INTERACTIONS BETWEEN AGRICULTURAL MANAGEMENT AND SOIL BIODIVERSITY: AN OVERVIEW OF CURRENT KNOWLEDGE

EDITED BY DIEGO SOTO-GÓMEZ, MERRIT SHANSKIY AND DAVID FERNÁNDEZ-CALVIÑO

NOVEMBER 2020

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PROLOGUE

Soil is a fragile and limited resource that has a profound impact on human well-being and health, as it is a major source of food and raw materials. Soil is essential as it cleans the air and water and maintains biodiversity. Therefore, soil is a system that has increasingly gained international relevance, and along with it, the need to elucidate how to manage our soils in a more sustainable way. This ultimate aim connects with the UN Sustainable Development Goals and several European initiatives (e.g. Green Deal, From Farm to Fork).

The SoildiverAgro H2020 project focuses on enhancing soil biodiversity, in order to increase soil fertility and plant growth and more specifically, within the framework of work package 2, this project aims to answer the critical questions regarding what are the most pressing problems and challenges in current agriculture. This has been addressed by performing surveys and organising discussion groups with all related key sectors (i.e. researchers, farmers, agronomic technicians, manufacturers, NGOs, public administrations, associations of consumers, etc.) that were actively involved. By adopting this multi-stakeholder approach, the main issues in modern agriculture have been defined and, through an exhaustive process of data compilation and literary review, the most promising management practices have been identified.

This book provides a comprehensive analysis of several crop management systems that can improve crop production and quality while enhancing soil quality, using socially acceptable, economically viable, and environmentally friendly techniques that favour soil biodiversity (regarding both macro- and microorganisms). Each chapter will open and discuss a certain aspect of soil biodiversity.

The importance of soil biodiversity is something that is often overlooked in the design of cropping systems. We often forget that soil biodiversity and its functional groups are the drivers and carriers of agrotechnologies that support and perform processes in soil.

With crop diversification (e.g. intercropping, multiple cropping, rotations, etc.), and its effect on soil macro- and microorganisms, the soil becomes a live medium and supportive environment which facilitates the functional basis for the overall ecosystem as we know it today.

Soils are very diverse and require site-specific, suitable tillage methods. Thus, tillage has a direct impact as a modifier of living habitats on belowground communities inhabiting cultivated soils.

Soil is a complicated functional system, where different soil fauna groups are linked within the food web. If the food web has enough loops and links, the soil fauna are strong and kept in balance, and are able to maintain control over populations of pathogenic fungi that affect certain crops.

Healthy soil promotes plant growth, mediated by different types of bacteria. There are also direct links between soil contamination and soil biodiversity, and today we are losing our soil biodiversity to overall environmental pollution. Often we do not grasp the importance of soil biodiversity loss, as we do not tend to observe it in our normal everyday lives. As soon as the environment becomes detrimental to aboveground species like butterflies, bees, koalas, birds, trees and flowers, we then begin to realise the scale of these changes.

Nowadays, soil degradation is estimated to affect up to 7 million hectares annually. We have increased the use of synthetic fertilisers; and in some areas, we are close to reaching our limit for resource extraction. It is vital to manage soil fertility, in different agroecosystems, in ways where plants and soil biodiversity can interact via robust connections, in order to sustain the surrounding environment.

As climatic conditions are changing, and our food cultures struggle with the changing weather and random pathogen outbreaks, there is greater need to develop warning systems that allow for early detection of pest- and pathogen outbreaks. Well-timed decisions in the fields can allow reductions in the use of agrochemicals, which will eventually contribute to a cleaner environment, and a reduced ecological footprint regarding pesticide residues in the surrounding environment. Soil quality is a parameter that depends on human activities and agricultural manipulations with regard to soil. The cultivation of cover crops has direct advantages on soil biodiversity, via the use of a diversity of plant species. Certain plant species are able to diminish harmful effects of pesticide residues on soil, through acting as trap crops while maintaining productivity and soil quality.

The present book includes all the mentioned topics in eleven chapters, plus a final chapter dedicated to a review analysis that will help farmers decide whether to use a specific tool, and help decision makers understand farmers' soil management decisions. This book has been possible thanks to an international and multidisciplinary collaboration among public and private agricultural sectors, to which the authors are grateful.

