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Soils and pulses

symbiosis for life

2016
INTERNATIONAL
YEAR OF PULSES

World
Soil Day

GLOBAL SOIL
PARTNERSHIP

Soils
and
pulses
symbiosis
for life

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List of Acronyms

A	Asia
BC	Before Christ
BGA	Nitrogen fixing cynobacterium
BNF	Biological Nitrogen Fixation
CBD	Convention on Biological Diversity
CEC	Cation-Exchange Capacity
DE	Digestible Energy
E	Europe and Eurasia
FAO	Food and Agriculture Organization of the United Nations
FYM	Farm Yard Manure
GHG	Greenhouse gas
GI	Glycemic Index
GM	Green Manure
GSP	Global Soil Partnership
HYV	High Yielding Varieties
INM	Integrated Nutrient Management
ITPS	Intergovernmental Technical Panel on Soils
IYP	International Year of Pulses
IYS	International Year of Soils
LAC	Latin America and the Caribbean
LADA	Land Degradation Assessment in Drylands
MDGs	Millennium Development Goals
ME	Metabolisable Energy
NA	North America
NENA	Near East and North Africa
PGM	Pulse Green Manure
PGPR	Plant growth-promoting rhizobacteria
RFD	Radiofrequency Facet Denervation
SDGs	Sustainable Development Goals
SMBC	Soil Microbial Biomass Carbon
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SP	Southwest Pacific
SSA	Africa and South of the Sahara
SSM	Sustainable Soil Management
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UPS	Underutilized Pulse Species
VAM	Vesicular Arbuscular Mycorrhiza
VGSSM	Voluntary Guidelines for Sustainable Soil Management
WHC	Water Holding Capacity

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Executive summary

The United Nations (UN) General Assembly declared 2015 the International Year of Soils (IYS) and 2016 the International Year of Pulses (IYP) to increase awareness and understanding on the importance of soils and pulses respectively for sustainable food production, food and nutrition security and essential ecosystem functions. In order to ensure due complementarities, close links have been maintained between these two celebratory events, taking account of the symbiosis between soil and pulses for contributing to food security and nutrition, and the achievement of the Sustainable Development Goals (SDGs). The development of this book started with the Seminar "Soils and pulses: symbiosis for life. A contribution to the 2030 Agenda" held in April 2016, jointly organized by the Permanent Representation of Italy to FAO, FAO and Biodiversity International.

Soils provide a range of ecosystem services that are fundamental to human well-being and life on Earth, but in spite of their crucial role, soils have been taken for granted for a long time. Population growth and associated changes in consumption patterns and diet are putting increasing pressure on soil resources, creating the need to grow more food on smaller units of land and to do so using less water. As a result, pressures on soil resources are reaching critical limits and soils are being continuously degraded (roughly 33 % of global land is already degraded). There is thus an urgent need to raise awareness on the importance of this strategic resource and to promote its sustainable management. Careful soil management can increase the food supply, providing a valuable lever for climate regulation and a pathway for safeguarding ecosystem services. Additionally, large economic benefits will be generated from the sustainable management of soil resources. According to the revised World Soil Charter: "soil management is sustainable if the supporting, provisioning, regulating, and cultural services provided by soil are maintained or enhanced without significantly impairing the soil functions that enable those services or biodiversity".

Equally, despite the importance of pulses (generally defined as "the edible seeds of various leguminous crops" and mostly referring to legumes harvested for dry grain) in contributing to food and nutrition security and sustainable agriculture, they are not well known to most. Pulses can be strategic allies in maintaining and increasing soil health, restoring degraded soils and improving overall human wellbeing. Farmers have known since the beginning of agriculture that legumes are important for soil health and agricultural techniques such as intercropping and crop rotation have been used for millennia. Pulses should therefore not only be planted for their immediate returns of high yields, but also because they will enrich the soils for subsequent crops. Pulses (and legumes in general) improve soil health due to the symbiotic presence of various soil bacteria (collectively called rhizobia) in the legume roots. As a result, pulses are responsible for the biological fixation of atmospheric nitrogen and for the solubilisation of phosphate ions from bound forms such as calcium and iron phosphates to make these nutrients available to plants. Besides their role in the nitrogen and phosphorous cycles, pulses also contribute to increasing soil organic matter, improving soil structure and maintaining soil biodiversity, leading to overall increased soil health.

By fixing atmospheric nitrogen and solubilizing phosphates, pulses contribute to reducing the need for synthetic fertilizers and, in doing so, greatly contribute to reducing the risk of soil and water pollution, supporting soil biodiversity, and combating and building resilience to climate change. Biological nitrogen fixation is particularly important for global agricultural productivity and might be considered one of the most important biological processes on the planet. It provides *circa* 100 million metric tonnes of N which leads to an annual saving of around USD10 billion in N fertilizer. Lentils alone could fix nitrogen in the range of 35-100 kg ha^{-1}. Furthermore, the reduced need for (or use of) synthetic fertilizers indirectly reduces the amount of greenhouse gases released into the atmosphere. Pulses also promote soil carbon sequestration and, ultimately, reduce soil erosion when included in intercropping farming systems and/or used as cover crops. Furthermore, due to their high nutritional value, pulses are also valuable allies in fighting hunger worldwide.

The symbiosis between soil and pulses is ultimately expressed in the cropping system. The inclusion of pulses in multiple cropping systems such as intercropping or in simple crop rotations is indeed considered important for the integrated management of the soil nutrients and for moving towards conservation and organic agriculture. In turn, this is of critical importance considering the need for intensifying food production while making better use of input resources and building resilience to climate change.

In summary, pulses are important food crops that can play a major role in addressing future global food security and environmental challenges, as well as in contributing to healthy diets. Pulses contain on average 19-25 percent protein, with over 30 percent in newly developed varieties. Due to their high nutritional value, pulses can improve the diet of the poorest who cannot rely on a diversified diet enriched by meat consumption. Nearly 80 percent of dietary protein in the developing world is plant protein, compared to 43.4 percent in developed countries where animal protein is mostly consumed.

This publication aims to provide an overview to decision makers and practitioners of the main scientific facts, information and technical recommendations regarding the symbiosis between soils and pulses. It highlights how good practices may be put in place to support ending hunger and malnutrition, adapting to climate change, halting land degradation and achieving overall sustainable development.

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1 | Introduction

The 68th United Nations (UN) General Assembly declared 2015 the International Year of Soils (IYS) (A/RES/68/232) and 2016 the International Year of Pulses (IYP) (A/RES/68/231) (UN, 2013). The IYS 2015 aimed to increase awareness and understanding on the importance of soils for food security and essential ecosystem functions (FAO, 2015a). The IYP 2016 aimed to heighten public awareness of the nutritional benefits of pulses as part of sustainable food production aimed towards food security and nutrition (FAO, 2016a). Within this framework, and pursuing the challenge of developing strengths and complementarities between international years, a clear link was created between the two Years to promote the symbiosis between soil and pulses for contributing to food security and nutrition, and the achievement of the Sustainable Development Goals (SDGs).

Soils provide a range of ecosystem services that are fundamental to human well-being and life on Earth, such as the provision of food and clean water, and climate regulation (FAO and ITPS, 2015). In spite of their crucial role, soils have been taken for granted for a long time. Population growth, together with changes in consumption patterns and diet, is putting increasing pressure on soil resources. There is the need to grow more food on smaller units of land and to do so using less water. Human pressures on soil resources are reaching critical limits that are jeopardizing our future and those of future generations (FAO and ITPS, 2015). There is thus an urgent need to raise awareness on the importance of this strategic resource and to promote its sustainable management. Careful soil management can increase the food supply, and provide a valuable lever for climate regulation and a pathway for safeguarding ecosystem services. Additionally, large economic benefits will be generated from the sustainable management of soil resources.

According to the revised World Soil Charter (FAO, 2015b) “soil management is sustainable if the supporting, provisioning, regulating, and cultural services provided by soil are maintained or enhanced without significantly impairing the soil functions that enable those services or biodiversity”. The Status of the World’s Soil Resources report identified ten threats that hamper the achievement of sustainable soil management (SSM). These threats are: soil erosion by water and wind, soil organic carbon loss, soil nutrient imbalance, soil salinization, soil contamination, acidification, loss of soil biodiversity, soil sealing, soil compaction and waterlogging. These different threats vary in terms of intensity and trend depending on geographical contexts, though they all need to be addressed in order to achieve sustainable soil management (FAO and

ITPS, 2015). According to the Voluntary Guidelines for Sustainable Soil Management (FAO, 2016b), soil degradation should be minimized using SSM, especially through soil conservation approaches that have been proven to be successful. Soil rehabilitation and/ or soil restoration should also be a priority to returning degraded soils to productivity, especially in historically sound agricultural or other production systems currently under threat.

In this context, pulses can be strategic allies in maintaining and increasing soil health, restoring degraded soils and improving overall human wellbeing. Farmers have known since the beginning of agriculture that legumes are important for soil health. Agricultural techniques such as intercropping and crop rotation have been used for millennia (Hirsch, 2001). In Roman times, Varro (37 BC) recommended in his *Rerum Rusticarum* to plant legumes in poor soils because they do not need much nutrients; these crops should not be planted for their immediate returns, namely high yields, but rather because they will enrich the soils for subsequent crops. For centuries, Native Americans have been cultivating beans, maize and squash together in a system called “the three sisters” (Landon, 2008). However, it was only at the end of the 19th century that scientists found the reason why legumes were improving soil health: the symbiotic presence of a soil bacterium in the root of the legumes. Currently, it is known that several bacteria are able to form symbiosis with legumes (Hirsch, 2001). Consequently, pulses are important food crops that can play a major role in addressing future global food security and environmental challenges, as well as in contributing to healthy diets.

This publication aims to provide decision makers and practitioners, with scientific facts, information and technical recommendations to understand the symbiosis between soils and pulses. It explores the way in which good practices could be implemented in contribution to the effort of ending hunger and malnutrition, adapt to climate change, halt land degradation and achieve overall sustainable development.

1.1 | Soil, a life enabling resource

The study of soil resources is relatively new to the traditional natural sciences, which may be the reason why the concept of 'soil' is often misunderstood. Like many common words, the word soil has several meanings. In its traditional meaning, soil is the natural medium for plant growth, but it has also been defined as a natural body consisting of layers (soil horizons) that are composed of weathered mineral materials, organic material, air and water. Soil is the end product of the combined influence of climate, topography, organisms (flora, fauna and humans) on parent materials (original rocks and minerals) over time. As a result, soil differs from its parent material in texture, structure, consistency, color, chemical, biological and physical characteristics (FAO, 2016c). Because soil formation is a time consuming process (the time depends on the environmental conditions), soils are considered a non-renewable natural resource on a human time scale (Osman, 2013).

The size and proportion of the soil particles (sand, silt and clay) is usually referred to as 'soil texture', a property which affects soil functions, in particular its retention capacity for nutrients and water (e.g., stormwater infiltration rates). The way in which the soil mineral particles are clumped together is called 'soil structure' and is influenced by the decay of organic matter and by the activity of soil organisms that are responsible for the formation of soil aggregates. The soil structure affects aeration, water movement, conduction of heat, plant root growth and resistance to erosion. 'Consistency' is the ability of soil to stick together and resist fragmentation. It is of use in predicting cultivation problems and the engineering of foundations. In general, soil color is determined by organic matter content, drainage conditions, and the degree of oxidation. It is usually used as an indication of wetness and waterlogged conditions, and as a qualitative means of measuring organic, salt and carbonate contents of soils. Another important soil physical characteristic is 'soil porosity', which refers to the number and size of pores within the soil and influences the movement of water and air into and within the soil. Ultimately, porosity is determines the potential of soil to provide oxygen to organisms decomposing organic matter and plant roots, and enables the movement and storage of water and dissolved nutrients (FAO, 2016c).

Looking at the chemical characteristics of soil, soil reaction is expressed in terms of 'pH', a measure of the acidity or alkalinity of the soil. Changes in pH can make certain ions available or unavailable in the soil based on their solubility at different pH levels. For instance, soils with pH (measured in water) <5.5 tend to have toxic levels of aluminium and manganese, while soils with pH >8.5 tend to disperse due to high levels of sodium. Soil organisms are hindered by high acidity, and most agricultural crops do best in mineral soils of pH 6.5. The 'cation-exchange capacity' (CEC) is the maximum quantity of total cations that a soil is capable of holding, at a given pH value, which can be available for exchange with the soil solution. CEC is used as a measure of soil fertility, nutrient retention capacity, and the capacity to protect groundwater from cation contamination. Sixteen essential nutrients for plant growth and living organisms can be found in the soil. Of these, carbon (C), oxygen (O), hydrogen (H), nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) are known as "macronutrients" because they are the most essential nutrients to plant growth. Iron (Fe), zinc (Zn), manganese (Mn), boron (B), copper (Cu), molybdenum (Mo) and chlorine (Cl) are known as "micronutrients" because plants need them in smaller amounts (Box 1). Excess Na, Ca, Mg, K, Cl, S and carbonates can result in soil salinity, while excess exchangeable sodium results in soil sodicity (FAO, 2016c).

The nitrogen and phosphorus cycles are described in Chapter 2, which also links to pulses cultivation. In Chapter 3, the role of soil organic carbon (SOC) in adapting and mitigating to climate change is described. Soil biological properties are also described in relation to the nitrogen and carbon cycles.

Box 1 | Different soils for different plants

A healthy soil is characterized by a moderate amount of organic matter and clay, ensuring a sufficient pool of retained plant nutrients and moisture. Moreover, for most agricultural purposes the soil should be relatively deep (>50 cm) and have a good internal and external drainage to avoid (seasonal) waterlogging and be free of harmful substances (salts, heavy metals, etc.). It should be realized that different crops have very different edaphic requirements and therefore some crops can thrive under moisture conditions where other crops would wilt. Olive trees and vineyards can be cultivated in soils with a high calcium carbonate content, while other crops such as pineapple prefer rather acidic conditions. Date palm can be grown at very high salt content, while spinach wilts at very high salt concentrations in the soil. Paddy rice does not mind waterlogging, while maize cannot stand it. Urban and infrastructural land use often has completely different soil requirements to rural and agricultural applications and it is therefore unwise planning to use the best agricultural land for urban expansion (FAO, 2016c).

1.1.1 | Ecosystem services and soil functions

Ecosystem services are defined as "the benefits provided by ecosystems to humans" (FAO, 2016d). These benefits can be direct (e.g. food production) or indirect (e.g. climate regulation), through the functioning of ecosystem processes that produce the direct services (FAO, 2016e). The Millennium Assessment (Millennium Ecosystem Assessment, 2005) classified these ecosystem services into four categories: supporting, provisioning, regulating and cultural, and linked them to the components of human well-being: security, basic material for good life, health, good social relations and freedom of choice and action. In this context, soils provide a range of ecosystem services that are fundamental to human well-being and life on Earth. The ecosystem services provided by the soil and the soil functions that support these services are listed in Table 1.

Table 1 | Ecosystem services provided by the soil *(left-hand column)* **and the soil functions that support these services** *(right-hand column)*

Ecosystem Services	Soil functions
Supporting services: Services that are necessary for the fulfilment of all other ecosystem services; their impacts on people are often indirect or occur over a very long time	
Soil formation	Weathering of minerals and release of nutrients
	Transformation and accumulation of organic matter
	Creation of structures (pores, aggregates, horizons) for gas and water flow and root growth
	Creation of charged surfaces for water and ion retention and exchange
	Succession of soil biodiversity communities
Primary production	Medium for seed germination and root growth
	Retention and supply of air, nutrients and water for plants
Nutrient cycling	Transformation of organic materials by soil organisms
	Retention and release of nutrients on and from charged surfaces
Regulating services: benefits obtained from the regulation of ecosystem processes	
Water quality regulation	Filtering and buffering of substances in soil water
	Transformation of contaminants

Water supply regulation	Regulation of water infiltration into soil and water flow within the soil
	Drainage of excess water out of soil and into groundwater and surface water
	Water vapour exchange with atmosphere
Climate regulation	Regulation of CO_2, N_2O, and CH_4 emissions
	Soil organic carbon sequestration
Erosion regulation	Retention of soil on the land surface
	Resistance of soil aggregates against soil erosion by wind and water
Flood regulation	Increasing infiltration and reducing runoff
	Slowing water movement from uplands to lowlands by surface-water retention and soil-water storage
Provisioning Services: products ('goods') obtained from ecosystems of direct benefit to people	
Food supply	Providing (healthy) water, nutrients, and physical support for growth of plants for human and animal consumption
Water supply	Retention and purification of water
Fibre and fuel supply	Providing water, nutrients, and physical support for plant growth, bioenergy, timber and fibre
Raw earth material supply	Provision of topsoil, aggregates, clay, peat etc.
Surface stability	Supporting human habitations and related infrastructure and provision of construction materials
Habitat	Providing habitat for soil fauna
Genetic resources	Source of unique biological materials (e.g., pharmaceuticals, biochemical and allelochemicals)
Cultural services: nonmaterial benefits which people obtain from ecosystems through spiritual enrichment, aesthetic experiences, heritage preservation and recreation	
Aesthetic and spiritual	Preservation of natural and cultural landscape diversity
	Source of pigments and dyes
Cultural Heritage	Preservation of archaeological and historical records

1.1.2 | Soil degradation

This section refers to the findings of the Status of the World's Soil Resources report developed by the ITPS (FAO and ITPS, 2015).

Soil health has been defined as "the continued capacity of the soil to function as a vital living system, within ecosystem and land use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal, and human health" (Doran et al., 2002). The health of soils depends on a number of physical, chemical and biological soil properties which in combination, determine a number of essential soil qualities that in turn guarantee that the soil can fulfil its ecological and productive function. Soil management has a considerable effect on how the soil may fulfil its ecosystem functions: mineral and organic fertilizer may compensate for poor inherent nutrient conditions in a soil; drainage may remedy hydromorphic conditions in soils, or leach salts when present; amendments (lime or gypsum) may correct very acidic or highly sodic soils. Apart from the fact that such interventions may have negative side effects (e.g. ground water contamination) they always have a cost in terms of labor and inputs (FAO and ITPS, 2015).

Soil degradation is defined as "the diminishing capacity of the soil to provide ecosystem goods and services as desired by its stakeholders" (FAO and ITPS, 2015). Global assessments of soil and land degradation started more than 40 years ago, but until now they have not provided a clear answer on where soil degradation takes place, what impact it has on the population, and what the cost to governments and land users would be if the decline in soil, water and vegetation resources continued unabated. Although institutional, socio-economic and biophysical causes of soil degradation have been identified locally in many case studies, they have seldom been systematically inventoried at national or regional level (FAO and ITPS, 2015). The major obstacle to the compilation of a comprehensive soil degradation map is the lack of appropriate soil input data.

In 2006, the European Union formalized the concept of threats to soil and its many functions in the Soil Thematic Strategy (CEC, 2006).Threats were defined as degradation processes including soil erosion by wind and water, organic matter decline, local and diffuse contamination, sealing, compaction, decline in biodiversity, salinization, floods and landslides of soil and rock material. These concepts were taken up in the Status of the World's Soil Resources report (FAO and ITPS, 2015) and listed as the ten major threats which are defined in Box 2. Table 2 presents a global summary of the condition and trends for the ten soil threats, listed in order of priority in the regions identified in Figure 1 (excluding Antarctica). While there is cause for optimism in some regions, the overwhelming conclusion from the regional assessment conducted by FAO and the ITPS is that the majority of the world's soil resources are only in fair, poor or very poor condition. The current outlook is that this situation will worsen unless concerted actions are taken by individuals, the private sector, governments and international organizations to rehabilitate and restore degraded soils (FAO and ITPS, 2015).

