor soil health.* Policymakers and national institutions responsible for the environment are demanding methods and tools to verify the impact of farming practices. While monitoring soil health is a very challenging task, efforts are under way to implement it at global[38], regional and national scales[39]. Monitoring the impact of agricultural production has advanced in developed countries, but is just beginning in many developing countries. FAO and its partners have developed a list of methods and tools for undertaking assessments and monitoring tasks[40]. Core land quality indicators requiring immediate and longer term development should be distinguished[41]. Priority indicators are soil organic matter content, nutrient balance, yield gap, land use intensity and diversity, and land cover. Indicators that still need to be developed are soil quality, land degradation and agrobiodiversity.

*Build capacity.* Soil health management is knowledge-intensive and its wide adoption will require capacity building through training programmes for extension workers and farmers. The skills of researchers will also need to be upgraded at both national and international levels, in order to provide the enhanced knowledge necessary to support soil management under SCPI. Policymakers should explore new approaches, such as support groups for adaptive research cooperation[42], which provide technical support and on-the-job training for national research institutions and translate research results into practical guidelines for small farmers. National capacity to undertake on-farm research must also be strengthened, and focused on address-

ing spatial and temporal variability through, for example, better use of ecosystems modelling.

*Disseminate information and communicate benefits.* Any large-scale implementation of soil health management requires that supporting information is made widely available, particularly through channels familiar to farmers and extension workers. Given the very high priority attached to soil health in SCPI, media outlets should include not only national newspapers and radio programmes, but also modern information and communication technologies, such as cellular phones and the Internet, which can be much more effective in reaching younger farmers.

Chapter 4

# Crops and varieties

*Farmers will need a genetically diverse portfolio of improved crop varieties, suited to a range of agro-ecosystems and farming practices, and resilient to climate change*