THE EDITORS

CONTENT

CHAPTER 1

TOWARDS AGROECOLOGICAL INTENSIFICATION: RELYING ON SOIL BIODIVERSITY FOR DELIVERY OF ECOSYSTEM SERVICES IN AGRICULTURAL SOILS

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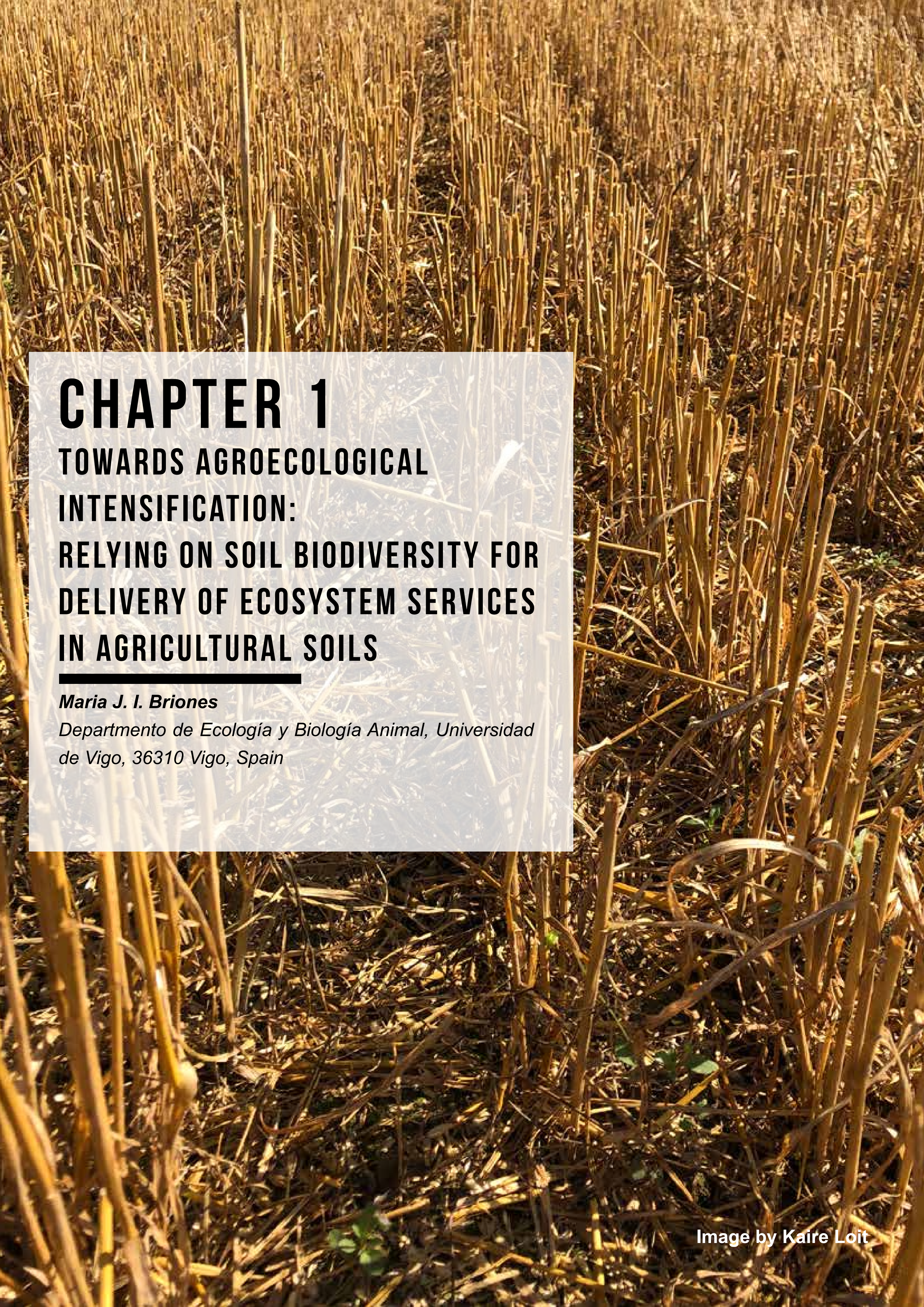

Image by Kaire Loit

ABSTRACT

Agricultural soils cover around 37% of Earth's land surface, and this percentage is expected to increase to meet future demands by the growing human population. Soil biodiversity is a crucial component of cultivated soils, but intensive agricultural practices interfere with the majority of the key soil functions performed by soil organisms. Despite the pivotal role of soil biota in promoting plant growth and soil fertility, they are typically ignored when designing soil protection guidelines, planning land use conversions and land management changes, or while implementing new soil management policies. This is the result of considering the soil as merely a substrate for growing food or building infrastructure; and consequently, we remain oblivious to the fact that, without this below-ground biodiversity, we cannot sustain the services we enjoy above-ground. This chapter provides quantitative data that demonstrates the need to integrate soil biodiversity within current agricultural practices. The focus is placed on promoting soil "internal inputs" rather than increasing "external inputs", if the aim is to achieve more sustainable production of agricultural goods.