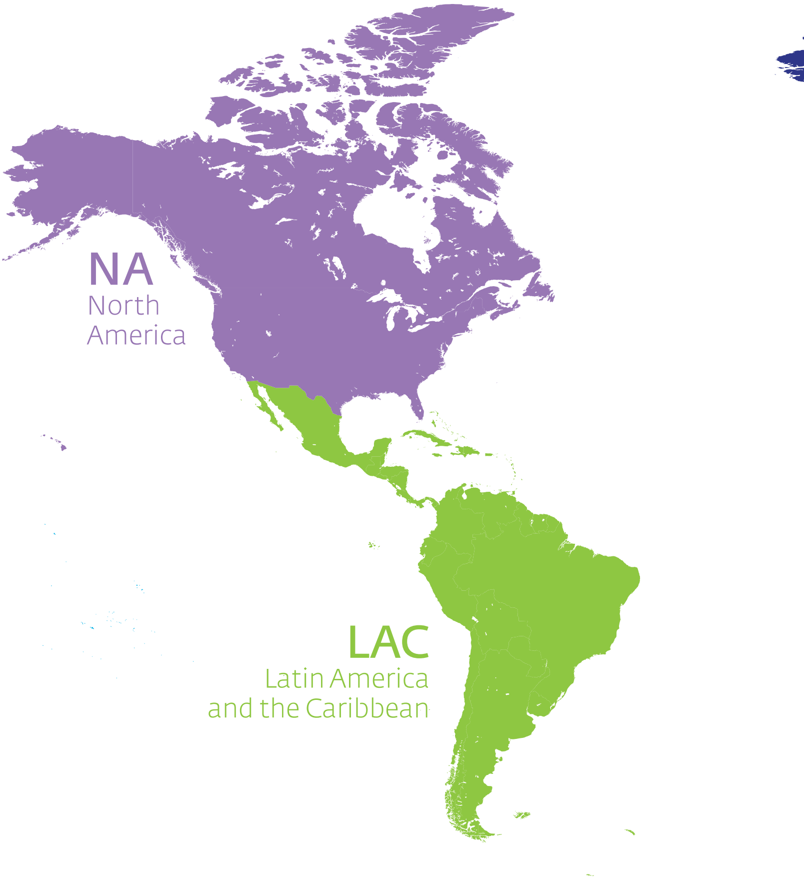
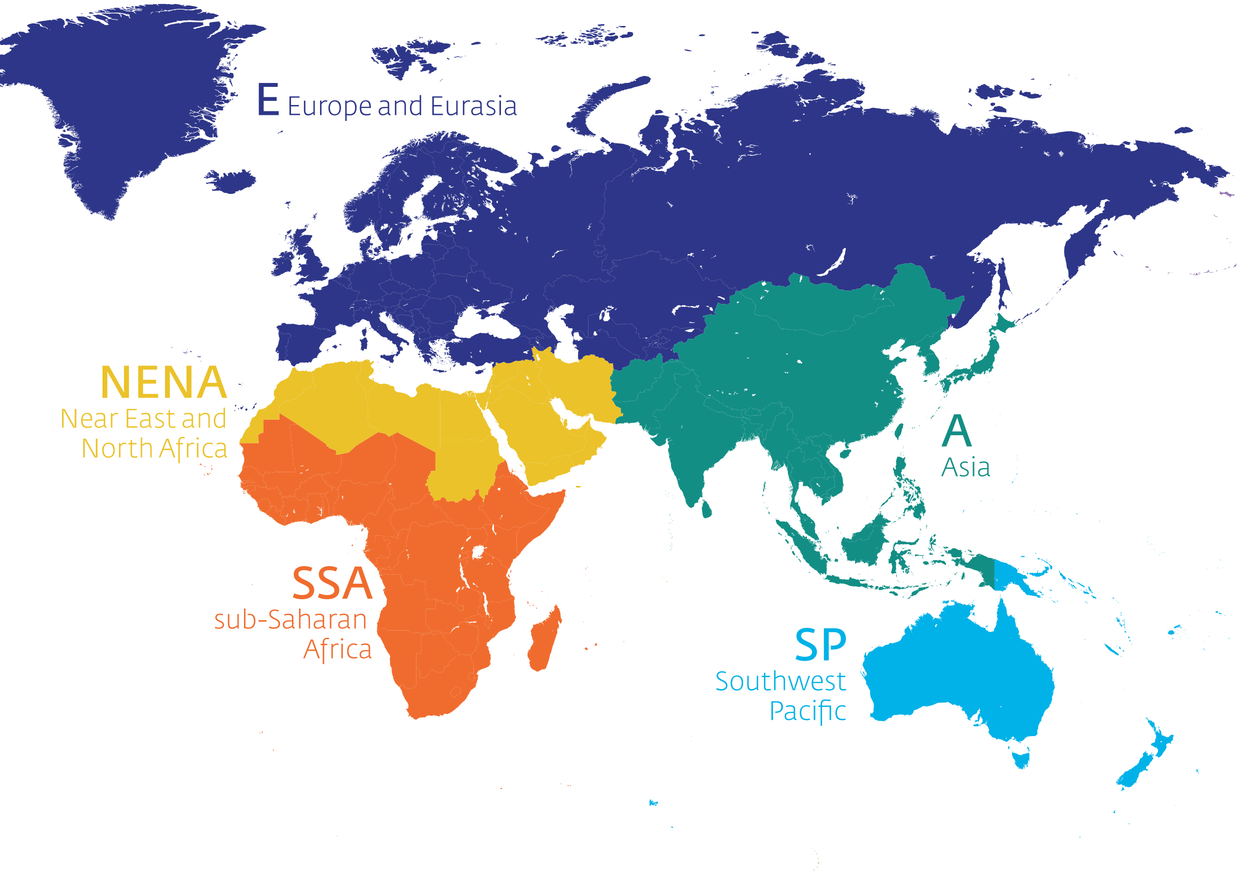


Figure 1 | Regions identified in the Status of the World's Soil Resources report *(FAO and ITPS, 2015)*



Box 2 | Definitions of Soil Threats *(FAO and ITPS, 2015)*

Nutrient imbalance refers to an excess or a lack of nutrients (mainly nitrogen, phosphorus and potassium) in the soil as a consequence of bad land use and management. It may result in soil contamination when nutrients are in excess and in loss of inherent fertility when nutrients are mined.

Soil acidification is defined as the lowering of the soil pH because of the buildup of hydrogen and aluminum ions in the soil and the leaching of base cations such as calcium, magnesium, potassium and sodium. Soil acidification negatively affects soil fertility and compromises the production capacity of most agricultural soils.

Soil biodiversity loss is a decline in the diversity of (micro- and macro-) organisms present in a soil. In turn, this prejudices the ability of soil to provide critical ecosystem services.

Soil compaction is defined as the increase in density and a decline of macro-porosity in a soil that impairs the functions of both the top- and subsoil, and impedes roots penetration and water and gaseous exchanges.

Soil contamination refers to the increase of toxic compounds (heavy metals, pesticides, etc.) in a soil that constitute, directly or indirectly (via the food chain), a hazard for human health and/or for the provision of ecosystem services assured by the soil.

Soil erosion is broadly defined as the removal of (top-) soil from the land surface by running water, wind, ice or gravity. It can be accelerated by human activities (tillage) and animals.

Soil organic carbon loss refers to the decline of organic carbon stock in the soil affecting its fertility status and climate change regulation capacity.

Soil salinization is defined as the increase in water-soluble salts in soil which is responsible for increasing the osmotic pressure of the soil. In turn, this negatively affects plant growth because less water is made available to plants.

Soil sealing refers to the permanent covering of the soil surface with impermeable artificial materials such as asphalt and concrete. This is generally related to urban development and infrastructure construction, which in most cases lead to the absolute loss of the soil resource and of most of its ecosystem services.

Soil sodification is defined as an increase of the exchangeable sodium content of the soil, often accompanied by a loss of soil structure. In turn, it negatively affects soil suitability for crop growth.

Water logging refers to an excess of water on top and/or within the soil, leading to reduced air availability in the soil for long periods.

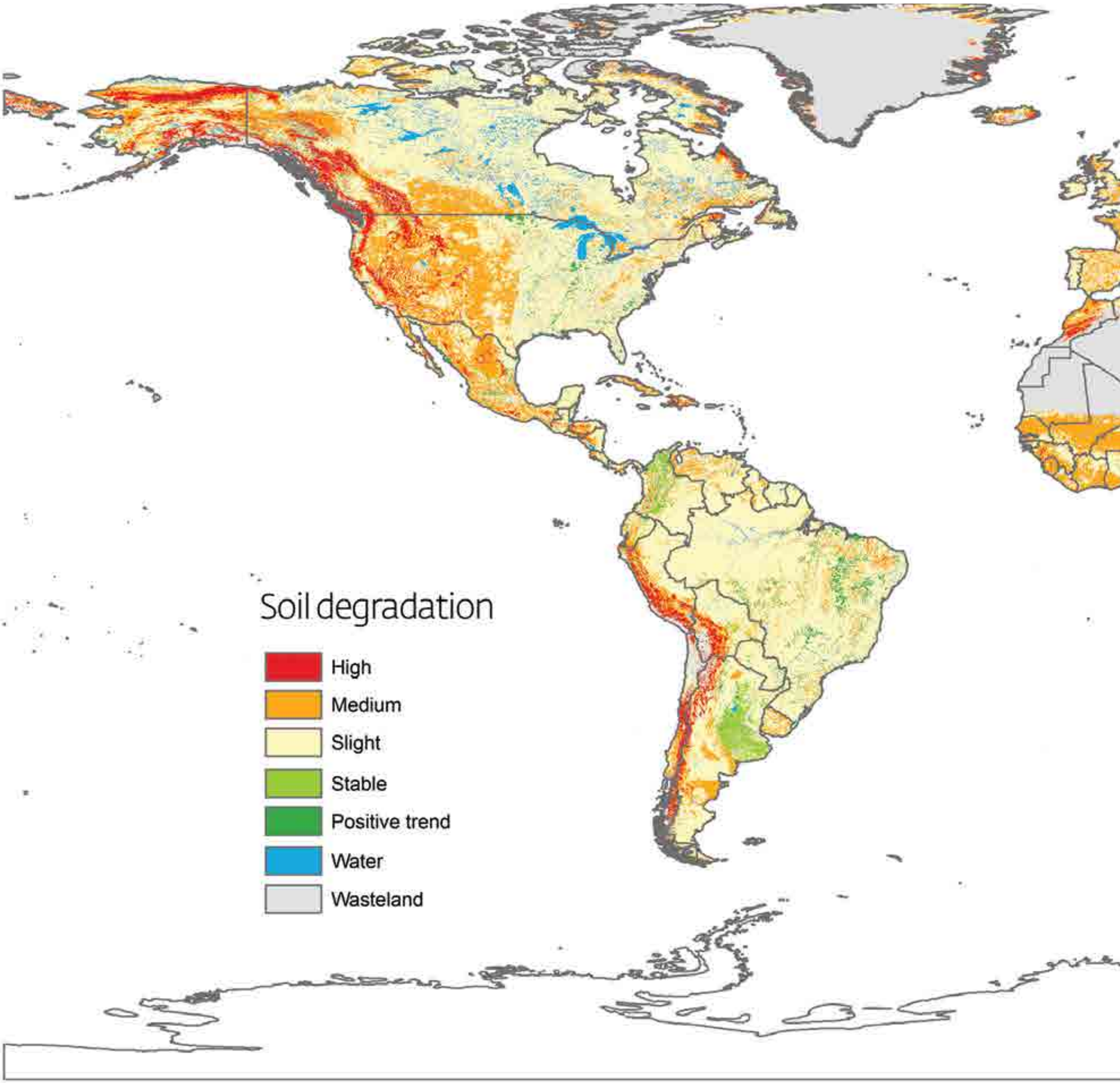
Table 2 | Summary of the condition and trend for the ten soil threats for the regions (excluding Antartica) identified in Figure 1 *(FAO and ITPS, 2015)*

Threat to soil function	Condition and Trend				
	Very poor	Poor	Fair	Good	Very good
Soil erosion	↙ NENA	↙ A ↙ LAC ↙ SSA	↗ E ↗ NA ↗ SP		
Organic carbon change		↗↙ A ↗↙ E ↙ LAC ↙ NENA ↙ SSA	↗ NA ↗↙ SP		
Nutrient imbalance		↙ A ↗↙ E ↙ LAC ↙ SSA ↙ NA	↙ SP	↗↙ NENA	
Salinization and sodification		↗↙ A ↙ E ↙ LAC	↙ NENA ↗↙ SSA	↗ NA ↗↙ SP	
Soil sealing and land take	↙ NENA	↙ A ↙ E	↗↙ LAC ↙ NA	= SSA ↙ SP	
Loss of soil biodiversity		↙ NENA ↙ LAC	↗↙ A ↙ E ↙ SSA	↗↙ NA ↗↙ SP	
Contamination	↙ NENA	↙ A ↗ E	↗↙ LAC	↙ SSA ↗ NA ↗ SP	
Acidification		↙ A ↗↙ E ↗ SSA ↙ NA	↗↙ LAC ↙ SP	↗↙ NENA	
Compaction		↙ A ↙ LAC ↙ NENA	↗↙ E ↗↙ NA ↗↙ SP	= SSA	
Waterlogging			↙ A ↗↙ E = LAC	↗↙ NENA = SSA ↗↙ NA ↗↙ SP	

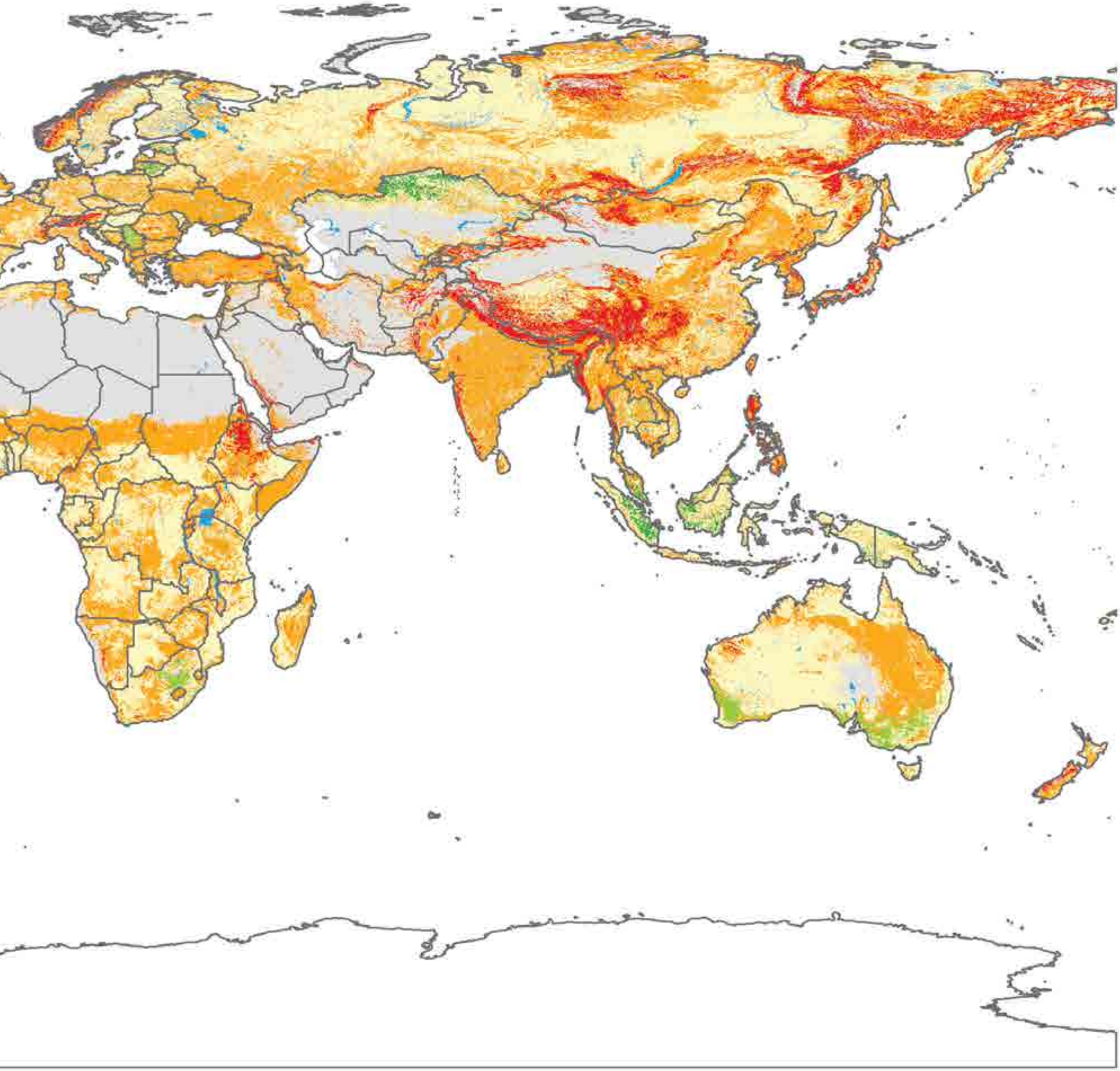
Stable = Variable ↗↙ Improving ↗ Deteriorating ↙

The Land Degradation Assessment in Drylands project (LADA) estimated that 43 percent of rangelands and 20 percent of croplands are degraded, while 33 percent of soils is degraded globally (Vargas et al., 2016). The land degradation classes' map (Figure 2) describes the overall status of the land in provision of biophysical ecosystem services and the processes of declining biophysical ecosystem services.

Figure 2 | Land degradation classes map *(Nachtergaele et al., 2011)*



The 32 percent of land is in areas with high provision of biophysical good and services status, but with medium to strong degradation processes while the largest part of the population 27 percent, lives in areas with a low status and a medium to strong degradation (Nachtergaele et al., 2011).



Drivers of global soil change

Drivers are referred as socio-economic as well as environmental changes operating in spatial and temporal levels in society, differing from one region to another, within and between nations. These include mainly demographics, economic wealth, scientific and technological innovation, markets and trade, distribution patterns, institutional and socio political frameworks, value systems, climate and climate change (FAO and ITPS, 2015).

The primary global drivers of soil change are population growth and economic growth. The 20th century has witnessed extraordinary population and economic growth and an associated revolution in agriculture. Between 1961 and 2000, global population grew by 98 percent but food production rose by 146 percent and per capita food production increased by 24 percent. Crop yields have more than doubled and quite remarkably, the area of arable land in use only increased by eight percent. Arable land per capita reduced substantially (0.45 to 0.25 ha). The key to this period was the dramatic increase in agricultural inputs and advances in crop breeding. The use of nitrogen fertilizer increased by a factor of seven, phosphorous fertilizer by a factor of three and irrigation water by a factor of two. The world population of 7.2 billion in mid-2013 is projected to increase by almost one billion by 2025. It is expected to reach 9.6 billion in 2050 and 10.9 billion in 2100. Most of this growth will occur in low-income countries (e.g., in West Africa). Estimates of global food demand based on these population forecasts and on expected dietary shifts indicate that production in 2050 will need to increase by 40-70 percent compared to 2010.

However, 20th century strategies that simply increase agricultural inputs are problematic because of the implications for global emissions of greenhouse gases, increasing scarcity of inputs and limited availability of cheap water. The global population is also becoming increasingly urbanized. One consequence is widespread urban encroachment onto good quality agricultural land. The rate of soil sealing is now a serious global problem with 66 percent of the global population projected to reside in urban areas by 2050 (54 percent in 2014).

Climate change is a further strong driver of soil change through its current and anticipated effects on land use and management. The impact of climate change on soil functioning is the largest source of uncertainty in any projections of the trends in key ecosystem services provided by the soil. Climate change will have significant impacts on soil resources by, for instance, changing the soil water availability due to changes of quantity and pattern of precipitation and higher temperatures. In turns this will influence the rate of actual evaporation, groundwater recharge, and the generation of runoff according to local conditions. Warming-induced changes in soil temperature and moisture regimes may increase the SOC decomposition rate and the acceleration of the risks of erosion and desertification can have a reinforcing feedback on climate change. A rising sea level associated with climate change will increase coastal erosion and shoreline retreat. In coastal lowlands that are insufficiently defended by sediment supply or embankments, tidal flooding by saline water will tend to penetrate further inland than at present, extending the area of perennially or seasonally saline soils.

1.1.3 | Sustainable soil management

As previously discussed, soil degradation limits the ability of soils to provide those ecosystem services enabling life on Earth and supporting human well-being. Thereafter, it is of critical importance to increase soil health and restore degraded soils in order to achieve sustainable development. In this context, soil health can be boosted through improving crop selection and rotation, keep the soil surface covered, increase the soil organic matter content and practice conservation tillage. A precondition for the successful implementation of sustainable soil management practices is the assessment of actual soil condition, which should drive decisions on the field (Box 3). At a higher level, soil health can be promoted by improving soil governance, increasing investment in sustainable soil management, establish soil information systems, develop capacities and strengthen extension on soils, and implement land use planning. Advocacy and awareness raising are the backbones to actions towards the promotion of sustainable soil management.

Box 3 | Sustainable Soil Management *(FAO, 2015b)*

"Soil management is sustainable if the supporting, provisioning, regulating, and cultural services provided by soil are maintained or enhanced without significantly impairing either the soil functions that enable those services or biodiversity. The balance between the supporting and provisioning services for plant production and the regulating services the soil provides for water quality and availability and for atmospheric greenhouse gas composition is a particular concern."

In order to score soil health and make a decision on the best management practices to adopt, the following soil characteristics should be assessed: soil depth, soil texture, soil structure (tillage pan, aggregate size distribution), soil crust, soil color, soil biota, roots, slaking and dispersion, pH, water infiltration, organic carbon, soil and water salinity. Many manuals such as the "Guidelines for Soil Description" by FAO are available for guiding users through the assessment of the soil conditions. However, most soil properties are affected by the farming system (FAO, 2000).

Sustainable soil management at all levels (local, national and global) require to increase the current investments. That is why awareness raising campaigns should aim at motivating stakeholders in investing on soil resources and providing information on the economics of soil degradation. Similarly to the economics of land degradation as defined by the UNCCD (ELD Initiative, 2014), the economics of soil degradation aim at highlighting the potential benefits derived from adopting sustainable soil management practices and make informed economic decisions. But no decision can be made without consulting well-structured and updated soil data; the development of national and global soil information systems, supported by effective extension programmes, is a crucial tool for practicing sustainable soil management. At this regard, international actions guided by the Global Soil Partnership (GSP) of the Food and Agriculture Organization of the United Nations (FAO) are taking place to enhance the quantity and quality of soil data and information, and harmonize methods, measurements and indicators for the sustainable management and protection of soil resources.

Soil governance concerns policies and strategies and the processes of decision-making by nation states and local governments on how the soil is utilized (FAO, 2016c). Since 2011, a positive momentum for soils has emerged because of the recognized role of soil resources in performing environmental, social and economic functions that enable life on Earth. Documents such as "The Future We Want" were produced and the GSP was established in order to improve soil governance and promote sustainable soil management for various functions. Outcomes of the later were the Revised World Soil Charter, the establishment of the World Soil Day on the 5th of December, the proclamation of 2015 as the International Year of Soils (IYS), the publication of the Status of the World's Soil Resources report, the development of the Voluntary Guidelines for Sustainable Soil Management (VGSSM) and the inclusion of soil into the Sustainable Development Goals (SDGs). The endorsement of the Revised World Soil Charter, the SDGs and the VGSSM are the major political achievements for the promotion of sustainable soil management at the international level of the last three decades (Vargas and Caon, 2016).