Keywords: agricultural practices; soil biota; soil functions; soil threats; sustainability.

1. INTRODUCTION

The success of the agricultural revolution led to rapid increases in the human population as a result of more efficient agricultural practices and, in turn, higher productivity rates. The scaling up of agricultural intensification has resulted in more than 80% of human food worldwide being derived from less than a dozen crop species (Herrera and Garcia-Bertrand 2018). As a consequence, more focus has been placed on protecting crops via massive applications of pesticides together with mineral fertilisers, rather than on maintaining the substrate (soil) and the organisms (soil biodiversity) living in it.

Agricultural intensification not only relies on greater chemical inputs, but also the use of heavy machinery such as tractors and implements (plough, harrow, chisel-disks), seeders, harvesters, etc. that boost production and sustain large-scale production. Although saving labour, the use of these devices results in profound changes in the soil environment (e.g. compaction, soil organic matter depletion, acidification, salinisation and pollution), which may lead to important alterations within soil communities, in terms of abundances, community structure, life-cycles and their interactions (e.g. food web effects). For example, intensive agricultural practices have direct negative effects on larger-sized organisms (e.g. earthworms, predaceous collembolans, and mites) (e.g., Tsiafouli et al. 2015; Briones and Schmidt 2017; Lago, Gallego, and Briones 2019). Consequently, soil communities in intensive systems tend to be dominated by smaller organisms, such as microbes and nematodes, and their populations primarily consisting of juveniles. These effects on soil food webs not only results in fewer species, but also the disappearance of key functional groups (a group of organisms that similarly affect a given process) and, with them, the services they provide for the functioning of these agroecosystems.

According to the FAO approximately two-thirds of agricultural land is used for arable crops (namely one-third for permanent grasslands and meadows, and one-third for permanent crops) (European Union 2015). As the world population is expected to rise to ten million (i.e. ten thousand million, or 109, as defined on the short scale) by 2050, the FAO anticipates that agricultural demand will increase by 50%, compared to 2013 (FAO 2017). As a result, we will need to either increase our land conversion rates or foster more efficient and sustainable management practices to meet future food demands. However, based on historic trends indicating that, despite an increasing human population, the total area harvested has remained relatively constant over time (FAO 2018), future increases in crop production rates may largely stem from agricultural intensification within existing soils (Kopittke et al. 2019). This will reduce the ability of soils to provide their many ecosystem services and, for this reason, a number of EU policies have been formulated that aim at maintaining, restoring and where necessary enhancing the provision of ecosystem services (Schulte et al. 2019).

The concept of High Nature Value farmland (HNVf) ties low-intensity farming systems to the support of high levels of biodiversity (Andersen et al. 2003). This means that at least 10% of the national utilised agricultural area should be managed under low- or no production (Pe'er et al. 2017). However, HNVf amounts to one-third of Europe's utilised agricultural area (European Union 2012). An HNVf indicator was established under the EAFRD (European Agriculture Fund for Rural Development) by implementing the Regulation 1974/2006/EC, in order to introduce environmental concerns into the EU Common Agricultural Policy (CAP). However, the indicator definition is only based on land coverage and biodiversity data from protected areas (Natura 2000), since current methodology in most EU Member States is not sufficiently developed to provide reliable measures of the condition of HNVf areas (Paracchini et al. 2008). Nevertheless, EU Member States are strongly encouraged to continue developing and refining the approaches used, so that quality/condition may be incorporated into future HNV assessments.

As an alternative approach, land sparing combines agricultural intensification with set aside areas for biodiversity conservation; and therefore, the focus is on services provided by protected areas that cannot be fulfilled by agricultural areas. Since most of the available evidence indicates that species benefit more from less intensive management, some studies advocate for land sparing as a promising strategy for reconciling high-yield agriculture with wildlife conservation (Phalan et al. 2011).

However, the dilemma of whether land sharing (low-yield wildlife-friendly agriculture) or land sparing (high yield agriculture together with protected areas for biodiversity) is better for ensuring sufficient food production, while preserving biodiversity, has not yet been fully resolved (Fischer et al. 2014; Kremen 2015).

In order to move forwards, other wildlife-friendly farming methods have been proposed, including those based on agroecological approaches, aimed at increasing productivity while regenerating biological interactions and functional properties (soil health, water storage, and pest and disease resistance) leading to sustainable, resilient systems (Bommarco, Kleijn, and Potts 2013; Kremen 2015). A better understanding of the potential benefits of using biological processes to develop more environmentally friendly management practices should require the inclusion of maintaining soil biodiversity as an integral component of the planning process.

In this chapter, the different contributions of soil biodiversity to ecosystem services in agricultural soils will be discussed. The overall aim is to place an agronomic value on soil biodiversity, so that it becomes integrated into management practices. Placing the focus on this valuable "internal input" could help reduce, or even stop, current intensive practices relying on "external inputs", in order to maintain or increase crop yields.

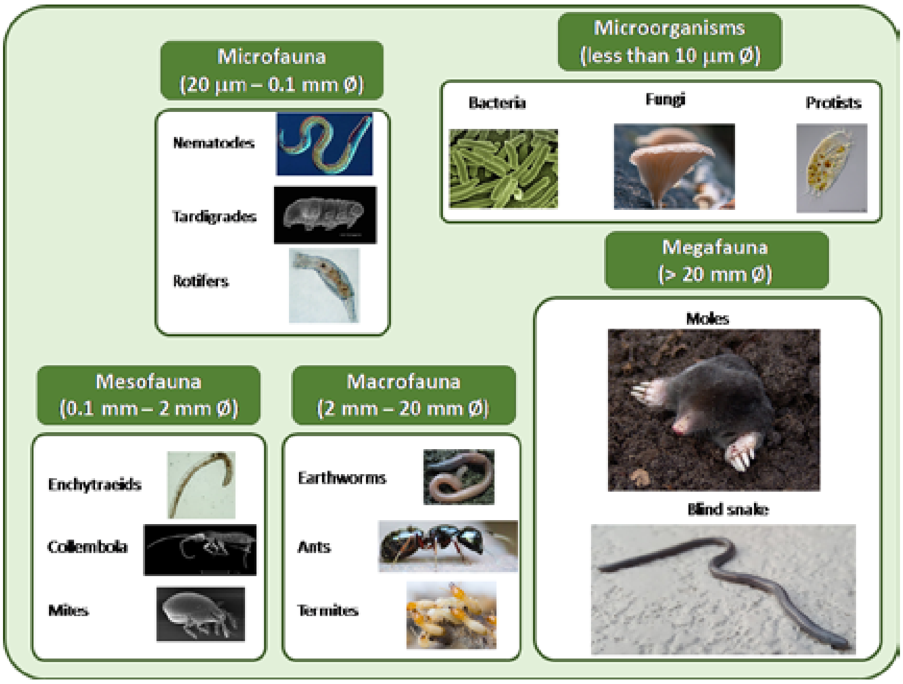

Figure 1.1. Soil biodiversity classification using body size (after Orgiazzi et al. 2016).

2.1. PROVISIONING SERVICES DELIVERED BY SOIL BIODIVERSITY

Soils and their biota are essential for agricultural production, and thus, they are key for the provision of the majority of our food. Nearly all crops are host plants for mycorrhizal fungi, on which they are highly dependent for maintaining plant fitness, via promoting nutrient and water uptake, as well as enhancing defenses against environmental stress and crop pests (Delavaux, Smith-Ramesh, and Kuebbing 2017; Fig. 1.2). Due to their strong specifity, selecting specific arbuscular mycorrhizal taxa for a given crop species represent the most promising approach for enhancing crop growth (Van Geel et al. 2

Other soil organisms affect plants by modifying plant phenology through changes in biotic (e.g. fungal biomass) and abiotic (e.g. soil structure) properties. Thus, it was observed that, in the presence of collembolans, flowering emergence of Poa annua was accelerated by two weeks (Forey, Coulibaly, and Chauvat 2015; Fig. 1.2).