1.1.3.1 | Policy instruments for promoting SSM

The Revised World Soil Charter

The first World Soil Charter was conceived and formulated, negotiated and adopted by the FAO member countries in 1981. The Charter was a major normative instrument agreed by member states that focused on land use planning and land evaluation. It called for a commitment to manage soil resources for long-term benefit rather than for short-term expediency but lacked to consider the wide range of ecosystem services provided by soil. Although the 13 principles listed in the charter are still valid, these needed to be updated and revised in light of new scientific knowledge gained over the past 30 years. This regards especially new issues such as soil pollution and its consequences for the environment, climate change adaptation and mitigation and urban sprawl impacts on soil availability and functions. The request for an update was also due to the need to address the outcome document of the United Nations Conferences on Sustainable Development (Rio 92 and 2012), that recognized the soil as important to economic grow, biodiversity, sustainable agriculture and food security, eradicating poverty, empowerment of women, climate change and water availability, in addition to just produce food, fibers and energy (FAO, 2015c).

In this framework, the Intergovernmental Technical Panel on Soils (ITPS) of the GSP was tasked to produce a new version of the World Soil Charter, which was endorsed by the 39th FAO Conference in 2015. The Revised World Soil Charter wants to be a vehicle to promote and institutionalize sustainable soil management at all levels.

Soils in the Sustainable Development Goals

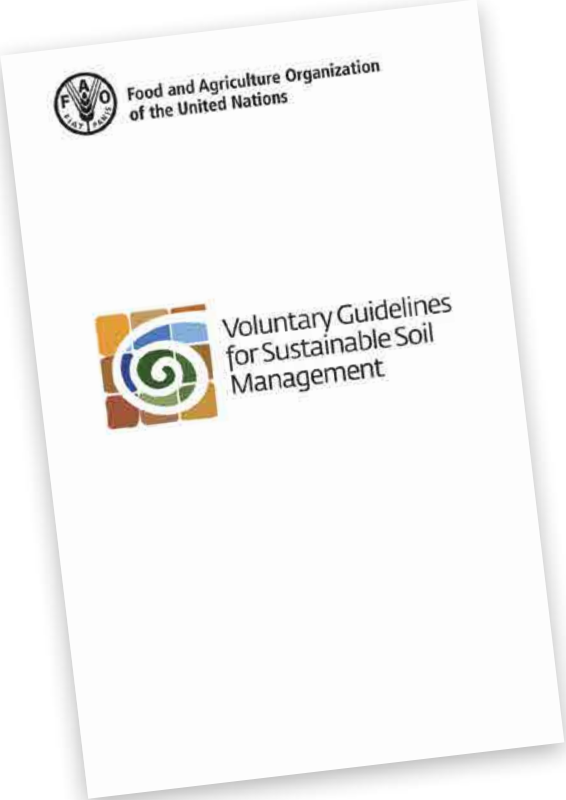
On 25 September 2015, the 193 Member States of the United Nations adopted the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development, global objectives expected to guide actions of the international community over the next 15 years (2016-2030). The SDGs build on the eight Millennium Development Goals (MDGs), but they also represent a shift in the world's vision and approach to development (United Nations, 2016). In this context, soils were recognized as crucial resources for achieving sustainable development so that six out of the 17 goals address soil preservation, management and restoration (see Table 3).

Table 3 | Soil in the SDGs

SDG #	Aim
SDG 2	Improve land and soil quality in order to "end hunger, achieve food security and improved nutrition and promote sustainable agriculture" (target 2.4)
SDG 3	Substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination in order to "ensure healthy lives and promote well-being for all at all ages" (target 3.9). Additionally, physical and mental health at any age are related to the consumption of healthy and nutritious food, which is related to soil quality. Therefore, the achievement of goal 3 by 2030 implies to reduce soil degradation in order to effectively increase food production and guarantee the supply of healthy food for all.
SDG 6	Preserve soils from degradation because of the role they play in guaranteeing the provision of clean water for drinking and agriculture (targets 6.1 and 6.6)
SDG 11	In order to "make cities and human settlements inclusive, safe, resilient and sustainable" effort should be put in protecting soils, which safeguard the world's cultural and natural heritage (target 11.4)
SDG 12	In order to "ensure sustainable consumption and production patterns", it is important to achieve the environmentally sound management of chemicals and all wastes throughout their life-cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment (target 12.4). Thereafter, it is important to sustainably manage and efficiently use soil resources (target 12.2).
SDG 13	Due to the recognized role of soils in sequestering CO_2, sustainable soil management and the restoration of degraded soils are assets in combating climate change and its impacts (target 13.3)
SDG 15	This SDG underlines the importance to "protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss" (targets 15.2 and 15.3)

The Voluntary Guidelines for Sustainable Soil Management

Within the framework of the GSP, Voluntary Guidelines for Sustainable Soil Management (VGSSM) were compiled at the purpose of presenting generally accepted, practically proven and scientifically based principles to promote SSM and to provide guidance to all stakeholders on how to translate these principles into practice, be it for farming, pastoralism, forestry or more general natural resources management. The VGSSM are of voluntary nature and are not legally binding. They elaborate the principles outlined in the revised World Soil Charter, taking into account the evidence provided in the Status of the World's Soil Resources report. The guidelines address technical aspects of sustainable soil management including core characteristics of sustainably managed soils, key challenges and potential solutions to address them. Especially, guidelines advise on (1) how to minimize soil erosion, (2) enhance soil organic matter content, (3) foster soil nutrient balance and cycles, (4) prevent, minimize and mitigate soil salinization and alkalinization, (5) prevent and minimize soil contamination and acidification, (6) preserve and enhance soil biodiversity, (7) minimize soil sealing, (8) prevent and mitigate soil compaction, and (9) improve soil water management (FAO, 2016b).


Food and Agriculture Organization of the United Nations

Voluntary Guidelines for Sustainable Soil Management

1.2 | Putting pulses on the map

Pulses are important food crops that can play a major role in achieving food security, nutrition and human health, contributing to make agriculture more sustainable and helping mitigate and adapt to climate change. However, despite the importance given to pulses by the establishment of the International Year of Pulses 2016 (UN, 2013), pulses are not well known to the most.

Generally, pulses are defined as "the edible seeds of various leguminous crops" (Gove, 1981) or "the edible seeds of leguminous plants" (Little et al., 1992); however, this concept is quite broad because it refers to all legumes species producing edible seeds. In this sense, this definition better applies to "grain legumes". According to FAO (1994), pulses are crop plants belonging to the *Leguminosae* family (commonly known as the pea family) that produce edible seeds and are used for human and animal consumption. However, only legumes harvested for dry grain are classified as pulses. Legume species used for oil extraction, (e.g., soybean *(Glycine max* (L.) Merr.*)*), groundnut *(Arachis hypogaea* L.*)*, and sowing purposes (e.g., clover (different species belonging to the genus *Trifolium* L.) and alfalfa *(Medicago sativa* L.*)*) are not considered pulses. Likewise, legume species are not considered as pulses when they are used as vegetables (e.g., green peas *(Pisum sativum* L.*)* and green beans *(Phaseolus vulgaris* L.*)*). Consequently, when common bean *(Phaseolus vulgaris* L.*)* is harvested for dry grain, it is considered a pulse; but when the same species is harvested unripe (known as green beans), it is not treated as a pulse (Calles, 2016).

Like other legume species, pulses have high protein content (19–33 percent) (Werner, 2005), which make of them an asset in achieving food security worldwide (Box 4). According to Campos-Vega et al. (2010), consumption of pulses may positively impact human health as they can reduce the risk of cardiovascular diseases, prevent diabetes and may protect against obesity, among other things. The importance of pulses in contributing to human health and achieve food security is discussed in chapter 3.2. Pulses are important crops for subsistence farming around the world and one of the major staples of poor smallholder farmers (Martiin, 2013). The basic needs for crop growth are heat, light and moisture. Unfortunately, in many regions of the world yields are low because climate unpredictability and the lack or low bioavailability of nutrients in the soil (Giller and Wilson, 1991). Although large agricultural entrepreneurs solve the plant nutritional problem by applying chemical fertilisers, smallholder farmers that cannot afford to use fertilisers to increase productivity of their crops can use pulses to increase the soil nutrient content.

In this context, one of the most important feature of pulses is their ability to utilize atmospheric nitrogen through a process called “biological nitrogen fixation”, which implies the creation of a symbiosis between the plant roots and soil bacterias. Only relatively few plant genera are able to fix atmospheric nitrogen and most of them belong to the *Leguminosae* family (Giller and Wilson 1991). Biological nitrogen fixation is particularly important for global agricultural productivity and might be considered one of the most important biological processes on the planet (Howieson et al., 2008). Additionally, it provides *circa* 100 million metric tonnes of N which leads to an annual saving of around USD10 billion on N fertilizer (Graham, 2008; Howieson et al., 2008). Besides N, legumes also play a role in freeing soil-bound P, thus making it available either for the companion or subsequent crops (Barber, 1995). Detailed information on the N and P cycles are provided in chapter 2.

The role of pulses in the N and P cycles is ultimately important to adapt to and mitigate climate change, helping to achieve the sustainable development goals (see chapter 3.1). However, climate is also one of the major constrains to pulses’ growth. Nitrogen fixation in the field can be negatively affected by the existing environmental conditions. According to Giller and Wilson (1991), soil temperatures above 50 °C might kill many soil bacteria, including those in symbiosis with pulses. Therefore, the quantity of rhizobia (the soil bacteria established inside the root nodules) in the soil can be drastically reduced when soil drier. These and other factors affecting pulses’ growth and performance in fixing N, need to be taken into account when introducing pulses to areas with environmental conditions different from the optimal. Still, in areas where climate is not a constrain, pulses can play a major role in improving soil structure and contributing to restore degraded soils (see chapters 2 and 3.3, respectively).

Box 4 | Pulses on the table

Cooking time is a major factor limiting the consumption of pulses (Cichy et al., 2015). People’s income has increased in different regions of the world, thus leading to changes in dietary patterns. In order to promote the consumption of pulses, new fast cooking varieties of pulses need to be selected or bred. Selection/breeding of such varieties could be conducted using genome-wide association analysis as suggested by Cichy et al. (2015). Additionally, fast cooking pulses will reduce the energy required for cooking, which is very important for regions where the availability of fire wood is an issue.

1.2.1 | The diversity of pulses

The *Leguminosae* family is divided into three sub-families: *Caesalpinioideae*, *Mimosoideae* and *Papilionoideae* (Lewis et al., 2005). According to Lewis et al. (2005), the sub-family *Papilionoideae* is the largest one and comprises 28 tribes. This sub-family includes all species considered pulses, other important grain legumes like soybean (*Glycine max* (L.) Merr.), groundnut and many important forage species like Brazilian lucerne (*Stylosanthes guianensis* (Aubl.) Sw.), and alfalfa. Taxonomic affinities of those species classified as pulses are presented in Table 4. It is important to note that most pulse species mentioned in this chapter belong to the tribe *Phaseoleae*.

Table 4 | Taxonomic affinities of pulse species

Sub-family	Tribe	Species
Papilionoideae	Genisteae	*Lupinus albus* L. *Lupinus luteus* L. *Lupinus angustifolius* L. *Lupinus mutabilis* Sweet
	Indigofereae	*Cyamopsis tetragonoloba* (L.) Taub.
	Phaseoleae	*Canavalia ensiformis* (L.) DC. *Mucuna pruriens* (L.) DC. *Cajanus cajan* (L.) Huth *Psophocarpus tetragonolobus* (L.) DC. *Sphenostylis stenocarpa* (Hochst. ex A. Rich.) Harms *Lablab purpureus* (L.) Sweet *Vigna angularis* (Willd.) Ohwi and H. Ohashi *Vigna radiata* (L.) R. Wilczek *Vigna mungo* (L.) Hepper *Vigna umbellata* (Thunb.) Ohwi and H. Ohashi *Vigna aconitifolia* (Jacq.) Maréchal *Vigna unguiculata* (L.) Walp. *Vigna subterranea* (L.) Verdc. *Phaseolus vulgaris* L. *Phaseolus lunatus* L. *Phaseolus coccineus* L. *Phaseolus acutifolius* A. Gray
	Cicereae	*Cicer arietinum* L.
	Fabeae	*Vicia faba* L. *Vicia sativa* L. *Lens culinaris* Medik. *Pisum sativum* L.

Although there is a large number of legumes species that could be placed in the category of pulses, only those classified as pulses by the FAO are herewith discussed (FAO, 1994). The classification made by FAO (Table 5) considers only those pulse species which have certain relevance in economic markets. Nevertheless, there are a large number of legumes species like Kersting's groundnut *(Macrotyloma geocarpum* (Harms) Maréchal and Baudet) that can be classified as pulses (Tindall, 1983).

Table 5 | Classification of pulses according to FAO (1994), including world production quantities

Fao Code	Commodity	Remarks[1]	Production[2]
176	Beans, dry	This is aggregated category which includes the following species: 1) common bean *(Phaseolus vulgaris)*, 2) lima bean *(Phaseolus lunatus)*, 3) scarlet runner bean *(Phaseolus coccineus)*, 4) tepary bean *(Phaseolus acutifolius)*, 5) adzuki bean *(Vigna angularis)*, 6) mung bean *(Vigna radiata)*, 7) mungo bean *(Vigna mungo)*, 8) rice bean *(Vigna umbellata)* and 9) moth bean *(Vigna aconitifolia)*.	25 093 616
191	Chickpeas	This category only includes chickpea *(Cicer arietinum)*.	14 239 010
187	Peas, dry	This category only includes pea *(Pisum sativum)*.	11 332 772
195	Cowpeas, dry	This category only includes cowpea *(Vigna unguiculata)*.	5 588 947
201	Lentils	This category only includes lentil *(Lens culinaris)*	4 885 271
197	Pigeon peas	This category only includes pigeon pea *(Cajanus cajan)*.	4 858 102
181	Broad beans	This category only includes broad bean *(Vicia faba)*.	4 297 465
210	Lupins	This category includes several species of the genus *Lupinus* L.	981 480
205	Vetches	This category only includes vetch *(Vicia sativa)*.	883 238
203	Bambara beans	This category only includes Bambara beans *(Vigna subterranea)*	287 793
211	Pulses, nes[3]	This is aggregated which includes species of minor relevance at international level: 1) hyacinth bean *(Lablab purpureus)*, 2) jack bean *(Canavalia ensiformis)*, 3) winged bean *(Psophocarpus tetragonolobus)*, 4) guar bean *(Cyamopsis tetragonoloba)*, 5) velvet bean *(Mucuna pruriens)* and 6) African yam bean *(Sphenostylis stenocarpa)*.	5 151 560

[1] *Scientific names are sourced from the updated taxonomic database Tropicos (MBG, 2016).*

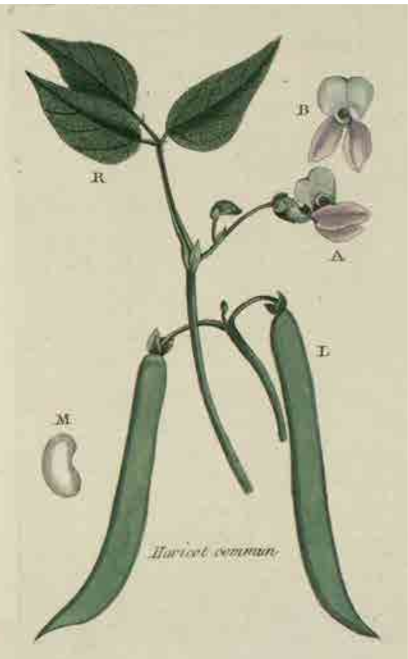
[2] *The unit of measurement is tonnes.*

[3] *Stand for "not elsewhere specified".*

The major categories of pulses can be described as follows:

Beans, dry

The "beans, dry" category (hereafter referred to as beans) was originally established to include only species belonging to the genus *Phaseolus* L. However, recent taxonomic studies have brought new evidence to bear on species delimitations in the genus *Phaseolus*. Consequently, five species originally assigned to this category are now treated as *Vigna* Savi (i.e., *Vigna angularis*, *V. radiata*, *V. mungo*, *V. umbellata* and *V. aconitifolia*). This situation has created some confusion because some FAOSTAT users assume that the category beans still includes only *Phaseolus* species and, what is more problematic, some users take for granted that beans only include the widely cultivated common bean species (*Phaseolus vulgaris*) (Deshpande et al., 1982; Eitzinger et al., 2016). For this reason, this category probably needs to be disaggregated in future, especially since beans are the pulses with the highest global production (see Table 6).



Phaseolus vulgaris - P. Bulliard
Bulliard, P., Flora Parisiensis, vol. 7: t. 507 (1776-1781)
Bibliothèque de l'Université de Strasbourg, France

Archaeological finds indicate that the genus *Phaseolus* originated exclusively from the Americas (Debouck and Hidalgo, 1985). Currently, four species are of economic importance, namely common, lima, scarlet runner and tepary beans (*Phaseolus vulgaris*, *P. lunatus*, *P. coccineus*, *and P. acutifolius*, respectively), of which the common bean is the most widely cultivated.

Contrary to *Phaseolus*, the genus *Vigna* has a pantropical distribution and the pulses of economic importance within this genus originated either from Africa or Asia (Chomchalow et al., 1993; Lewis et al., 2005). All species listed under the category beans (e.g., *Vigna angularis*, *V. radiata*, *V. mungo*, *V. umbellata* and *V. aconitifolia*) originated from Asia, although the exact site of origin of some of these species has not been identified (Chomchalow et al., 1993). *Vigna angularis* probably originated from China where some wild types have been found (Lee, 1993). Likewise, wild types of *Vigna umbellata* have been found in India, Central China and Malaysia; therefore, South and Southeast Asia is considered the centre of origin (Lampang, 1993). There is important evidence indicating that *Vigna aconitifolia*, *V. mungo* and *V. radiata* originated within the boundaries of what is India today (Fuller and Harvey, 2006).

India, Myanmar and Brazil are the largest producers of beans (FAO, 2014). However, due to the aggregated nature of the bean category, it does not reflect the Indian production quantity in this category is mainly based on *Vigna* species, while the Brazilian production quantity is mainly based on *Phaseolus* species.

Chickpeas

The "chickpeas" category is not aggregated and includes only the species *Cicer arietinum*. Even so, chickpeas are the pulses with the second highest global production (see Table 6). Based on archaeological remains, it is generally accepted that chickpeas originated in the present-day border region of Turkey and Syria (southeast Turkey) where three species closely related to chickpea are found (van der Maesen, 1987; Millán et al., 2016). Chickpea is listed as one of the first domesticated pulses, together with other important crops like wheat and barley (Millán et al, 2016). India, Australia and Pakistan are the largest chickpea producers (FAO, 2014). Chickpeas production in Iran is reported as case study in Box 5.

Cicer Arietinum
Rare Book Division, The New York Public Library.
(1772 - 1793).

Box 5 | Case Study: Chickpeas production in Iran

Drought is a common abiotic stress limiting chickpea production in different parts of Iran (Sabaghpour, 2005). Chickpea and lentil frequently suffers from drought stress towards the end of the growing season. After flowering and during pod setting and seed formation, drought is often accompanied by heat stress under rain-fed conditions (Sabaghpour, 2004). Terminal drought stress considerably reduces chickpea productivity during spring planting in comparison to autumn and entezari sowing. Research (Sabaghpour, 2006) was positive about the possibility to plant chickpea in autumn, lentil in milder environments and entzari planting in harsh (severely cold) environments.

Peas, dry

The "peas, dry" category (hereafter refer to as peas) is not aggregated and includes only the species *Pisum sativum*. Peas are the pulses with the third highest world production (see Table 6). There is archaeological evidence which confirms the existence of pea in the Near East and Central Asia as far back as 10 000 years BC. This makes pea one of the world's oldest domesticated crops (Warkentin et al., 2016). Canada, China and Russia are the largest pea producers (FAO, 2014)

Pisum sativum
Rare Book Division, The New York Public Library
(1772 - 1793)

Cowpeas, dry

The "cowpeas, dry" category (hereafter refer to as cowpeas) is not aggregated and includes only the species *Vigna unguiculata*. Cowpeas are the pulses with the fourth highest world production (see Table 6). There is controversy regarding whether the centre of origin for cowpeas is located in Asia or Africa (Luadtong, 1993); however, since wild types of cowpeas have only been found in Africa, it has been accepted that cowpea should have originated in Africa (Maréchal, 1978; Smartt, 1990). Nigeria, Niger and Burkina Faso are the largest cowpea producers (FAO, 2014).

Vigna unguiculata
Blanco, M., Flora de Filipinas, t. 285
(1875)

Lentils

The "lentils" category is not aggregated and includes only the species *Lens culinaris*. Lentils are the pulses with the sixth highest global production (see Table 6). It is generally accepted that lentils were domesticated in the Fertile Crescent region in the Middle East within the boundaries of what is Iraq today. This is the same region where humankind changed from hunter-gatherers to agriculturalists. Like chickpeas and peas, lentils were one of the first domesticated pulses (Stefaniak and McPhee, 2016). Canada, India and Australia are the largest lentil producers (FAO, 2014).

Lens culinaris
Thomé, O.W., Flora von Deutschland Österreich und der Schweiz, Tafeln, vol. 3: t. 450 (1885)
www.BioLib.de

Pigeon peas

The "pigeon peas" category is not aggregated and includes only the species *Cajanus cajan*. Pigeon peas are the pulses with the seventh highest global production (see Table 6). According to Tindall (1983), pigeon peas originated from tropical Africa; however, India is currently considered the most probable centre of origin since the closest wild relative *(Cajanus cajanifolius* (Haines) Maesen*)* is also found in this region (Fuller and Harvey, 2006). Nevertheless, pigeon peas are currently cultivated in Africa, Asia and the Americas. India, Myanmar and Malawi are the largest pigeon pea producers (FAO, 2014).