Similarly, macrofauna, in particular earthworms, are known for their positive effects in promoting plant growth, by accelerating mineralisation of soil organic matter, improving soil structure, releasing plant growth regulators, stimulating beneficial symbionts and suppressing pathogens

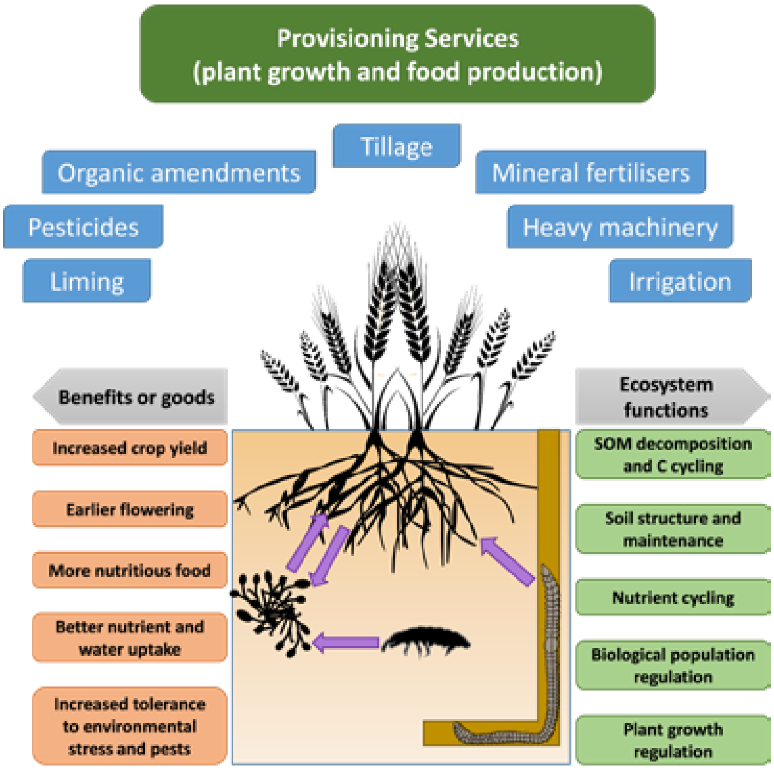

Figure 1.2. Contribution of soil biodiversity to provisioning services: plant growth and food production rely on soil biodiversity activities (e.g. accelerated mineralisation of soil organic matter, improved soil structure, release of plant growth regulators, stimulation of beneficial symbionts, suppression of pathogens) that underpin ecosystem functioning and result and direct and indirect benefits to humans. Certain agricultural practices have adverse impacts on soil organisms and, in turn, crop growths.

(Laosi et al. 2010; Fig. 1.2). A meta-analysis of the available literature on the effect of earthworm presence on crop yields indicated that their presence in agroecosystems leads to a 25% increase in crop yield, as well as a 23% increase in aboveground crop biomass (van Groenigen et al. 2015). Furthermore, the presence of an abundant earthworm community enhances not only crop yields, but also fruit quality, where nutrient content is increased under less intensive agricultural practices (Lago et al. 2015; Fig. 1.2). Therefore, more sustainable farming practices promoting greater abundances within critical soil taxa, will result in food with higher nutritional value. In relation to this, a global analysis has concluded that consumers who switch to organic fruit, vegetables and cereals would get 20-40% more antioxidants, with no increase in caloric intake (Barański et al. 2014).

2.2. SUPPORTING SERVICES DELIVERED BY SOIL BIODIVERSITY

Suitable soil for agriculture should have a "crumby" structure that holds soil organic matter and water, and should be resilient against different management practices. Biogenic aggregation (i.e. resulting from secretions produced by various soil organisms and plant roots) is a much faster process than physicogenic aggregation (i.e. through physical and chemical forces occuring during soil drying and rewetting, as well as organo-mineral interactions) (Silva Neto et al. 2016). For example, mycorrhizal fungi play an important role in the formation of water-stable aggregates and species belonging to the order Glomales secrete a sticky protein (glomalin) that binds soil particles (Wright and Upadhyaya 1996). Similarly, several bacterial polysaccharides have soil-adhesive properties (Akhtar et al. 2018). A global meta-analysis has shown that bacteria contribute strongly to both macro- (>250 µm) and micro-aggregates (<250 µm), while fungi typically strongly affect only macro-aggregation (Lehmann, Zheng, and Rillig 2017; Fig. 1.3). Besides microorganisms, mesofauna (e.g. collembolans, mites) and macrofauna (e.g. earthworms, termites), also contribute to the formation of both micro- and macro-aggregates by burrowing and casting (Six et al. 2002; Zanella, J-P., and Briones 2017; Fig. 1.3).