Cajanus cajan
Blanco, M., Flora de Filipinas, t. 167 (1875)

Broad beans

The “broad beans” category is not aggregated and includes only the species *Vicia faba*. Broad beans are the pulses with the eighth highest global production (see Table 6). Broad bean is also an ancient crop together with chickpea, peas and lentils. The exact site of origin of broad beans has not been identified (Maxted, 1995); however, domestication of broad beans most probably occurred in the Fertile Crescent region where several archaeological remains have been found (Duc et al., 2016). China, Ethiopia and Australia are the largest producers of broad beans (FAO, 2014).

Vicia faba
Rare Book Division, The New York Public Library.
(1772 - 1793)

Lupins

The “lupins” category is aggregated and includes several species of the genus *Lupinus*. Lupins are the pulses with the ninth highest world production (see Table 6). Currently, four species are of economic importance: *Lupinus albus*, *L. angustifolius*, *L. luteus* and *L. mutabilis*. The Balkans is most probably the centre of diversity of *Lupinus albus* while *L. luteus* may have originated from the western Mediterranean where genetic diversity of this species is very high. On the other hand, the centre of origin for *L. mutabilis* is located in the new world, in the central Andes while it is not clearly defined where the centre of *L. angustifolius* is located (Cowling et al., 1998). Australia, Poland and Russia are the largest producers of lupins (FAO, 2014).

Lupinus
Zorn, J., Oskamp, D.L., Afbeeldingen der artseny-gewassen met derzelver Nederduitsche en Latynsche beschryvingen, vol. 5: t. 404 (1800)
www.BioLib.de

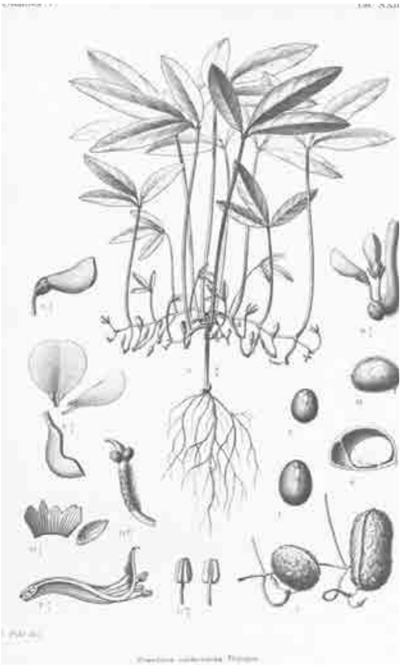
Vetches

The “vetches” category is not aggregated and includes only the species *Vicia sativa* (common vetch). Vetches are the pulses with the tenth highest world production (see Table 6). Common vetch is native to southern Europe (Frame, 2005). This species is mainly used in animal nutrition (FAO, 1994) and Ethiopia, Russia and Mexico are the largest producers of common vetches (FAO, 2014).

Vicia Sativa
Thomé, O.W., Flora von Deutschland Österreich und der Schweiz, Tafeln, vol. 3: t. 449 (1885)
www.BioLib.de

Bambara beans

The “bambara beans” category is not aggregated and includes only the species *Vigna subterranea*. Bambara beans are the pulses with the eleventh highest world production (see Table 6). It is generally accepted that Bambara bean is native to the African continent; however, the exact area where the species originated is a matter of debate (Heller et al., 1997). Bambara bean is mainly cultivated in Africa, with Mali, Burkina Faso and Cameroon as the largest producers (FAO, 2014).



Vigna subterranea
A. Engler (1844-1930) - Die Pflanzenwelt Ostafrikas und der Nachbargebiete vol. 2 tabl. 22
Wikipedia

Pulses, nes

The "pulses, nes" category is aggregated and includes several pulse species of minor relevance at international level. The "pulses, nes", as an aggregate, are the pulses with the fifth highest world production (see Table 6). The likely centre of origin for *Lablab purpureus*, *Psophocarpus tetragonolobus*, *Cyamopsis tetragonoloba* and *Mucuna pruriens* is Asia, though the exact site of origin of some species is still debated; Canavalia ensiformis' centre of origin is Central America and the Caribbean while *Sphenostylis stenocarpa* originated in Africa (Wihstler and Hymowitz, 1979; Tindall, 1983; Chomchalow et al., 1993). The largest producers of "pulses, nes" are India, Australia and Russia (FAO, 2014)

Lablab purpureus
Blanco, M., Flora de Filipinas, t. 292 (1875)
Wikipedia

According to IIPR (2011), dry beans contributed about 32 percent to global pulses production followed by dry peas (17 percent), chickpea (15.9 percent), broad beans (7.5 percent), lentils (5.7 percent), cowpeas (6 percent) and pigeonpea (4.0 percent). In the triennium 2007-2009, average production of 61.2 million tonnes shows a positive annual growth of 0.7 percent per annum over 55.03 million tonnes recorded in 1997. Comparative data from the 1980's revealed phenomenal annual growth of 2.85 percent which was mainly attributed to positive growth of 0.87 percent in surface area od production and 1.83 percent in productivity. Developing countries contribute about 74 percent to the global pulse production. India, China, Brazil, Canada, Myanmar and Australia are the major pulse producing countries with relative shares of 25 percent, 10 percent, 5 percent, 5 percent and 4 percent, respectively.

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\2 | Pulses as architects of soil health

Pulses contribute to soil health in various ways. They are responsible for the biological fixation of atmospheric nitrogen and for the solubilisation of phosphate ions from bound forms such as calcium and iron phosphates to make these nutrients available to plants. Besides their role in the nitrogen and phosphorous cycles, pulses also contribute to increasing soil organic matter, improving soil structure and maintaining soil biodiversity, leading to overall increased soil health.

2.1 | The role of pulses in nutrient (re)cycling

Soil health is one of the most relevant dimensions for which land management efforts have to be intensified in order to achieve environmental sustainability. As defined by Doran et al. (1994), soil quality is "the ability of soils to interact with the ecosystem in order to maintain the biological productivity, the environmental quality and to promote animal and vegetal health". Soil fertility refers to the ability of the soil to support and sustain plant growth, including through making N, P and other nutrients available for plant uptake (FAO and ITPS, 2015). Nutrient exchanges between organic matter, water and soil are essential to soil fertility and need to be maintained for sustainable production purposes. When the soil is exploited for crop production without restoring the organic matter and nutrient content, the nutrient cycles are broken, soil fertility declines and the balance in the agro-ecosystem is destroyed (FAO, 2015). In this context, the rhizosphere microbiome can play an important role in the nutrient cycle (Mommer et al., 2016; Berg et al., 2014).

Plants require at least 16 elements to complete their life cycle, these are: carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), molybdenum (Mo), boron (B), and chlorine (Cl). In addition to the above, some of the lower plants further require cobalt (Co), vanadium (V) and silicon (Si). Of all these elements, C, H, O, N, P, K, Ca, Mg and S are required in large quantities and are therefore called macronutrients, while all the others are called micronutrients. The elements C, H, and O are obtained mainly from air and water and the rest from the soil (Loganathan, 1987). The macro and micro (or trace) elements are made available to plants by breakdown of the mineral and organic matter in the soil. Availability of these nutrients depends on how much is present in the soil, the form in which it is present, the rate at which it is released from organic matter or mineral particles and the soil pH (e.g., its acidity or alkalinity) (FAO and ITPS, 2015).

Other sources of nutrients in the soil and plant system are (Lal, 2004):

1. Decomposition of plant residues, animals remains, and soil microorganisms;
2. Fertilizer applications including mineral N, mineralizable N, soil nitrate, soil P, K, S, Ca, Mg, B and Zn;
3. Composts, organic amendments and manures (animal, vegetable);
4. Microbial-based fertiliser;
5. N-fixation by legumes;
6. Inorganic industrial by-products;
7. Atmospheric deposition; and
8. Deposition of nutrient-rich sediment from erosion and flooding.

The proportion of nutrients held on the clay and humus particles influence deficiencies such as K, Ca and Mg which are held on the surface of clay particles and are directly taken up by plant roots from the soil solution. An excess of K can create a deficiency of Ca or *vice versa*, while acid soils high in Mn often cannot supply enough Co for rizhobium bacteria, with a consequent effect on N fixation by legumes. Also, in very acid soils, Mn and Fe make P unavailable to plants by "fixing" it in insoluble complexes. The chemical relationships influencing soil fertility are complex and affected by the parent material from which soil develops, the type of clay present, and the proportions of different sized particles (e.g. sand, silt, clay), which also have important effects on soil structure (FAO and ITPS, 2015).

Soil fertility can be maintained when nutrients are efficiently recycled through the soil food web and the soil-plant-microbe-animal system (Watson, 2002). During these biogeochemical processes, analogous to the water cycle, nutrients can be transformed into plant available forms, held in the soil, or even lost to air or water. Overall, the fertility and functioning of soil strongly depends on interactions between the soil mineral matrix, plants and microbes; these are responsible for both building and decomposing the soil organic matter (SOM) and therefore for the preservation and availability of nutrients in soils. To sustain this service, the balanced cycling of nutrients in soils must be preserved (FAO and ITPS, 2015).

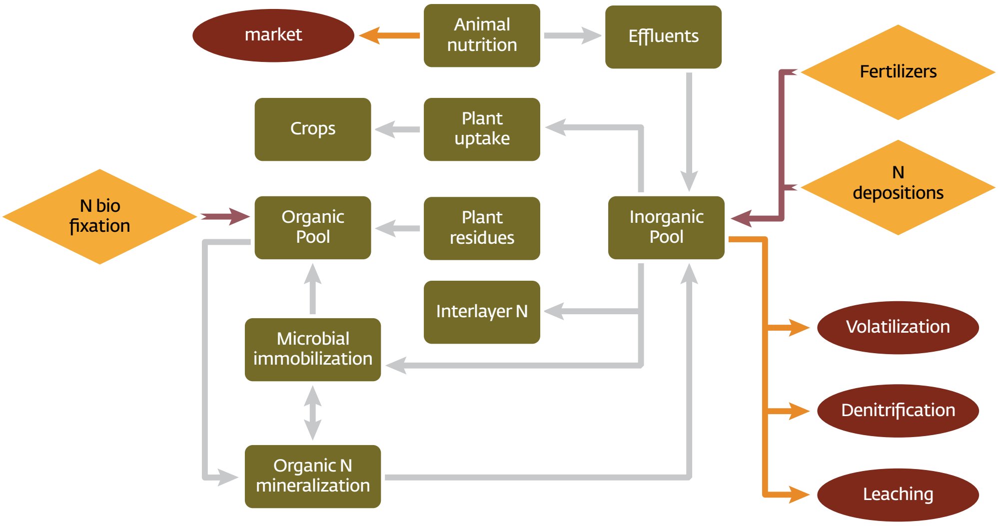
Decomposition by soil microorganisms is at the center of the transformation and cycling of nutrients through the environment. Decomposition returns carbon and nutrients from the complex material (plant resides and manure from animal and forage, plant-derived products, plant-derived foods) to the soil. Decomposition breaks down organic matter and returns these components into biological circulation so that they are available to plants and other organisms (Bot and Benites, 2005). Pulses, and legumes in general, therefore play an important role in the nitrogen and phosphorus cycles due to the symbiosis between the plant roots and the soil bacteria.

2.1.1 | Nitrogen Cycle

After carbon, N is the most abundant nutrient in all forms of life, since it is contained in proteins, nucleic acids and various other compounds. Humans and animals ultimately acquire their N from plants, which in terrestrial ecosystems occurs mostly in mineral form (e.g. NH_4^+ and NO_3^-) in the soil. The parent material of soils does not contain significant amounts of N (as opposed to P and other nutrients), and new N enters the soil through the fixation of atmospheric N_2 by a specialized group of soil biota. However, the largest flux of N into soils is generated through the continuous recycling of internal N into the plant-soil system: soil mineral N is taken up by the plant, it is fixed into biomass, and eventually N returns to the soil in the form of plant debris. Here, plant debris is decomposed by the soil biota and part of the N is mineralized to make it newly available for plant growth. Part of the plant debris is transformed into soil organic matter (SOM) and the remainder of the plant N contained therein ultimately comprises the largest stock of stable N in soil. Nitrogen is lost from the soil to the water system by leaching and to the atmosphere by gas afflux (NH_3, N_2O and N_2). In most ecosystems, N availability can limit productivity and it is therefore necessary to ensure that N is effectively cycled in the soil-plant system with minimal losses (FAO and ITPS, 2015).

Nitrogen exists in many forms and different physical states in both organic and inorganic compounds, so transformations between these forms make the N-cycle rather complex (see Figure 3).

Figure 3 | Nitrogen Cycle *(Modified from Benedetti, 1995)*



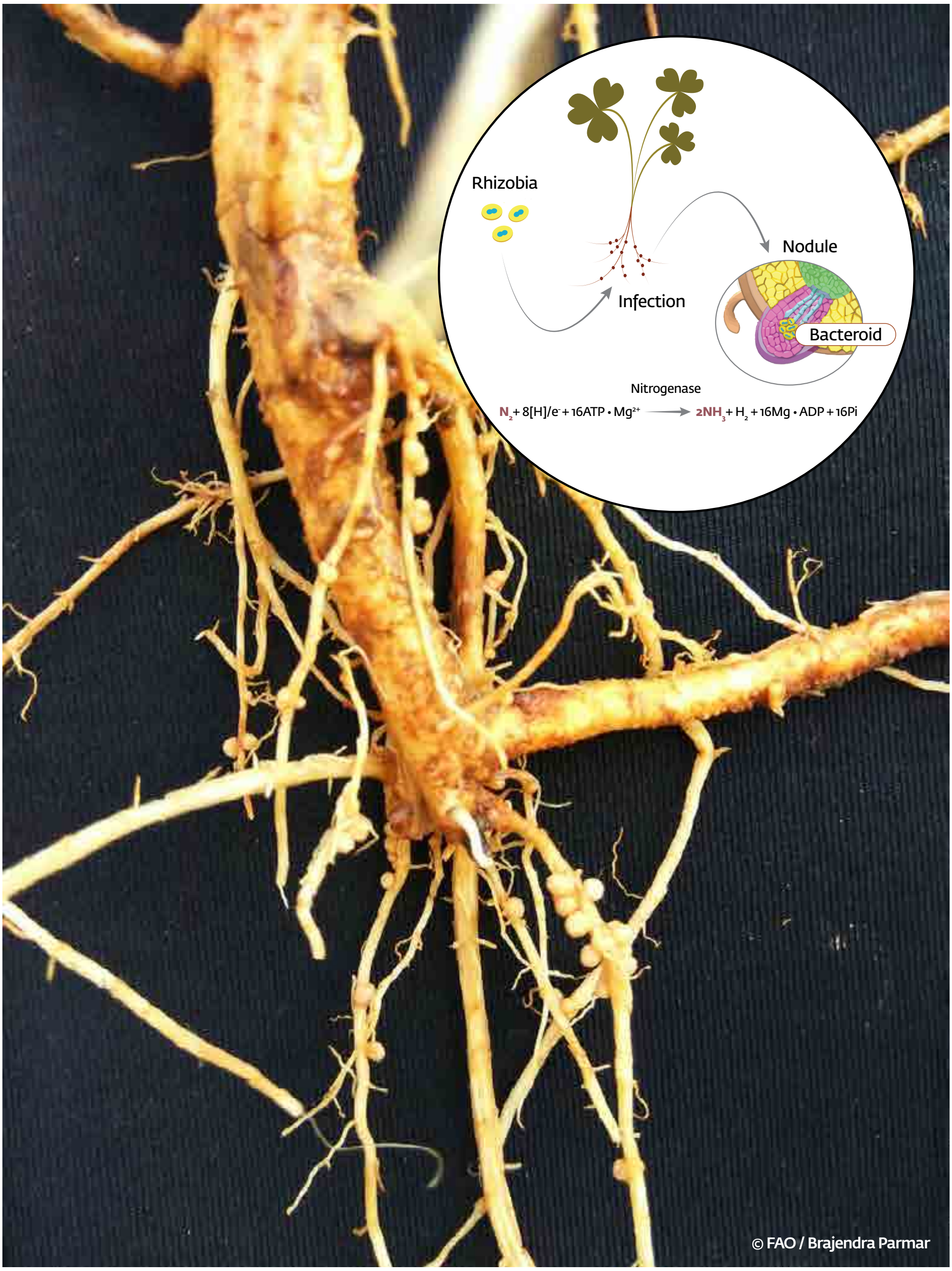
According to (Robertson and Groffman, 2015), the main sources of biochemical N transformations are:

- **Nitrification** – conversion of ammonium-N (a cation held in soil by CEC) to nitrate-N (a soluble anion easily lost in runoff or leaching);
- **Denitrification** – conversion of plant-available nitrate-N to N-gases that are unavailable to plants and easily lost from soil;
- **Mineralization** – biological breakdown of organic-N and release as plant-available ammonium-N;
- **Immobilization** (assimilation) – uptake of inorganic-N from soil and incorporation into organic-N compounds in microbes (N becomes unavailable to plants);
- **N-Fixation** – conversion of N-gas in the air to organic-N that becomes available to plants (performed by bacteria associated with roots of legumes and other plants, and some free-living soil microbes); and
- **Biological** transformations of nitrogen.

Looking at the contribution of legumes (pulses) to the N cycle, special attention is given to Biological Nitrogen Fixation (BNF). These plants, in symbiosis with certain types of bacteria are able to convert atmospheric nitrogen (N_2) into nitrogen compounds (ammonium) that can be used by plants, while also improving soil fertility (FAO, 2016a). The symbiosis occurs in nodules formed on the plant roots, where the nitrogen-fixing bacteria are hosted (see Figure 4 and Box 6). The most common type of symbiosis occurs between members of the plant family *Leguminosae* and soil bacteria of the genera *Azorhizobium*, *Bradyrhizobiurn*, *Photorhizobium*, *Rhizobium*, and *Sinorhizobium* (collectively called *rhizobia*). Because nitrogen fixation involves the transfer of large amounts of energy, the nitrogenase enzymes that catalyze these reactions have sites that facilitate the high-energy exchange of electrons. Oxygen, being a strong electron acceptor, can damage these sites and irreversibly inactivate nitrogenase, so nitrogen must be fixed under anaerobic conditions (Zahran, 1998).

Figure 4 | Picture showing nitrogen fixation, in red gram (pigeon peas)

Modified from Teng et al. (2015)



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Legumes and actinorhizal plants regulate gas permeability in their nodules, maintaining a level of oxygen within the nodule that can support respiration, but is sufficiently low to avoid inactivation of the nitrogenase (Kuzma et al., 1993). Lectin activation directs particular rhizobia to appropriate hosts and facilitates attachment of the rhizobia to the cell walls of a root hair (Van Rhijn et al., 1998; Etzler et al., 1999). Nodule formation involves two simultaneous processes, namely 1) infection and 2) nodule organogenesis. During the infection process, rhizobia that are attached to the root hairs release Nod factors, inducing a pronounced curling of the root hair cells. The rhizobia become enclosed in the small compartment formed by the curling. The nodule as a whole develops such features as a vascular system (which facilitates the exchange of fixed nitrogen produced by the bacteroids for nutrients contributed by the plant) and a layer of cells to exclude from the root nodule interior. In some temperate legumes (e.g., peas), the nodules are elongated and cylindrical because of the presence of a nodule meristem (Belimov et al., 1995). The nodules of tropical legumes, such as soybeans and peanuts, lack a persistent meristem and are spherical (Rolfe and Gresshoff, 1988).

The effectiveness of legumes in biological N_2 fixation is very variable and dependent on environmental, nutritional, biological and genetic factors. Therefore, their effect on soil fertility is also likely to be variable according to different management regimes. The level of N_2 fixation is generally related to the health status of the host plant and is therefore affected by factors affecting plant growth such as water, temperature, nutrients and light. However, since N_2 fixation is the product of symbiosis between the host legume and the bacterium, factors affecting the bacterium may also affect the host plant. Hence, the level of N_2 fixation may also be influenced by factors that specifically affect the activity of the rhizobium rather than the host such as temperature, soil pH, nutritional status (particularly N and Mo) and others (Haque et al., 1986).

Provision of nitrogen derived from BNF to the subsequent crops ('nitrogen effect') increases yields especially where subsequent crops receive low or moderate levels of fertiliser. The nitrogen effect has been reviewed in detail by various authors (Chalk, 1998; Giambalvo et al., 2004; Peoples et al., 2009b; Köpke and Nemecek, 2010). Extensive research on the N contributions of legumes has revealed considerable difficulties in accounting for the below-ground plant N, plant N that is mobilised over time, site- and management-specific factors, and alternative paths of N take-up. Under alternative paths in N take-up such as 'pool substitution', the labelled legume N is immobilized by soil bacteria and older N from the soil nutrient pool is mineralised and taken up by the subsequent crop instead. High amounts of increased N uptake in subsequent crops results from uptake of N from BNF or through 'pool substitution', as well as enhanced root health, root growth, and mineralization (Kirkegaard et al., 2008, Peoples et al., 2009a).

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Box 6 | Inoculation

Inoculation is the process of introducing the appropriate Rhizobium bacteria to the soil in sufficient numbers to ensure successful nodulation using products called nitrogen inoculants (Kremer and Peterson, 1982). The aim of inoculation is to provide sufficient numbers of viable and effective rhizobia to induce rapid colonization of the rhizosphere allowing nodulation to take place as soon as possible after germination and produce optimum yields (Thompson, 1988). The efficacy of inoculation varies as a function of several factors, all of which affect the number of viable rhizobia available for infection of legume roots (Deaker et. al., 2004). Inoculation is done by coating the seed with a liquid or peat-based powder inoculant, or by treating the soil with granular or liquid inoculants (Domergues et.al., 1979). Rhizobia invade the roots of legumes and form nodules which become miniature 'fertilizer factories', taking nitrogen from the air and supplying up to 50 percent or more of the pulse crop's requirements. Rhizobium bacteria are not very mobile in the soil, so the inoculant must come in direct contact with the developing seedling for infection of root hairs to occur. Specific pulse crops require specific Rhizobium species for nodulation (Tilak and Singh, 1994), for example, a Rhizobium species capable of nodulation in lentil and pea crops is not capable of inducing nodulation in chickpea, see table 6. Hence, if the wrong Rhizobium species is used, inoculation will have no beneficial effect. Soils commonly lack sufficient numbers of the correct Rhizobium bacteria to optimize the nitrogen fixation process and inoculation is therefore very important (Subba Rao et al., 1993).

Table 6 | Cross inoculation groups of Rhizobium *(Subba Rao et al., 1993)*

Rhizobium sp.	Cross Inoculation group	Legume Types
R. legumnosarum	Pea Group	Pisum, Vicia, Lens
R. phaseoli	Bean group	Phaseolus
R. trifolii	Clover group	Trifolium
R. melloti	Alfalfa group	Melilotus,Medicago,Trigonella
R. lupini	Lupini group	Lupinous,Orinthopus
R. japonicum	Soybean group	Glycine
Rhizobium sp.	Cowpea group	Vigna, Arachis

Each pulse crop supplies a different amount of its own nitrogen requirement. For instance, dry beans can derive up to about 50 percent of their requirement, peas and lentils can derive up to 80 percent, and fababeans up to 90 percent. So each crop has a different ability to derive nitrogen from the air. In other words, fababeans are great fixers of nitrogen, peas and lentils are good, but dry beans are medium nitrogen fixers (Domergues et al., 1979). Since rhizobium bacteria are specific to each pulse crop, industry has developed different types of inoculants to be used on different types of pulses and there are various inoculant products available. Some are more convenient to use than others, so growers should pick the one best suited to their crops and needs (Kumar, 2003). Some commonly used inoculant types are:

Dry peat-based inoculants: This seed-applied inoculant is the most common type of inoculant sold in Canada. The peat carrier serves to feed the rhizobia and prolong their survival in the soil until the roots are ready to be nodulated.

Liquid inoculants: Liquid inoculants are packaged in plastic bladders that allow the rhizobia to breathe and remain healthy during storage.

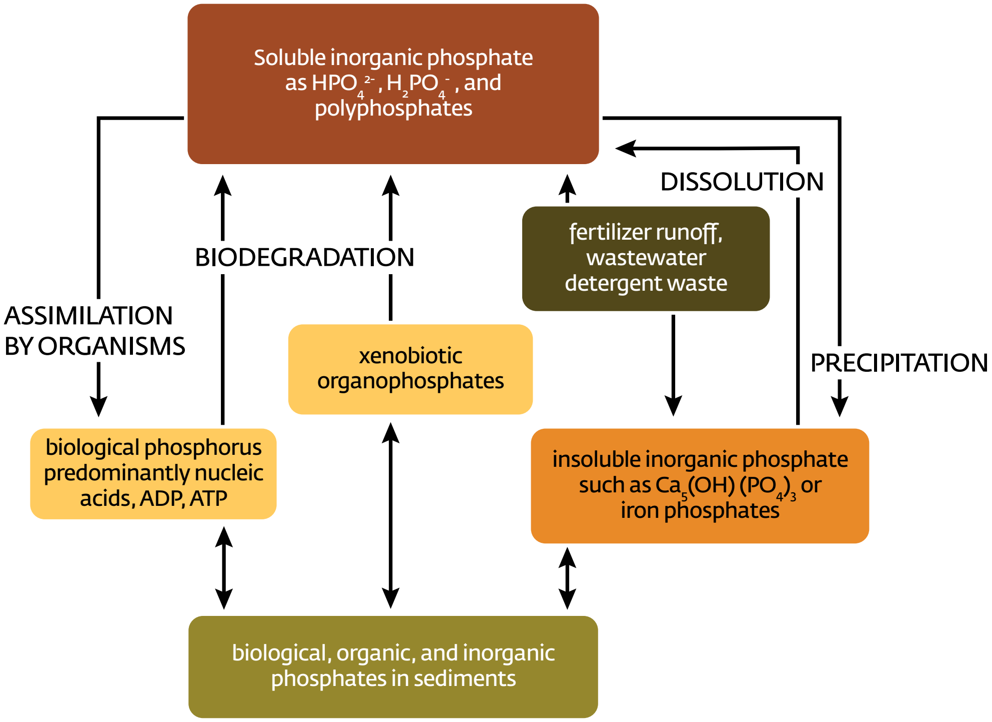
Granular inoculants: The small granules of granular inoculants are designed to be applied at low but very uniform rates in the seed furrow. Granular inoculants are applied through fertilizer attachments as a single product or mixed with dry fertilizer (Hegde and Brahmaprakash, 1992).

2.1.2 | The phosphorous cycle

Phosphorous is an essential element for all living organisms. In plants, P has functions of a structural nature in macromolecules such as nucleic acids and of energy transfer in metabolic pathways of biosynthesis and degradation (FAO, 2004). It cycles internally in the plant-soil system, moving from the parent material, by weathering, to biochemical molecules (e.g. nucleic acid, phospholipids) and back to mineral forms after decomposition (e.g. H_3PO_4). In natural soils P is among the most limiting nutrients, since it is present in small amounts and only available in its soluble forms, which promptly react with calcium, iron and aluminium cations to precipitate as highly insoluble compounds. Adsorbed on those compounds, P can be lost to the aquatic system through erosion and surface runoff. As a consequence humans started to mine "primary" P and added it to soils in the form of mineral fertilizer (FAO and ITPS, 2015).

Phosphorus requirements of forage legumes are comparable to those of pure grassland. A major distinction between legumes and non-legumes is that legumes are generally able to solubilise soil phosphates through root exudates (Nuruzzaman et al., 2005) and the deep rooting of some species contributes to efficient nutrient utilisation (Jensen and Hauggaard-Nielsen, 2003). Roots of most legumes release carboxylic acids that solubilise phosphate ions from bound forms such as calcium and iron phosphates that are otherwise unavailable to plants and immobile in the soil (see Box 7). The process is to an extent self-regulating: the lower the phosphorus concentration in the soil, the more acid is released, and depending on the species, up to 8 acids are released (Egle et al., 2003). This also benefits the phosphorus uptake of cereals grown in combination with the legume (Li et al., 2007) and cereals grown after a legume crop (Nuruzzaman et al., 2005). One side-effect of the release of acids by legume roots is a gradual acidification of the soil, usually countered by periodic applications of lime, and partially countered by the alkalinity of the crop residues (Figure 5).

Figure 5 | Phosphorous Cycle *(Modified from Northern Arizona University, 2004)*



Box 7 | Bio-fertilizers

A large number of bacterial species inhabiting the rhizosphere are known to have beneficial effects on and positively facilitate plant growth. Such bacteria are generally referred to as plant growth promoting rhizobacteria. Plant growth-promoting rhizobacteria (PGPR) that are aggressively colonize the rhizosphere in the presence of a competing microflora (Kennedy et al., 2004). Based on their activities, Somers et al. (2004) classified PGPR as bio-fertilizers (increasing the availability of nutrients to plants), phytostimulators (promoting plant growth usually by producing phytohormones), rhizoremediators (degrading organic pollutants, lowering of ethylene concentration, producing antibiotics and antifungal metabolites and inducing systemic resistance) and bio-pesticides (controlling diseases mainly by producing antibiotics and antifungal metabolites).

Bio-fertilizers are "microbial inoculants which contain live or latent cells of selected strains of nitrogen fixing, phosphate solubilizing microorganisms used for application to seed, soil or composting areas to accelerate certain microbial processes; thus augmenting the availability of nutrients in an easily assimilable forms to plants" (Amanullah, 2015). Bio-fertilizers are low cost, eco-friendly and sustainable, do not require non-renewable source of energy during their production and improve growth and quality of crops by producing plant hormones, vitamins etc., to supplement chemical fertilizers (Natarajan et al., 2002). Although most of these organisms have been on the job for centuries, they only received attention as manageable agricultural inputs in the 20th century.

Bio-fertilizer technology involves the artificial multiplication and inoculation of soil/plant with these microorganisms (microbial inoculants/bio-fertiliser) to increase their population in soil and thereby hasten their biological activity and improve availability of plant nutrients (Amanullah, 2015). Bio-fertilizers can be classified in (a) nitrogen-fixing bio-fertilizers and (b) phosphorous mobilizing bio-fertilizers.

Nitrogen-fixing bio-fertilizers are (Singh and Kapoor, 1999):

- **Azolla**, a floating fresh water fern which is ubiquitous in distribution. The fern harbors a nitrogen fixing cynobacterium (BGA) called *Anabaena azollae* at all stages of its growth and development;
- **Blue green algae** (BGA), also known as cynobacteria, are photosynthetic bacteria. The BGA fix nitrogen through exudation and microbial degradation of dead algal cells;
- **Azospirillum**, an associative symbiotic nitrogen fixing bacterium with a high nitrogen fixing potential, found to be associated with the root system of many grasses;
- **Azotobacter**, aerobic free living N fixing bacteria. This organism widely occurs in the rhizosphere of many plants. They fix N in the rhizosphere and provide it to the plant. Their inoculations are useful for cereals and non leguminous crops; and
- **Rhizobium**, gram negative soil bacteria. They form a symbiotic association with leguminous plants to form nodules in the roots of host plant. These nodules are the sites of nitrogen fixation. Active nodules contain a red pigment called 'leghaemoglobin'. The leghaemoglobin pigment regulates the oxygen diffusion within the nodule. Intensities of nitrogen fixation is directly proportional to the amount of haemoglobin present in nodules. They fix atmospheric nitrogen and thus not only increase the production of the inoculated crops, but also leave a fair amount of nitrogen in the soil, which benefits the subsequent crops. Rhizobium spp. are the best bio-fertilizers for legumes.

The application of bio-fertilizers to crops is presented in table 7 (Amanullah, 2015)

Table 7 | Application of bio-fertilizers to crops *(Amanullah, 2015)*

Bio-fertilizer	Crops
Rhizobium	Crop specific biofertilizers for legume like Groundnut, Soybean, Redgram, Green-gram, Black-gram, Lentil, Cowpea, Bengal-gram and Fodder legumes
Azotobacter	Cotton, Vegetables, Mulberry, Plantation Crop, Rice, Wheat, Barley, Ragi, Jowar, Mustard, Safflower, Niger, Sunflower, Tobacco, Fruit, Spices, Condiment, Ornamental Flower
Azospirillum	Sugarcane, Vegetables, Maize, Pearl millet, Rice, Wheat, Fodders, Oil seeds, Fruit and Flower
Blue Green Algae	Rice, banana
Azolla	Rice
Phosphate Solubilizing Microorganisms	All Crops (non specific)
VAM fungi	For variety of plants

Phosphorous mobilizing bio-fertilizers are broadly divided in two groups namely phosphate solublizing microorganisms and phosphate absorbers such as vesicular arbuscular mycorrhiza (VAM) fungi (e.g., Glomus, Gigaspora, Amanullah, 2015). Phosphate solublizers are represented by several bacteria, particularly those belonging to genera Pseudomonas and Bacillius, and fungi belonging to Penicillium and Asprergillus genera. Phosphate solubilizers have the ability to solubilize the insoluble inorganic phosphorus in soil to make it available to plants. The solublization mechanisms appear to be either acid production or chelating of metal and release of phosphorus (Singh and Kapoor, 1999). Phosphate absorbers refers to some fungi forming symbiotic association with root of certain plants and helping in absorbing phosphorus and other nutrients like zinc, iron and manganese. Such fungus-root association is called mycorrhizae (Singh and Kapoor, 1999). There are mainly two types of mycorrhizae:

- Ectomycorrhizae: generally found in trees and important in forest management;
- Endomycorrhizae: found in the majority of crop plants. They play a role in supplying phosphorus and other nutrients to plants. Among these, VAM are common in field crops.

2.2 | The role of pulses in maintaining soil biodiversity

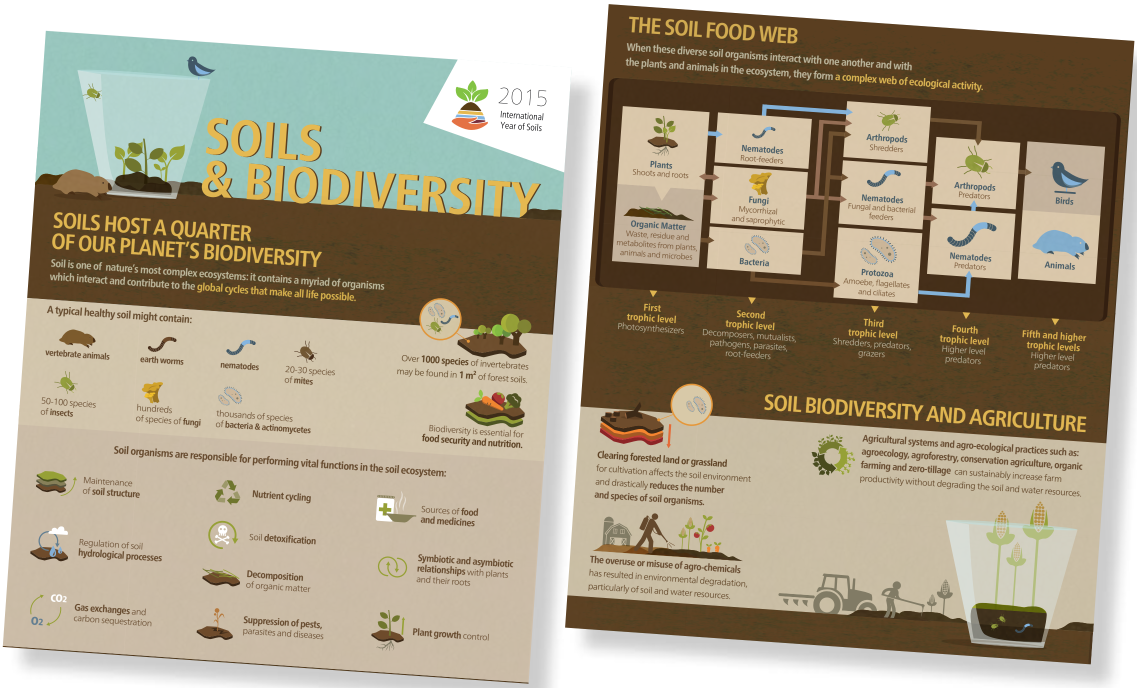
Soil biodiversity reflects the variability among living organisms, including a myriad of organisms not visible with the naked eye, such as micro-organisms (e.g. bacteria, fungi, protozoa and nematodes) and meso-fauna (e.g. acari and springtails), as well as the more familiar macro-fauna (e.g. earthworms and termites), see Box 8. Plant roots can also be considered as soil organisms in view of their symbiotic relationships and interactions with other soil components. These diverse organisms interact with one another and with the various plants and animals in the ecosystem forming a complex web of biological activity. Soil organisms contribute a wide range of essential services to the sustainable function of all ecosystems. They act as the primary driving agents of nutrient cycling, regulating the dynamics of soil organic matter, soil carbon sequestration and greenhouse gas emission, modifying soil physical structure and water regimes, enhancing the amount and efficiency of nutrient acquisition by the vegetation and enhancing plant health. These services are not only essential to the functioning of natural ecosystems, but constitute an important resource for the sustainable management of agricultural systems (FAO, 2016c; Reinhart et al., 2010; Schnitzer et al., 2011; Mommer et al., 2016; Philippot et al., 2013). In addition, a high soil biodiversity provides ecosystems with not only greater resistance and resilience against disturbance and stress, but also improves the ability of ecosystems to suppress diseases. All these features are particularly important for mainstreaming soil health, which is the foundation of food security and health (FAO, 2016a).

Box 8 | Biodiversity and Biological resources

The Convention on Biological Diversity (CBD) gives a formal definition of biodiversity. Article 2 of the Convention states that: "biological diversity means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems". Biodiversity is not only the sum of all ecosystems, species and genetic material. Rather, it represents the diversity and the variability within and among them. It can be distinguished from the expression "biological resources", which refers to the tangible components of ecosystems. Biological resources are real entities while biological diversity is rather an attribute or a descriptor of the living communities (strains within species, the genetic variability of microbes around the world, etc.). This expansive definition is extremely useful for describing life on Earth, determining the biotic composition of an ecosystem, and addressing the rapid changes occurring at temporal and spatial scales to the ecosystem, such as the increasing rate of species extinction (CBD, 1992).

In the soil there is a complex web of microorganisms that can exceed 100 million units per gram of soil (Torsvik et al., 2002). According to FAO (2016b), a typical healthy soil might contain vertebrate animals, earth worms, nematodes, 20-30 species of mites, 50-100 species of insects, hundreds of species of fungi and thousands of species of bacteria and actinomycetes (Figure 6). Fungal and bacterial diversity (Canfora et al., 2014; Hawksworth, 2001; Schmit and Mueller, 2007) contributes to litter decomposition through saprophytic activities and improves plant nutritional status, regulating several ecosystem functions (Wardle et al., 2004; van der Heijden et al., 2008). The high variability of soil microbial communities is due to physical, ecological, climatic and structural soil differences, and to a large variety of land management systems. Considering the fact that microbial communities play a crucial role in the functioning of plants by influencing their physiology and development, and given ecological services provided by soil biodiversity, soil organisms are crucial for sustainability of agroecosystems.

Figure 6 | Soils and biodiversity *(FAO, 2016b)*



2015 International Year of Soils

SOILS & BIODIVERSITY

SOILS HOST A QUARTER OF OUR PLANET'S BIODIVERSITY

Soil is one of nature's most complex ecosystems: it contains a myriad of organisms which interact and contribute to the **global cycles that make all life possible.**

A typical healthy soil might contain:

vertebrate animals

earth worms

nematodes

20-30 species of **mites**

50-100 species of **insects**

hundreds of species of **fungi**

thousands of species of **bacteria & actinomycetes**

Over **1000 species** of invertebrates may be found in **1 m²** of forest soils.

Biodiversity is essential for **food security and nutrition.**

Soil organisms are responsible for performing vital functions in the soil ecosystem:

Maintenance of **soil structure**

Nutrient cycling

Sources of **food and medicines**

Regulation of soil **hydrological processes**

Soil **detoxification**

Decomposition of organic matter

Symbiotic and asymbiotic relationships with plants and their roots

Gas exchanges and carbon sequestration

Suppression of pests, parasites and diseases

Plant growth control

THE SOIL FOOD WEB

When these diverse soil organisms interact with one another and with the plants and animals in the ecosystem, they form **a complex web of ecological activity.**

SOIL BIODIVERSITY AND AGRICULTURE

Clearing forested land or grassland for cultivation affects the soil environment and drastically **reduces the number and species of soil organisms.**

Agricultural systems and agro-ecological practices such as: agroecology, agroforestry, conservation agriculture, organic farming and zero-tillage can sustainably increase farm productivity without degrading the soil and water resources.

The overuse or misuse of agro-chemicals has resulted in environmental degradation, particularly of soil and water resources.

Microbial communities involved in food farming are strictly related to and influenced by many genomic interactions and food competitions throughout the entire farm and food supply chain. In this framework, it is important to collect and map microbial genetic resources, invest in isolating new strains and regulate microbial resources management (property rights, in situ conservation, exchanges of microbial genetic resources). Due to global changes driven by population growth (e.g., climate change and land-use change) soil resources are at a higher risk of degradation and their biotic communities are facing species extinction, strain substitution, and competition with invasive species (Pauls et al., 2013), see Box 9. The risks of genetic erosion and strain or species substitution is a serious threat for the conservation of soil biodiversity, which also affects the soil's productive capacity.

Box 9 | Measuring soil biodiversity

Unlike plants or animals, microbial diversity cannot be examined directly with a preliminary visual approach but requires a series of complex laboratory analyses following random sampling of substrates. These procedures are often expensive and time consuming, leading to either a reduced number or extent of the monitored sites, or a decrease in the quality of the descriptors. A broad picture of soil microbial communities may be provided through the use of integrative methods, to assume a comprehensive view of this complex and dynamic ecosystem (add reference). Rapid and comprehensive methodologies to assess soil microbial communities has rapidly transformed the understanding of microbial biodiversity over the past decade. However, the researcher's perception of environmentally variability and the scale at which specific properties like salinity are measured can misrepresent the spatial scale at which microbial groups shape their structure and function. Space and scale in population, community, and ecosystem processes are increasingly recognized as fundamental factors in the study of microbial functions and activities in soil (Ettema and Wardle, 2002).

2.3 | The role of pulses in improving soil structure

Soil organic matter is a complex mixture of carbon compounds consisting of plant and/or animal organic materials, and the conversion products of those materials in soils (FAO and ITPS, 2015). Decomposition of organic matter is largely a biological process that occurs naturally. Its speed is determined by three major factors: soil organisms, the physical environment and the quality of the organic matter. In the decomposition process, different products are released: carbon dioxide (CO_2), energy, water, plant nutrients and resynthesized organic carbon compounds. Successive decomposition of dead material and modified organic matter results in the formation of more complex organic matter called humus through a process called humification (FAO, 2005).

Humus affects soil properties in various ways. As it slowly decomposes, organic matter colours the soil darker; increases soil aggregation and aggregate stability; increases the cation exchange capacity (CEC - the ability to attract and retain nutrients); and contributes N, P and other nutrients to the soil. Soil organisms, including micro-organisms, use soil organic matter as food. As they break down the organic matter, any excess nutrients (N, P and S) are released into the soil in forms that plants can use through mineralization. The waste products produced by microorganisms are also part of the soil organic matter. This waste material is less decomposable than the original plant and animal material, but it can be used by a large number of organisms. By breaking down carbon structures and rebuilding new ones or storing the C into their own biomass, soil biota plays the most important role in nutrient cycling processes. The organic matter content, especially the more stable humus, increases the capacity to store water and store (sequester) C from the atmosphere (FAO, 2005).

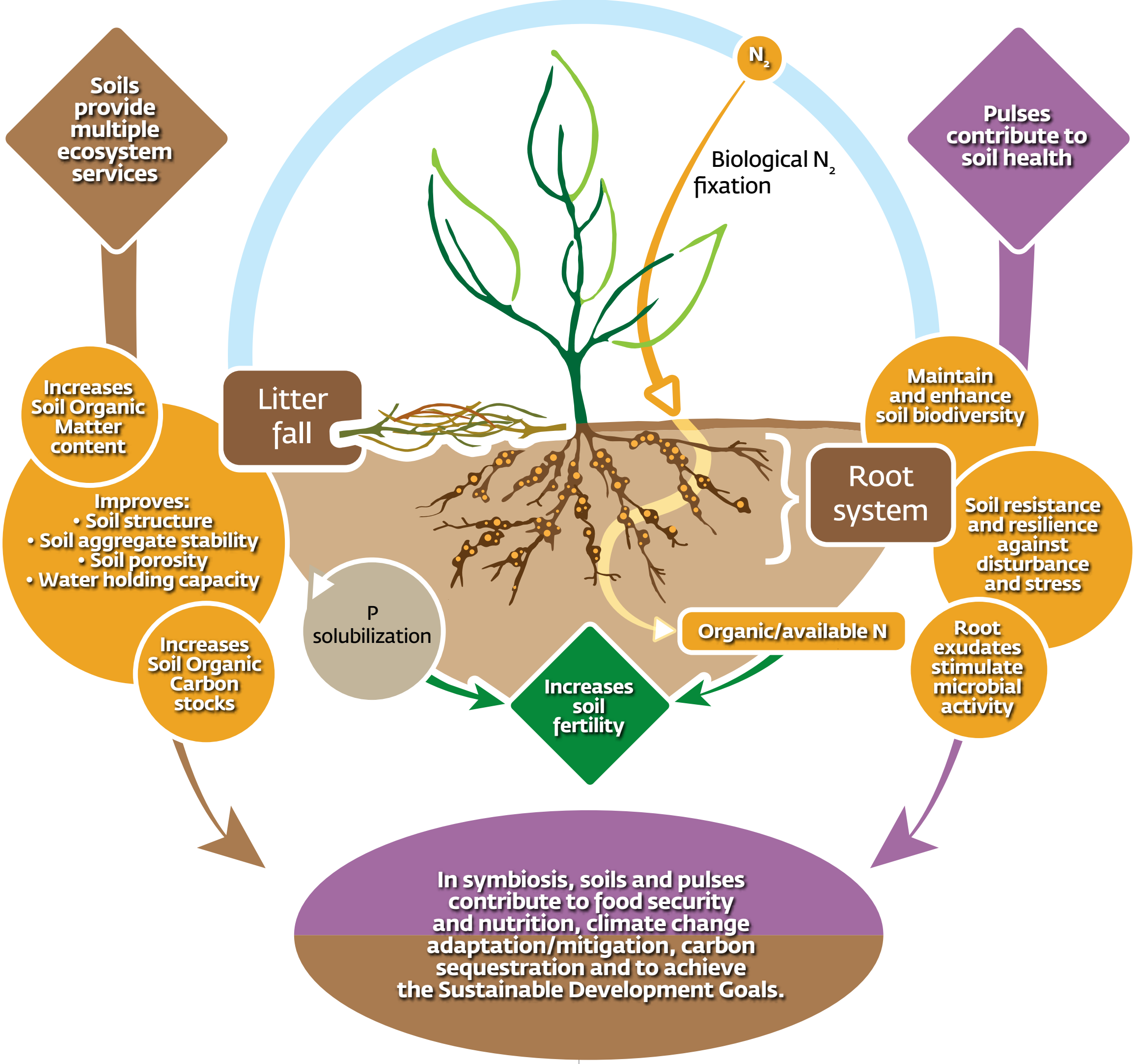
Besides its role in recycling nutrients, soil organic matter has the important function of improving soil structure (FAO and ITPS, 2015), which refers to the natural organization of soil particles into discrete soil units (aggregates or peds) that result from pedogenic processes (FAO, 2006). The soil fauna and some of the resistant soil organic components are involved in binding soil particles into larger aggregates. Aggregation is important for better soil structure, aeration, water infiltration and resistance to erosion and crusting (FAO and ITPS, 2015). Improvements in soil structure resulting from legume production is usually a longer term benefit which results from, amongst others, an increase in stable soil aggregates which, in turn, increases pore space and tilth, thereby improving soil aeration and water holding capacity (USDA, 1998). Forage legumes are especially effective in improving soil structure due to their large and deep root systems and their longer growth periods.

Direct root action, especially by forage legumes, affects soil structure by binding and compressing soil particles which, in turn, affects soil aggregation and aggregate stability. Physiologically, root exudates affect soil structure by stimulating microbial activity and by producing polysaccharides and proteins. These exudates can stimulate mycorrhizal fungal growth which produces hyphae that spread into the soil matrix and, in effect, act as an extension of the root system which can increase aggregate stabilization (Gould et al., 2016). The excretion of glomalin-related soil protein by arbuscular mycorrhizal fungi is especially important in aggregate formation. Glomalin is an insoluble, hydrophobic, glycoprotein (Wright et al., 1996) which is considered to be especially important in soil aggregation (Nichols and Millar, 2013). In fact, various authors have found a strong positive correlation between glomalin concentration and the amount of water stable aggregates (Harner et al., 2004; Rillig, 2004; Bedini et al., 2009).

Increasing the amount of active or readily decomposable soil organic matter and microbial life helps to bind more soil particles together, making the soil more friable and less erosive. For example, using legume green manure and legume-grass hay crops increased surface soil structure by increasing the degree of stable aggregation (Campbell et al., 1993). Leguminous green manures specifically aid macro-aggregation through direct action of roots, as well as through the production of cementing agents resulting from microbial activities. These actions help to bring together primary soil particles and micro-aggregates (Sultani et al., 2007).

A summary of the symbiosis between soil and pulses is represented in Figure 7

Figure 7 | The symbiosis



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3 | Soils and pulses - a symbiosis for contributing to the achievement of the Sustainable Development Goals

Pulses can play an important role in addressing hunger, food insecurity, malnutrition, environmental degradation, climate change impacts and human health, thereby supporting the overall achievement of the SDGs. By fixing atmospheric nitrogen and solubilizing phosphates (free soil-bound phosphorous), pulses contribute to reduce the need for synthetic fertilizers. In doing so, pulses inadvertently contribute to reducing the risk of soil and water pollution, supporting soil biodiversity, and combating and building resilience to climate change. Furthermore, the reduced need for (or use of) synthetic fertilizers indirectly reduces the amount of greenhouse gases released in the atmosphere. Pulses also promote soil carbon sequestration and, ultimately, reduce soil erosion when included in intercropping farming systems and/or used as cover crops. Due to their high nutritional value, pulses are also valuable allies in fighting hunger and malnutrition worldwide.

Food production, food security and climate change are intrinsically linked. Whether in the form of droughts, floods or hurricanes, climate change impacts every level of food production and ultimately, the price instability of food and the food security of affected farming communities (IPCC, 2015). While its impact varies across crops and regions, climate change puts global food security even more at risk and increases the dangers of undernutrition in poor regions (FAO, 2016c). Climate change also contributes to shifting the production areas of food and non-food crops around the world. Unless urgent and sustainable measures are established and implemented, climate change will continue to exert pressure on agricultural ecosystems, particularly in regions and for populations that are the most vulnerable. This chapter presents the role of pulses in the soil system in adapting to and mitigating climate change, their contribution to food security and nutrition, and their support in the provision of ecosystem services and in restoring degraded soils.

3.1 | Climate change adaptation and mitigation, the role of soils and pulses

Many aspects of the climate system are showing evidence of a changing climate *(IPCC, 2013)*. Appropriate policy responses combining agroecosystems as key assets can strengthen adaptation and contribute to building the resilience of communities and households to local and global change (African Development Bank et al., 2003). Adaptation is one of the policy options to climate change that is influencing development practices (IPCC, 2007). It refers to adjustments to practices, processes and systems to minimize current and/or future adverse effects of climate change and take advantage of available opportunities to maximize benefits (Eriksen et al., 2007). In this context, agricultural adaptation to climate change is the manner in which farmers update their expectations of the climate in response to unusual weather patterns and how they translate their perceptions into agricultural decisions.

According to Maddison (2006), if farmers learn gradually about the change in climate, they will also learn gradually about the best techniques and adaptation options available. Following this theory, farmers learn about the best adaptation options in three ways: (1) learning by doing, (2) learning by copying, and (3) learning from instruction. There is recognition that farmers' response vary when faced with the same stimuli. Such varied responses, even within the same geographic area, are partly related to the variety of agricultural systems involved and the different market systems in which farmers operate (Bryant et al., 2000). A more important factor of varied farmers' responses is the differences between farmers in terms of personal managerial and entrepreneurial capacities and family circumstances. Also, farmers can be influenced by their peers' perceptions and by values present in their communities as well as their professional associations. A review of literature on the adoption of new technologies identified farm size, tenure status, education, access to extension services, market access and credit availability, agro-climatic conditions, topographical features, and the availability of water as the major determinants of the speed of adoption (Maddison, 2006).

Adaptations can either be planned or autonomous with the latter being done without awareness of climate change predictions but rather based on experience and prevailing conditions (Eriksen et al., 2007). Autonomous adaptation is the reaction of a farmer to changing precipitation patterns by changing crops or applying different harvest and planting/sowing dates. Planned adaptation measures are conscious policy options or response strategies that are often multi sectoral in nature, aimed at altering the adaptive capacity of the agricultural system or facilitating specific adaptations. Examples are using deliberate crop selection and distribution strategies across different agro-climatic zones, substitution of pulse crops in traditional cereal based cropping pattern and resource substitution induced by scarcity (Easterling, 1993). In this framework, pulses have a broad genetic diversity from which improved varieties can be selected or bred. This diversity is a particularly important attribute since more climate-resilient cultivars can be developed. For example, scientists at the International Center for Tropical Agriculture are currently working on developing pulses varieties that can grow at temperatures above the crop's normal 'comfort zone'. Since climate experts suggested that heat stress will be the biggest threat to bean production in the coming decades, these improved pulse varieties will be of critical importance, especially for low-input agricultural production systems (Russel, 2015).

The use of drought-resistant crop varieties has been tried by smallholder farmers as adaptation methods to climate change in Nigeria, Senegal, Burkina Faso and Ghana (Ngigi, 2009). Pigeon pea remains one of the most drought-tolerant legumes and is often the only crop that gives some grain yield during dry spells when other legumes such as field beans will have wilted and perhaps dried out. The ability of pigeon pea to withstand severe drought better than many legumes is attributed to its deep roots and osmotic adjustment in the leaves. The legume also maintains photosynthetic function during stress better compared to other drought-tolerant legumes such as cowpea (*Vignaunguiculata* L. Walp.). Its unique polycarpic flowering habit further enables the crop to shed reproductive structures in response to stress. Introducing pulses into existing farming systems can be key to increasing resilience to climate change (see Box 10). For example, agroforestry systems, also including pulses like pigeon peas, support adaptation through diversification of the income source, increased resilience to climate extremes and increased productivity. In addition to adaptation, agroforestry systems also sequester more carbon than field crops alone (Wollenberg et al., 2012). Pulses are climate smart as they simultaneously adapt to climate change and contribute towards mitigating its effects.

Soil organic carbon stocks are very important when addressing climate change adaptation and mitigation. The potential for carbon sequestration by soils is high and varies spatially and temporarily. Increasing inputs of soil organic matter into the soil is the basis for boosting carbon sequestration. The inclusion of pulses in farming systems could foster this process, thus building system resilience to adapt to and mitigate climate change.

Box 10 | The importance of gene banks for climate change adaptation

Genetic material of pulse crops and wild relatives conserved in the gene banks of the Consultative Group for International Agricultural Research centres and national and international gene banks, represents a good investment in adapting to climate change. The genetic resources stored in these gene banks are held in trust under the auspices of FAO through an agreement with the International Treaty on Plant Genetic Resources for Food and Agriculture. These resources are freely available for research, breeding and training in food and agriculture. In other words, the traits needed for adapting to future climate scenarios can be sourced from the gene reservoir that are preserved at the gene banks network (FAO, 2016d).

The inclusion of pulses in mixed cropping systems and their use to increase the soil water content, are examples of adaptation strategies relying on the symbiosis between soil and pulses as elaborated below.

Mixed cropping involves growing two or more crops in proximity within the same field. Crop diversification is a high priority adaptation measure in both irrigated and non-irrigated areas that serves as insurance against rainfall variability. Multiple cropping systems (intercropping, sequential cropping or crop rotation, etc.) including at least a pulse crop in the crop rotation, allows cereal-based cropping systems to be better adapted against climactic adversities (Subbarao et al., 2000).

Mixed cropping system are commonly practiced in Tanzania where cereals (maize, sorghum), legumes (beans) and nuts (groundnuts) are grown together. The advantages of mixing crops with varying attributes relate to maturity period (e.g. maize and beans), drought tolerance (maize and sorghum), input requirements (cereals and legumes) and end users of the product (e.g. maize as food and sunflower for cash). Research conducted by Mendelsohn et al. (2000), reveals that the planting of different varieties of the same crop is considered to be one of the most important adaptations strategies to climate change in all African countries except Cameroon and South Africa. Different planting dates are also considered important adaptation strategies in African countries such as Egypt, Kenya and Senegal (see Box 11). Growing legumes (pulses) provides both nitrogen and non-nitrogen benefits to subsequent crops due to their ability to fix atmospheric N (see table 9) and their use as green manure. Properly inoculated/nodulated legumes can fix up to 50-90 percent of their N requirements from the atmosphere, obtaining the remaining 50-10 percent N from the soil. Additionally, N is also exuded from legume roots during the growing season and the legume residue decomposes and recycles the nutrients faster than non-legume residues. However, pulse crops do not provide as much nitrogen and crop residues to the soil as a biennial or perennial legume because of their annual growth habits (Biedcrbeck et al., 1996).

Adding pulses to crop rotations commonly lowers greenhouse gas (GHG) emissions due to lower fertilizer requirements (particularly given the large amount of energy used in fertilizer production), regardless of water availability. Up to 70 percent of the non-renewable energy used in Western Canadian cropping systems is due to the use of fertilizers, particularly nitrogen (Hoeppner et al., 2000). Research in Swift Current, Canada (Campbell et al., 1992; Gan et al., 2014), assessing net GHG emissions from four cropping systems (fallow-flax-wheat, fallow- wheat-wheat, continuous wheat, and lentil-wheat), found the lentil- wheat system to clearly outperform the others. This was due to the lower rates of nitrogen fertilizer required by the wheat crop in the rotation and the increased nitrogen availability, which enhanced plant biomass accumulation.

Table 8 | Etimates of nitrogen fixed by legumes
(Wani and Lee, 1992; Peoples and Crasswell, 1992)

Crop	Nitrogen fixation (kg ha^{-1})
Alfalfa	100-300
Chickpea	23-97
Clover	100-150
Cluster bean	37-196
Common Bean	3-57
Fenugreek	44
Groundnut	27-206
Pea	46
Soybean	45-450
Cowpea	9-125
Black gram	119-140
Green gram	50-66
Lentil	35-100
Pigeon pea	4-200

Box 11 | Change in cropping pattern and calendar of planting

In Tanzania, to avoid crop production risks due to rainfall variability and drought, staggered planting is very commonly used by most farmers. In this practice, crops are planted before rain onset (dry land) on uncultivated land. In some plots crops were planted immediately after rain, while others were planted a few days after the first rains. In fields which were planted prior to cultivation, tillage commenced in the third week after the onset of rain which destroyed early geminating weeds and reduced weeding. This was done purposely to distribute risk by ensuring that rain was utilized to the maximum by the crop planted in the dry fields (Liwenga, 2003).

Adopting soil conservation measures that conserve soil moisture: Soil conservation techniques are increasingly practiced in Burkina Faso, Kenya, Senegal and Niger (The World Bank, 2007). According to (Nicole et al., 2015), farmers in Kamenyanga and Kintinku ensure proper timing of different farming activities, burying crop residues to replenish soil fertility, burning crop residues to enhance quick release of nutrients and allowing livestock to graze on farmlands after harvest in order to increase the soil organic matter content. In Tanzania, farmers used contour ridges as a strategy to minimize soil erosion to encourage better root penetration and enhance soil moisture conservation (Lema and Majule, 2009). In Senegal and Burkina Faso, local farmers have improved their adaptive capacity by using traditional pruning and fertilization techniques to double trees' density in semi-arid areas (Akinnagbe and Irohibe, 2014). These techniques help to improve soil structure and reverse degradation. In this framework, the conservation of the soil organic carbon is critical. Local farmers in the Sahel, conserve soil carbon by practicing minimum-tillage, apply mulch and making use of other soil conservation techniques. The application of natural mulches to the soil contributes to moderating soil temperatures and buffering extremes, suppressing diseases and harmful pests, and conserving soil moisture (IPCC, 2007).

No-till/minimum tillage systems allow farmers to take increased advantage of the growing season and to avoid fallow periods. A number of studies (Johnston et al., 1999), have been conducted to evaluate the effect of tillage on grain yield of peas (table 10). In general, peas are either unaffected or show improved grain yields in response to reduced tillage. Similar results are obtained with lentil, which is broadcasted in standing paddy fields (ICARDA, 2013). The benefits of practicing no/minimum-tillage appear to be greater in drier regions where this technique allows the soil to store more water and increase the number of crops in the rotation with less fallow (Kassam et al., 2012).

Table 9 | Pea yield response to tillage, expressed as relative to the conventional or minimum tillage treatment *(Johnson et al., 1999).*

Location	Conv. Till	Min-Till	No-Till
	----- Relative (%) grain yield response -----		
Carmen (Black soil)	100	--	107
Portage (Black soil)	100	--	96
Melfort (Black soil)	100	94	105
Tisdale (Gray soil)	100	99	97
Indian Head (Black soil)	100	105	108
Saskatoon (Dark Brown soil)	--	100	132
Scott (Dark Brown soil)	--	100	128
Swift Current & Assiniboia (Brown soil)	--	100	105-110

3.2 | Contribution to food security and nutrition

According to (FAO, 2001b), "food security exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life". Food insecurity is a major issue for many people and households in poor and developing countries with an estimated 795 million people being undernourished worldwide (FAO, 2001b). The future global food system therefore faces two major challenges: i) meeting the world's food security and nutrition needs in ways that ensure good health, and ii) fostering environmental sustainability and resilience of agricultural production systems in a world of unpredicted climate challenges. Pulses can contribute to meeting both these challenges.

In terms of nutrition and food security, pulses provide a good source of plant based protein as well as fibre, vitamins (e.g., B vitamins) and minerals such as iron, potassium, magnesium and zinc. Over 60 percent of total utilization of pulses is for human consumption, while the rest is for animal feed. The importance of pulses in human diets varies from region to region and country to country, with a general trend of higher consumption in lower income nations where pulses are part of the traditional diet. The utilization of pulses as proportion of total food consumption in developing countries is over 75 percent, compared to 25 percent in developed countries (Odendo et al., 2011). An estimated 25 percent of total pulse use goes to feeding animals such as pigs and poultry. Complementing animal feed with improved varieties of pulses has shown to significantly improve animal nutrition and livestock yield, which in turns supports food security (Odendo et al., 2011). A study in West Africa (Schlecht et al., 1995) showed that during the dry season, animals fed with cowpea hay, along with rice feed meal, gained 95 kg, compared to 62 kg for animals that did not receive the cowpea fodder. As a result, farmers that used cowpea fodder could benefit from an extra 50 kg of meat per year and over 300 kg of cereal grain from the improved soil health.

The recent Second International Conference on Nutrition (ICN2) and its Rome Declaration on Nutrition (FAO and WHO, 2014) noted that over two billion people suffer from various micronutrient deficiencies, particularly vitamin A, iodine, iron and zinc. Soil deficiencies of micronutrients constitute a serious issue at global level since conventional soil fertilization practices generally focus on macronutrients (N, P and K), leaving the replenishment of micronutrients unattended. The symbiosis of soils and pulses could address this issue as pulses could contribute various micronutrients (e.g. zinc) to the soil and subsequent crops.

In addition to contributing to a healthy, balanced diet, the nutritional quality of pulses makes them particularly helpful in the fight against some non-communicable diseases. The World Health Organization (WHO, 2005) estimated that up to 80 percent of heart disease, strokes, type two diabetes, and over a third of cancers could be prevented by eliminating risk factors, such as unhealthy diets. Promoting better eating habits would be one solution, with pulses as an essential component that can help lower blood cholesterol and attenuate blood glucose, both of which are key factors in preventing diabetes and cardiovascular disease. Eating pulses as a replacement for some animal protein also helps limit the intake of saturated fats and increases the intake of fibres. Therefore, increased production and greater utilization of pulses for healthy diets are relevant in achieving several of the UN's Sustainable Development Goals (SDGs), including: a) end poverty in all its forms everywhere (SDG 1), b) end hunger, achieve food security and improved nutrition and promote sustainable agriculture (SDG 2), c) ensure healthy lives and promote well-being for all at all ages (SDG 3), d) ensure sustainable consumption and production patterns (SDG 12) and take urgent action to combat climate change and its impacts (SDG 13) (FAO, 2016e).

3.2.1 | Nutritional value of pulses

In recent years, studies have demonstrated potential health benefits of pulses as nutrient-rich food, with an associated risk-reduction for some chronic diseases (Rondini et al., 2012). Beyond meeting dietary recommendations, the demonstrated benefits refer to the effect of their components on maintaining metabolic, cardiovascular and gastrointestinal health (Hosseinpour-Niazi et al., 2015; Mudryj et al., 2014). The nutrient composition varies among different pulses (Table 11) and may be influenced by several factors including environmental conditions, storage, processing and genetics. The commonality of pulses is their significantly higher protein content than that of the most important cereal crops. Pulses contain on average 19-25 percent protein, with over 30 percent in newly developed varieties (Singh, 2016). Due to their high nutritional value, pulses can improve the diet of the poorest who cannot rely on a diversified diet enriched by meat consumption. Nearly 80 percent of dietary protein in the developing world is plant protein, compared to 43.4 percent in developed countries where animal protein is mostly consumed.

Table 10 | Nutrient profile of raw and dried pulses

(per 100 g edible portion on fresh weight basis) (FAO, 2012; USDA, 2015)

Pulse	Energy[a] (kcal) kJ	Protein (g)	Fat (g)	CHO[b] (g)	Dietary fibre (g)	Iron (mg)	Zinc (mg)	Folate (mcg)
Bambara groundnut *(Vigna subterranea)*	(326) 1360	20.1	5.90	33.6	28.9	3.30	3.38	n.a.
Broad beans *(Vicia faba)*	(300) 1260	26.1	1.80	31.7	26.3	6.10	3.1	423
Cowpea *(Vigna unguiculata)*	(316) 1330	21.2	1.30	47.2	15.3	7.30	4.61	417
Lentils *(Lens culinaris)*	(336) 1420	25.4	1.80	49.3	10.7	7.00	3.9	295
Pigeon pea *(Cajanus cajan)*	(300) 1260	18.4	1.50	43.2	20.2	4.70	1.96	456
Adzuki bean *(Vigna angularis)*	(310) 1310	19.9	0.53	50.2	12.7	4.98	5.04	622
Pinto bean *(Phaseolus vulgaris)*	(316) 1330	21.4	1.23	47.1	15.5	5.07	2.28	525
Black bean *(Phaseolus vulgaris)*	(288) 1210	21.3	1.20	37.0	21.8	6.5	2.9	444
Navy bean *(Phaseolus vulgaris)*	(315) 1330	22.3	1.50	45.5	15.3	5.49	3.65	364
Mung bean *(Vigna radiata)*	(324) 1370	23.9	1.15	46.3	16.3	6.74	2.68	625
Red kidney bean *(Phaseolus vulgaris)*	(314) 1330	22.5	1.06	46.1	15.2	6.69	2.79	394
Chickpeas *(Cicer arietinum)*	(340) 1430	21.2	5.40	45.5	12.4	5.40	3.2	557
Mungo bean *(Vigna mungo)*	(315) 1330	25.2	1.64	40.7	18.3	7.57	3.35	216
Lupines *(Lupinus albus)*	(356) 1490	36.17	9.74	21.5	18.9	4.36	4.75	355
Green peas *(Pisum sativum)*	(308) 1290	18.4	1.40	42.4	26.0	3.50	2.39	138

[a] *Metabolizable energy calculated from the energy-producing food components.* [b] *Available carbohydrate*

Pulses typically contain about two to three times the amount of protein found in cereal grains like wheat, rice and barley. It is important to note, however, that the amino acids in pulses are plant-based and as such are less bioavailable to humans than meat-based proteins. However, the protein quality is significantly improved when pulses are eaten together with cereals, as proteins from pulses and cereals are complementary with their respective limiting essential amino acids. Rice and beans are a classic example: Rice is high in the amino acid methionine and low in the amino acid lysine, while most pulses are high in lysine and low in methionine. When eaten together, these two foods provide a more "complete" protein profile (Pulse Canada, 2016).

Moreover, pulses have a low fat content and no cholesterol, as well as a low glycemic index (GI). The latter refers to a relative ranking of carbohydrate in foods according to how they affect blood glucose levels. Foods with a low GI value (55 or less) are more slowly digested, absorbed, and metabolized, thus causing a lower and slower rise in blood glucose and insulin levels, with positive implications for type two diabetes. For example, the GI for chickpeas is 36, 13 for dhal, 42 for mung bean and 25 for dried peas. While pulses are low in calories (for instance 340 kcal $100g^{-1}$ raw and dried chickpeas), they are high in complex carbohydrates and dietary fibre, which means they are slowly digested and give a feeling of satiety (FAO, 2016f). The dietary fibre in pulses is not generally absorbed by the body and thus increases stool volume and transit. Dietary fibre also serves to bind toxins and cholesterol in the gut so these substances can be removed from the body. This improves heart health and lowers blood cholesterol (FAO, 2016f).

Pulses are a significant source of minerals that have key functions in the human body. Pulses' high iron content makes them a potent food for preventing iron deficiency anemia in women and children, especially when combined with food containing vitamin C to improve iron absorption. Pulses are also a source of magnesium, which helps maintain nerve and muscle function, and strengthens bones; potassium, which helps maintain healthy blood pressure; phosphorus, which is essential for healthy bones and teeth; and zinc, which is important for proper immunological function. Pulses are also a good source of B-vitamins such as folate, which is essential for nervous system function and especially important during pregnancy to prevent fetal neural tube defects. Pulses' high B-vitamin content may also contribute to their cancer fighting properties (Kalogeropoulos et al., 2010).

Finally, pulses contain a host of bioactive compounds, which may have beneficial effects on human health through cholesterol-reducing and anti-carcinogenic activities. Phytates, for example, while historically considered "anti-nutrients" because of their inhibiting effects on iron and zinc absorption, are now increasingly recognized for their anti-inflammatory and cancer fighting properties (Dahl et al., 2012; Messina, 2014).

3.2.2 | Pulses for livestock feeding and nutrition

Pulses are also important in livestock and poultry diets. Nutritional information of major pulses used for animal feed are reported in table 12.

Table 11 | Proximate composition (% air-dry basis), energy content (MJ kg^{-1} air- dry basis) and essential amino acid content (g 16gN^{-1}) of legume seeds or meal *(Batterham and Egan, 1987; Edwards, 2004; Petterson et al., 1997).*

Component	Chick pea	Faba bean	Field pea	N-L lupin	Albus lupin	Yellow lupin	Mung bean	Navy bean	Peanut meal	Pigeon pea
Crude protein	19.5	23.1	23.4	28.9	35.8	38.3	23.9	22.7	47.4	18.3
Dry matter	89.1	90.6	90.7	89.7	91.4	91.5	89.8	89.7	91.5	88.8
Crude fibre	7.0	6.9	6.1	13.0	10.6	16.3	3.9	4.2	13.1	10.5
Ether extract	3.9	1.2	1.2	5.4	9.4	5.6	1.3	1.5	1.2	3.3
Ash	2.9	3.2	3.0	2.8	3.3	3.5	3.7	4.1	4.5	4.5
Nit-free ext	55.7	56.3	57.0	40.2	-	-	57.0	57.2	25.3	52.2
DE - Pig	16.2	13.7	14.4*	14.2	16.9	16.4	15.6	15.6	11.9	13.5
ME - Cattle	12.1	13.1	11.3	12.0	11.9	15.3	11.4	11.3	10.6	8.0
ME - Chick	12.2	11.2*	11.5*	8.9	-	-	10.5	9.7	9.2	-
ME - Pig	14.8	12.9	14.1	-	-	-	14.1	14.2	10.2	12.4
ME - Sheep	11.5	11.5*	12.0*	12.2	-	-	11.7	11.7	11.5	8.9
Threonine	3.3	3.5	3.8	3.4	3.5	3.3	3.2	4.5	2.7	3.9
Valine	3.5	4.4	4.7	3.6	3.7	3.4	6.0	5.2	4.0	4.1
Methionine	1.0	0.8	0.6	0.6	0.7	0.7	0.8	0.7	0.7	0.8
Isoleucine	4.2	3.8	4.3	3.9	3.8	3.7	4.8	4.6	3.4	3.8
Leucine	7.4	7.3	7.8	7.5	6.3	7.9	7.2	8.3	6.8	7.1
Phenylalanine	5.2	4.1	4.6	3.7	3.4	4.0	4.8	5.8	4.9	8.4
Histidine	2.5	2.5	2.7	2.7	1.9	2.7	2.0	2.8	2.2	3.3
Lysine	5.8	6.2	7.3	4.7	4.3	5.4	6.8	6.9	3.3	5.8
Arginine	9.8	9.4	10.3	10.2	12.2	11.3	6.0	6.7	12.8	6.2
Tryptophan	0.64	0.7	0.83	0.60	1.0	0.78	1.8	1.7	0.83	0.74

** DE is digestible energy, ME is metabolisable energy.*

Lupins tend to be the most used pulse for beef cattle, dairy and sheep feeding. The importance of lupins in dairy is related to the ability of this pulse to enhance milk production and quality, and can represent up to 30 percent of the animal meal ratio. Narrow-leafed lupins and field peas are the most commonly used pulses in poultry diets, where they can represent up to 30 percent of the animal meal ratio, depending on the type and age of poultry. Narrow-leafed lupins and peas are also widely used for pig feeding, where they are found together with peas, faba beans, chickpeas and mung beans. Additionally, pulses are not stranger to aquaculture, where lupins are used as aqua feed ingredients (Batterham and Egan, 1987; Edwards, 2004; Petterson et al., 1997).

Food processing methods are not 100 percent efficient and some waste products are produced. Although these waste products were traditionally dumped at landfills sites (Patras et al. 2011), nowadays they are regarded as food processing by-products and partially used as feed (Gustavsson et al., 2011). Pulse milling has an efficiency of approximately 75 percent, which means that 25 of the processed pulses are by-products (e.g., husk, powder, broken). In India alone, 2.5 million tonnes of pulse by-products are produced annually (Patras et al., 2011). These by-products can be used feed based on their high nutritional value for ruminant and non-ruminant animals. High protein content pulse by-products can improve the feed conversion ratio of monogastric animals thus decreasing the associated methane emissions. Therefore, the use of pulse by-products can lead not only the more rational use of available resources, but can also contribute to mitigating climate change.

3.2.3 | Underutilized pulses

Underutilized pulse species (UPS) are domesticated and semi-domesticated pulse species which can potentially contribute to food security, nutrition and income generation, but they have been marginalized or even forgotten by researchers, breeders and policy makers, see table 13. According to Padulosi et al. (2013), UPS are important because they may be adapted to local environments and may be useful in improving nutrition, generating income, and promoting cultural diversity, among other positive features. However, production of these species can be very laborious since they are not supported by modern technologies. Other reasons for the underuse of some pulse species are their mistaken association with rural poverty and their old-fashioned connotation. However, it is essential to investigate the potential usefulness of these UPS as food source and their role in food security and nutrition.

Table 12 | Underutilized pulse species *according to Padulosi et al. (2013).*

Common name	Scientific name
Mungbean	*Vigna radiata* (L.) R. Wilczek
Adzuki bean	*Vigna angularis* (Willd.) Ohwi & H. Ohashi
Ricebean	*Vigna umbellata* (Thunb.) Ohwi & H. Ohashi
Chocho, tarwi	*Lupinus mutabilis* Sweet
Bambara groundnut	*Vigna subterranea* (L.) Verdc.
Jack bean	*Canavalia ensiformis* (L.) DC.
Grasspea	*Lathyrus sativus* L.
Lablab	*Lablab purpureus* (L.) Sweet
Pigeon pea	*Cajanus cajan* (L.) Huth
African yam bean	*Sphenostylis stenocarpa* (Hochst. ex A. Rich.) Harms
Kersting's groundnut	*Macrotyloma geocarpum* (Harms) Maréchal & Baudet

3.3 | Pulses for restoring degraded soils

As described in chapter 1.1, 33 percent of global soils are degraded. Soil degradation is a multi-faceted process manifesting in a variety of forms and affecting about 1.5 billion people. Globally, 78 percent of degraded lands are in humid areas (Bai et al., 2008). Land degradation has accelerated during the last two centuries due to increasing population pressure and higher demand for food, forage, shelter, energy and other requirements. This, in turn, led to soil erosion by wind and water, soil contamination, soil acidification and sodification, soil sealing, soil nutrient imbalance, loss of soil organic carbon, soil compaction, waterlogging and loss of soil biodiversity (FAO and ITPS, 2015). It has been estimated that in the last two centuries, humans have cleared or converted 70 percent of the grasslands, 50 percent of the savannah, 45 percent of the temperate deciduous forest, and 27 percent of the tropical biomass for agriculture (FAO, 2011).

According to Lal (2004), land degradation is a challenge especially in drylands and those areas where natural resources are scarce. For instance, desertification causes disturbance of plant-microbe symbiosis which are a critical ecological factor in helping further plant growth in degraded ecosystems (Requena et al., 2001). In this framework, it is to be mentioned that soil is a non-renewable resource within human lifespan and that world is losing soil 10 to 20 times faster than it is replenishing. There is concern among soil scientists over the fast depletion of the soil resources, with 30 percent of arable lands worldwide becoming unproductive in the past four decades (Montgomery, 2010; Harteminh, 2008). Soil degradation hampers the ability of soil to provide ecosystem services enabling life on Earth and has to be halted and reversed toward the achievement of land degradation neutrality.

In recognition of the impacts of soil degradation on human well-being and the broad environment, national governments and the international community started to move toward the implementation of measures and policies to preserve and restore soil health. In this context, the Global Soil Partnership of the United Nations is supporting the process by endorsing international documents such as the revised World Soil Charter and the Voluntary Guidelines for Sustainable Soil Management, aiming to guide countries towards the practice of sustainable soil management and the achievement of a soil degradation neutral world. According to the Voluntary Guidelines for Sustainable Soil Management (FAO, 2016b), soil degradation should be minimized using sustainable soil management, especially through soil conservation approaches that proved to be successful. Soil rehabilitation and/or soil restoration should also be a priority, returning degraded soils to productivity, especially in historically sound agriculture or other production systems currently under threat.

Pulses can restore degraded soils by biologically fixing nitrogen, mobilize nutrients such as phosphorous, increase the amount of organic matter through root biomass and leaf fall, improve microbial biomass, and protect soil from erosion by keeping it covered and promoting the formation of soil aggregates through their deep root systems (Ganeshamurthy, 2009; Venkateswarlu et. al., 2007). Ganeshamurthy (2009) stated that pigeon pea both as monocrop and in mixed cropping with millets or groundnut, reduced run-off and soil erosion up to 59 percent in India. Pulses used as green manure or cover crops also helps to conserve soil moisture and reduce the amount of artificial inputs and agrochemicals to the crops. Indeed, by supporting soil biodiversity, pulses increase ecosystem resilience to pests and diseases and avoid the development of antimicrobials resistance (Howieson et al., 2000). The use of pulses in soil restoration, can be promoted by highlighting their high economic return per unit investment.

3.4 | Implementing the symbiosis

The symbiosis between soil and pulses and its effect is ultimately expressed in the cropping system. The inclusion of pulses in multiple cropping systems such as intercropping, or in simple crop rotations, is indeed considered important for the integrated management of soil nutrients and for moving towards conservation and organic agriculture (Amanullah and Khalid, 2016), see Box 12. In turn, this is of critical importance considering the need for intensifying food production while making better use of input resources and building resilience to climate change.

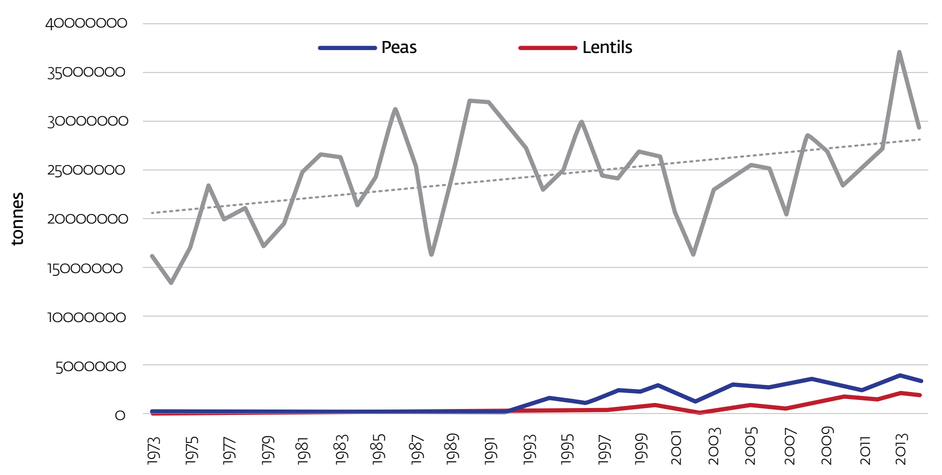
Box 12 | The Canadian success story

The Canadian Prairies play a very important role in the agricultural sector since they provide 32 million hectares of arable land (MacWilliam et al., 2014). In these semi-arid Prairies, the predominant cropping system has historically been the cereal-fallow rotations. This system was adopted in order to reduce soil moisture deficits which usually increase the risk of crop failure (Lupwayi and Kennedy, 2007). Additionally, the system relied on the intensive use of machinery for seedbed preparation and for weed control (Zentner et al., 2002). Production systems in these prairies have achieved an increase in crop yield and farm incomes and improved the use efficiency of needed inputs. However, soil and water erosion have contributed to the loss of soil organic matter which has negatively impacted the soil health and contributed to soil salinization (Zentner and Campbell, 1988).

Increasing concerns about soil and environmental degradation, together with the low prices of cereal grains and the redesign of government policies and programmes led to changes in land use practices and to the inclusion of pulses into the rotations (Zentner et al., 2002). According to Lupwayi and Kennedy (2007), the introduction of pulses in the Canadian Prairies has had a positive impact on biological soil processes. Soil biota is very important for agricultural systems as they can enhance crop performance by increasing mineral solubilisation, nitrogen fixation, production of plant hormones and suppressing pathogens (Lupwayi and Kennedy, 2007). Cereal-pulse rotations in the Canadian Prairies have contributed to increasing soil microbial population and enzyme activities which have positively impacted soil health (Biederbeck et al., 2005). Nitrogen recycling is also positively correlated with high soil microbial activity (Vigil and Kissel, 1995). Crop diversification in the Canadian Prairies has also contributed to mitigating diseases through biological pest control (Lupwayi and Kennedy, 2007). In general, the inclusion of pulses in wheat dominated agriculture has contributed to improving soil health, thus increasing sustainability of these cropping systems. Additionally, there is a large amount of nitrogen fixed by pulse crops in Canada and in 2004 this was as high as 171 million kg and represented 6.6 percent of the total nitrogen fertilizers used in the Canadian Prairies in the same year (Lupwayi and Kennedy, 2007), which means farmers can save money on the necessary inputs.

Additional to the environmental benefits provided by crop diversification in the Canadian Prairies, there is a very important economic benefit resulting from wheat production which could be maintained and even increased (Graph 1). Pulse production has already increased over time and represents a new source of income.

Graph 1 | Production of peas, lentils and wheat in Canada since the introduction of cereal-pulse rotations *(FAO, 2015)*



Inclusion of pulses in the cropping system needs to be viewed as a long-term benefit for resource conservation due to their ability to fix N, withstand drought (thanks to their low water requirements), and their lower dependence on external inputs like fertilizer. These characteristics contribute to making pulses an important component of a balanced and diversified cropping system (Kushwaha, 2007; IIPR, 2012). Besides being exuded from the roots during the growing season, N is also released into the soil through the decomposition of the crop residues. Legume residues decompose faster than non-legume residues, making more N available to the subsequent crop in the rotation than if a non-legume was grown (Singh et al., 2011). Rekhi and Meelu (1983) found that incorporation mungbean crop residues in a rice-wheat system not only added 100 kg N ha^{-1} to the soil, but also maintained high availability of N during various growth stages of a rice-chickpea system (up to 1.7 t ha^{-1}). On average, the nutrient contribution by these leaf litters varies between 8-15 kg N, 2.5-5.0 kg P and 8-24 kg K per hectare, see Box 13. Residue incorporation also resulted in higher soil available N (24.6%), P (11.5%), and K (18.5%) compared to the initial fertility levels. The pulse green manure (PGM) crops have C:N ratios of 14-15 at 30 days and 18-19 at 60 days (Table 14). At 30 days old, PGM mineralizes within 15 days to yield 41-43 percent biomass N, while at 45 days old a PGM crop took 30 days to mineralize the same amount of biomass N. A 60 day old PGM crop, when incorporated, released 20-30 percent of biomass N after 15 days and 26-30 percent after 30 days. The biomass N release rates depend on plant characteristics like lignin content, C:N ratio, N content, age of the residue, etc. (Rao et al., 2009). Examples of incorporation of green manure in the field are shown in Figures 8 and 9.

Table 13 | Phytomass/grain production and nutrient contributions by pre-kharif green manures (2003 to 2007). *Rao et al., 2009*

Green manure	Phytomass (t ha^{-1})		Grain yield (kg ha^{-1})		Lignin Content (%)		L:N ratio[1]	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Greengram	12.50-30.50	20.41	470-570	510	8.50-8.65	8.58	4.12-4.20	4.16
Cowpea	18.5-45.82	39.50	450-480	463	6.50-6.90	6.70	3.30-3.70	3.50
Sunhemp	43.00-95.89	65.54	-	-	4.00-5.20	4.60	1.43-2.60	2.02
Dhaincha	40.00-92.49	60.18	-	-	4.50-4.80	4.65	1.92-2.30	2.11

Nutrient Contribution and Rice Grain yield (t ha^{-1})

Green manure	N (kg ha^{-1})		P (kg ha^{-1})		K (kg ha^{-1})		C:N ratio	Grain Yield (t ha^{-1})
	Range	Mean	Range	Mean	Range	Mean		
Greengram	29-36	33	3.1-4.0	3.6	20-22	22	19.5	6.39
Cowpea	38-50	42	3.5-3.8	3.7	29-35	31	19.0	6.34
Sunhemp	89-103	94	8.5-9.0	8.7	77-82	77	14.0	6.40
Dhaincha	85-91	89	5.2-7.4	6.7	56-58	57	13.0	6.30
Fallow	-	-	-	-	-	-	-	4.70

[1] Lignine/nitrogen ratio

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Box 13 | Leaf litter of pulses

Pulses contribute to soil organic matter through leaf litter, owing to a short gestation period, high survival percentage and quick growth (Foresight, 2011). The decay rate of the leaf litter can be an indicator of the nutrient release rate of each species. A very rapid decomposition rate underscores the utility of the legume leaf mulch as an efficient soil enricher, as well as organic plant nutrient supplement, particularly for short duration crops. Leaf litter of leguminous species has also been found to hold promise as a fairly nutritive organic mulch for medium and long duration crops and to contribute to long term weed management. Mulch from pulses can also be used in agroforestry or as a bio ameliorant or nutrient accumulator (Budelman, 1988) (Figure 10).

Figure 8 | Leaf litter of some pulses

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Growing pulse crops in rotation with other crops also enables the soil to support larger, more diverse populations of soil organisms that contribute to maintaining and increasing soil fertility. A study conducted in a rice-cowpea cropping system in Mandya, India (Rao et al., 2009), indicated that INM and radiofrequency facet denervation (RFD) treatments supported higher microbial biomass than the control. The highest microbial biomass increase (97%) was observed with a combination of 50 percent NPK, 25 percent green manure (GM-N), and 25 percent farmyard manure (FYM-N). Similar trends were observed for dehydrogenase activity, which significantly improved with organic manuring and inorganic fertilizer application compared to the unfertilized control in acid soils. Microbial biomass carbon content increased in all the FYM treatments by 93 percent and 69 percent compared to the control and RFD treatments, respectively. Overall, the study indicated improvement in some of the soil microbial quality indicators with balanced fertilization, INM and sole organic manuring compared to the control at different sites. Incorporation of urdbean and mungbean residue raised the organic carbon level by 35.48 percent compared to the control. Residue incorporation also resulted in higher soil available N (24.6%), P (11.5%), and K (18.5%) compared to the initial fertility levels (tables 15 and 16). Soil physical parameters such as bulk density, particle density, percent pore space and water holding capacity (WHC) also improved under residue incorporation plots when compared to residue removal plots, see table 17 (IIPR, 2012). The study also recorded periodic increases in soil microbial biomass carbon (SMBC).

Table 14 | Microbial biomass carbon in maize and rice based cropping systems *(Ali and Venkatesh, 2009)*

Cropping system	Microbial biomass carbon (g g^{-1})			
	Control	Crop residue + biofertilizers + FYM at the rate of 5 t/ha	Inorganic fertilizers (NPKSZnB)	Mean
Maize-wheat	247	298	291	279
Maize-wheat-mungbean	327	350	338	338
Maize-wheat-maize- chickpea	310	338	334	327
Pigeonpea-wheat	295	305	301	300
Rice-wheat	262	305	300	289
Rice-wheat – mungbean	367	376	361	368
Rice-chickpea-rice – wheat	305	342	358	335
Rice-chickpea	301	336	338	325

Table 15 | Effect of pulse based cropping systems on soil chemical properties *(IIPR, 2012)*

Cropping system	Available P (kg ha^{-1})	Available K (kg ha^{-1})	Available S (kg ha^{-1})	DTPA –Zn (kg ha^{-1})	B (kg ha^{-1})
Maize-wheat	16.0	173.0	17.3	0.6	0.9
Maize-wheat- mungbean	17.2	186.0	19.4	1.1	0.9
Maize-wheat-maize- chickpea	18.0	185.9	18.5	0.8	1.0
Pigeonpea-wheat	16.8	183.2	19.1	0.8	1.0
Rice-wheat	18.55	234.2	14.10	1.68	0.86
Rice-wheat- mungbean	18.37	271.6	16.71	1.60	0.89
Rice-wheat-rice- chickpea	21.20	247.9	17.54	1.69	0.92
Rice-chickpea	21.55	243.4	17.15	1.82	0.93

Table 16 | Effect of crop residue incorporation on soil physical properties *(Singh et al., 2008)*

Treatments	Bulk Density (g cc^{-1})	Particle Density (g cc^{-1})	Pore space (%)	WHC (%)
Residue magement				
Mungbean 1	1.38	2.42	45.5	37.3
Urdbean 1	1.39	2.39	44.65	38.3
Mungbean 2	1.38	2.38	46.80	38.3
Urdbean 2	1.38	2.40	47.00	41.60
Mungbean 3	1.34	2.38	47.32	42.50
Urdbean 3	1.35	2.39	48.23	45.10
Mungbean 4	1.32	2.36	49.63	46.40
Urdbean 4	1.33	2.35	48.20	45.90
Control	1.44	2.50	38.15	33.40
CD (p=0.05)	0.05	0.10	3.51	3.8

Note: 1- Incorporation; 2- Incorporation + irrigation; 3- Chopping + incorporation; 4- Chopping + incorporation + irrigation

3.4.1 | Intercropping

Increasing interest in sustainability and environmental concerns have brought attention back to the practice of intercropping as growing two or more crops amongst each other (Ebanyat et al., 2010). Critical elements for the practice of successful intercropping are (a) no overlap in the time of peak nutrient demands of component crops, (b) minimizing the competition for light among component crops, (c) growing complementary crops, and (e) component crops should have a difference in maturity of at least 30 days (Siddique et al., 2008). The main advantage of intercropping is the more efficient utilization of the available resources and the increased cumulative crop productivity compared to each individual crop in the mixture (Agegnehu et al., 2008). Armed with deeper and more profuse root systems, pulse crops can utilize greater amounts of water stored in the profile and can stand drought better than the shallow-rooted crops. In general, the combination of two or more crops with different rooting patterns, such as combining a shallow rooted species with a deep rooted species, should give a better total water and nutrient extraction potential than either crop grown alone, or than the combination of two crops with similar rooting patterns (Matusso et al., 2012; Siddique et al., 2008).

The slow initial growth habit and deep tap root system of pulse crops such as pigeonpea makes them more suitable for intercropping with coarse cereals and oilseeds crops under rainfed conditions (see Figure 11) (Ali and Venkatesh, 2009). This is because the reproductive growth of these intercrops does not coincide with that of the main crop and the yield of cereal crops is not affected adversely (Singh et al.,. 2008). On the contrary, Bitner (2010) stated that the quantity and nutritive quality of cereals (protein content) increase following a pulse crop. In paired row planting systems such as pigeonpea-wheat and pigeonpea-sorghum, IIPR (2009) high productivity was achieved in terms of pigeonpea equivalent yield. In addition, companion crops to pigeonpea such as urdbean, mungbean, cowpea, soybean and sorghum appreciably suppressed the weed flora under both uniform and paired row planting (Figure 12). However, weed suppression under uniform row planting (1:1) was considerably higher (30.8 percent) than paired row planting (16.7 percent), mainly due to closer sowing. Of the various companion crops, cowpea was the most effective weed suppressor with the best suppression under uniform row planting (43.4 percent), followed by paired row systems (22.6 percent).

Figure 9 | Cereal based intercropping system

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Figure 10 | Pulse based intercropping *(IIPR, 2009)*

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Lentil + linseed intercropping (2:1)

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Chickpea + mustard intercropping

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Pigeonpea + sorghum intercropping (2:1)

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Pigeonpea + urdbean intercropping

Figure 11 | Intercropping of maize with black gram
Figure 12 | Row intercropping of maize with Arachis species

Pearl millet-urdbean and pearl millet-mungbean were found to be highly productive (land equivalent ratio >2), particularly in paired row system (2:1) (Kumar et al., 2012). Measuring the leaf area duration of a sorghum and pigeonpea intercropping system, Willey et al. (1983) reported that the leaf angle of crops affected the amount of light transmitted to lower components of the system, and influenced the distribution of the light to different levels of the leaf area within the canopy. Early and competitive seedling growth is highly desirable to partially control weed growth, especially in low input cropping systems. The growth of one species in a mixture may also may be suppressed by allelopathy, an important interaction in weed/crop combinations or in multiple cropping systems.

In India, maize is cultivated both during the rainy season (from April to October) and in spring (from mid-November to April/May). Sowing common bean and maize in a row ration of 2:1 resulted in a common bean yield equivalent of 1794, 998 and 2283 kg ha-1 in sole common bean, sole maize, and common bean, maize systems. High yields were obtained by sowing maize in every fourth row of mungbean/urdbean during the rainy season and after every row of vegetable pea during spring. In order to minimize the shading effects of maize over pulses, sowing should follow the North-South direction (IIPR, 2009). Medium and short cereal crop plants provide less competition for light to an under story legume or intercropped cereal of another species (Figures 13 and 14). Height differences between two components may be more important than the absolute height of each component, and the interaction of component crop height with relative planting densities must be considered. In the maize-bean system, however, a climbing cultivar of beans appears to have greater yield potential than a bush type with simultaneous planting (Francis et al., 1976).

Figure 11 | Intercropping of maize with black gram

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Figure 12 | Row intercropping of maize with Arachis species

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The beneficial effect of pulses is more pronounced in maize as compared to sorghum after chickpea and pigeonpea. Willey et al. (1983) reported that sorghum dry matter production was only 5 percent lower than monoculture crop yields, whereas pigeonpea dry matter production was 53 percent of a sole crop. In the study, the faster growing crop (sorghum) was planted at a density close to that of the sole crop and received little competition from the slower growing species (pigeonpea) early in the season. Similar results have been obtained from intercropping mixtures of two slow-growing understory species that have shorter maturity times than pigeonpea such as pigeonpea-soybean and pigeonpea-groundnut (Kumar et al., 2012). Sowing chickpea with barley and wheat at a row ration of 2:1 resulted in higher yields than mixing and broadcasting (Figure 16), however, barley genotypes differed in their suitability for intercropping with peas. Optimum mixtures vary with the species, density response of each component, type of intercropping system, relative prices for the crops, and alternative schemes for the greatest total exploration of the growth environment.

Figure 13 | Pulse based cropping system

3.4.2 | Crop rotation

Although soil productivity largely depends on a number of physico-chemical and biological characteristics, the ultimate output is governed by the practice of precise agronomic operations, matching crop production systems with land capability, efficient management of external inputs like seed, water, nutrients etc., and maintaining a synergy between conservation and exploitation of resources such as soil and water (Foresight, 2011). In this context, rotating different crops on the same land (crop rotation) may improve nutrient use efficiency (FAO, 2016a; Rao et al., 2013).For instance, growing nitrate catch crops such as pulses could substantially reduce nitrogen lost through leaching in humid and sub-humid regions (FAO, 2001a). In a crop rotation, the order of planting crops belonging to different families is planned for a period of two, three or more years. This way, the build-up of pathogens and pests that often occur when one species is continuously cropped, is mitigated.

Factors to be considered for planning a crop rotation are the soil type, the crop type, the desired duration of the rotation, the presence of livestock on the farm, the occurrence of pests and diseases, the price and availability of agricultural products, and the cost labor. Therefore, a good rotation should be adaptable to the existing soil climate and economic factors; based on proper land utilization; contain a sufficient number of soil improving crops to maintain and build up organic matter content of the soil; provide sufficient fodder for livestock reared on farm; arranged to ensure economic production and labor utilization; arranged to support weed control, plant diseases and pests; and provide maximum area under most profitable cash crop adopted in the area.

In the crop rotation, leguminous crops like beans, peas, groundnut, mung bean, black bean, cowpea, pigeon pea can be sown in-between the seasons of cereal crops like wheat, maize, mustard, vegetables and pearl millet (FAO, 2013). Thanks to the ability of pulses to biologically fix nitrogen, producers can apply less N fertilizers to the crops in the rotation while still getting high yields. The yield of cereals grown after pulses is usually 0.5–1.5 t ha-1 higher than that of cereals grown after cereals without N-fertilizer (FAO, 2015) (see Table 18). To generate equivalent yields in the cereal-cereal sequence, 40–100 kg fertilizer N ha-1 needs to be applied. Associated co-benefits of using pulses in crop rotation include improved nutrient cycling, soil tilth and soil physical properties, and ultimately enhanced weed control. Crop rotation may also influence the rate of N mineralization or the conversion of organic N to mineral N by modifying soil moisture, soil temperature, pH, plant residue, and tillage practices (Dalias, 2015).

Table 17 | Nitrogen economy due to inclusion of pulses in sequential cropping *(Subbarao, 1988).*

Preceding pulse crop	Following cereal	Fertilizer N- equivalent (kg N ha^{-1})
Chickpea	Maize	60
Chickpea	Rice	40
Pigeonpea	Wheat	40
Mungbean	Rice	40
Urdbean/mungbean	Wheat	30
Lentil	Maize	30
Fieldpea	maize	25
Rajmash	Rice	10
Cowpea	Rice	40
Cowpea	Wheat	43

3.4.2.1 | Efficient utilization of rice fallow lands with pulses

Efficient management of turn around period is critical in ensuring the success of rice based cropping systems. Zero tillage/minimum tillage after rice in uplands gives better grain yield in cowpea and mung bean compared to intensive high tillage. Puddling increases soil bulk density and adversely affects soil conditions by destroying granular crumb structure for subsequent rabi crops like wheat, mustard, potato etc. Various cropping patterns which included the production of various pulses during rice fallow in mixed systems using brown manuring has increased bulk density, total P and exchangeable K, Ca, Mg and decreased water stable aggregates, soil pH, CEC, organic carbon, total N and C:N ratio. Using such rice fallow after the rainy season, can potentially support a winter pulse after rice depending on soil type and depth (Vishwakarma et al., 2006). Following are some of examples:

Rice-pea: According to Vishwakarma et al. (2006), paddy rice is harvested during the second week of November and peas are sown on the third week of November in order to make use of the residual soil moisture. Substantial water is saved by planting upland crops into rice stubble immediately after the harvest in medium and heavy textured soils when top surface moisture contents are close to saturation. In addition, this particular cropping system can further enhance the early establishment of upland crops and root penetration to lower layers before soil moisture is depleted. See Figure 16.

Figure 14 | Rice-pea

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Rice-Pea + Mustard + Beans + Radish + Maize: Rice is the main crop of this cropping system in which mustard seeds are broadcasted during the last ploughing. Although farmers do not follow a definite planting geometry, it was noticed that seeds of different crops are not mixed together when sowing. Grain legumes and oil seeds mature with residual moisture after rice, hence crop sequences in rainfed areas vary with soil types, particularly with the water retention capacity of soil. In bunded rainfed uplands (lateritic red loam soils), short duration rice crops could be followed by arhar, green gram or black gram for early sowing. On the other hand, horsegram, safflower and linseed could be harvested two to three weeks later when preceded by longer duration varieties of rice. Farmers believe that the higher the numbers of crops in rotation, the higher the assurance to have at least some operational income, since the likelihood is that not all crops would fail as a result of unforeseen damage (Vishwakarma et al., 2006). See Figure 17.

Figure 15 | Rice-Pea + Mustard + Beans + Radish + Maize

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Rice-Mustard + mungbean + Lady’s finger + Brinjal + Pigeon Pea:

Since short duration rice crops are grown during the rainy season, other pulse or mustard crops can be sown afterwards. After harvesting the paddy, mustard is broadcast in the field and seeds of beans, lady’s finger and maize are dibbled. Thereafter, brinjal are transplanted in the month of November. Under assured irrigation, it is possible to grow multiple crops per year by selecting proper varieties and making suitable adjustments to planting and sowing dates. Growing rice crops in summer and during the rainy season, followed by wheat/mustard/vegetables, recorded higher grain production over the total yield of rice-wheat and rice-mustard/vegetable (Vishwakarma et al., 2006).

Choice of mixed crop for brown manuring

Rice + mung bean or any other short duration pulse crop have been found to be the best cropping systems with 3.5 to 4 tonnes ha-1 total rice equivalent yield. Mung bean is a short duration (65 days) pulse crop which not only has high potential to be included in human diets, but also improves soil fertility. Brown manuring in direct seeded rice is quite an effective method for improving soil health, weed management and productivity (Figure 18). Mung beans have become a high-value cash crop, even on marginal land, with improved cultivars out performing traditional cultivars. Mung bean high yielding varieties truly deliver high yields when grown in the appropriate seasons with optimum inputs supplied at the right time (Bhatt et al., 2016).

Figure 16 | Brown manuring featuring pulses in rice fields

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3.5 | Recommendations

The implementation of the symbiosis soils and pulses constitute a vehicle to contribute to the achievement of the Sustainable Development Goals. The following recommendations are suggested to successfully implement this symbiosis:

- Promote the sustainable management of soils by implementing the revised World Soil Charter and the Voluntary Guidelines for Sustainable Soil Management;
- Invest in targeted research and extension programmes on the symbiosis under different geographic contexts;
- Capitalize in the long term through incorporating pulses in cropping systems for their carbon sequestration benefits;
- Increase the integration of pulses in cropping systems to complement the dietary needs, especially of the rural poor;
- Promote the adoption of the symbiosis between soils and pulses by making use of good practices and providing incentives that facilitate uptake;
- Develop awareness raising campaigns to demonstrate the multiple benefits of adopting a soil-pulses symbiosis; and
- Capitalize on the combined environmental (increased soil health) and socio-economic (potential income generation) benefits of producing pulses – to increase income and improve soil and human health.

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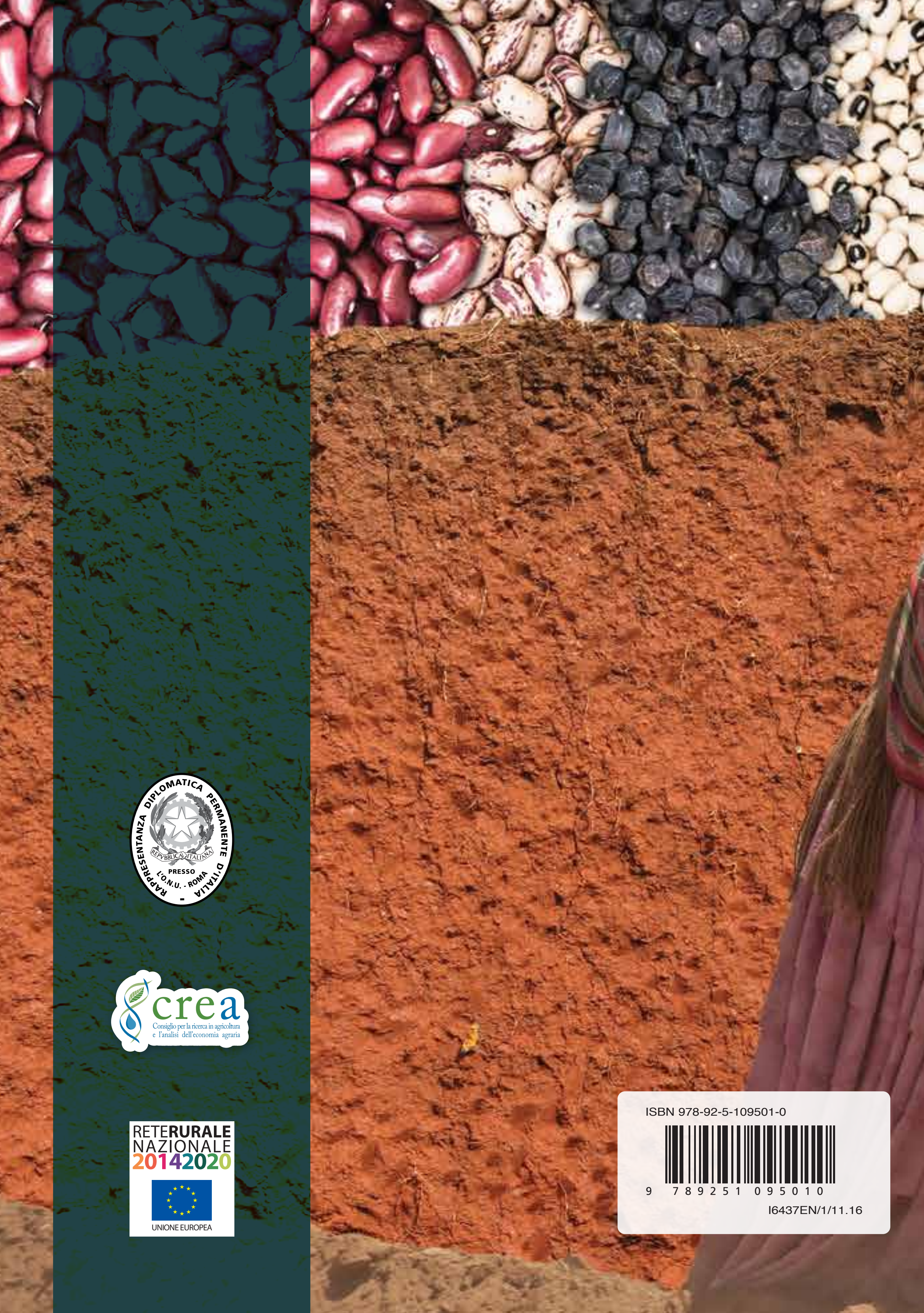

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