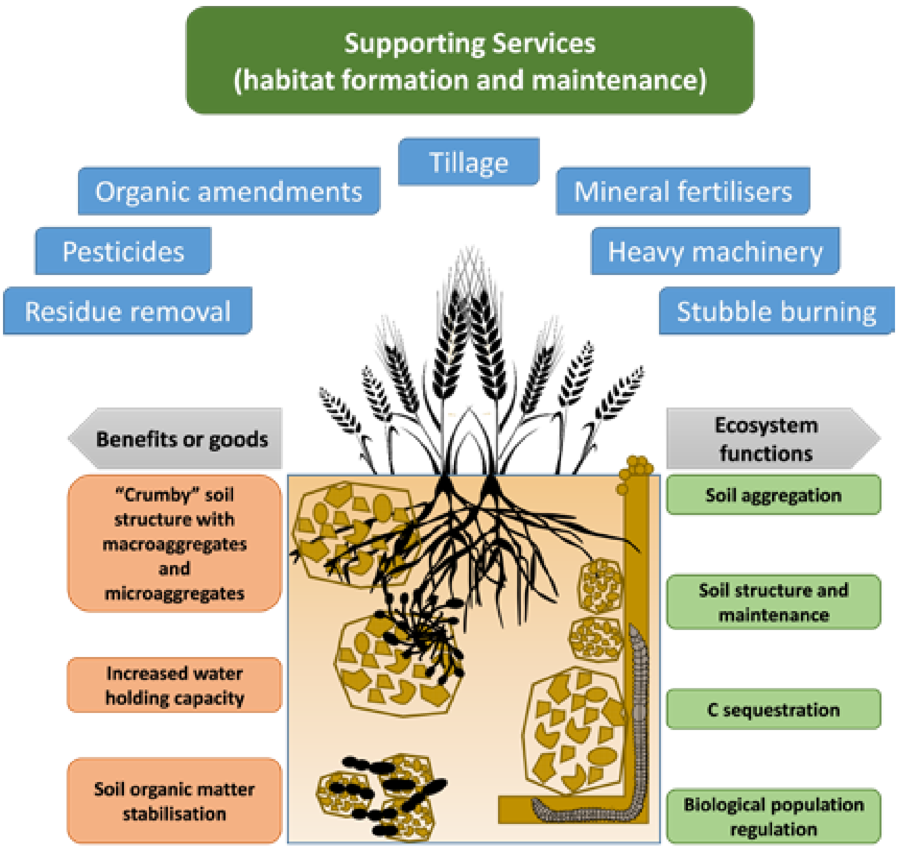

Figure 1.3. Contribution of soil biodiversity to supporting services: soil formation and maintenance rely on soil biodiversity activities (biogenic aggregation) that underpin ecosystem functioning and result and direct and indirect benefits to humans. Certain agricultural practices have adverse impacts on soil organisms and thus alter soil structure.

Intensive research on the influence of aggregate formation on soil organic matter stabilisation has highlighted an important distinction in this relationship (reviewed by Six et al. 2004). It was concluded that: (1) microaggregates, more son than macroaggregates confer long-term protection to soil orgnic matter; and (2) macroaggregate turnover is a crucial process, influencing the stabilisation of soil organic matter (Fig. 1.3). These findings have important implications for agricultural management, since macroaggregates appear to be less stable and more influenced by soil management than microaggregates (Sandén et al. 2017). Indeed, reduced tillage, as well as no-tillage with residue retention, have both shown to significantly increase carbon sequestration and soil aggregation in deep soil, compared to conventional tillage with residue removal (Wang et al. 2019; Fig. 1.3). Furthermore, the interactions between soil organisms offer opportunities for using soil biota mixtures to enhance soil aggregation in agricultural soils (Lehmann, Zheng, and Rillig 2017).

2.3. REGULATING SERVICES DELIVERED BY SOIL BIODIVERSITY

Regulating services include benefits, such as water supply and quality, nutrient cycling, climate regulation and pest control. The water holding capacity of soils is strongly linked to pore density, size and connectivity. Optimal conditions for plant growth occur when 60% of soil pore volume contains water (Künast et al. 2010), although water contained within micropores can be difficult for plant roots to extract. In contrast, macropores create easier pathways for the water to flow, and if they are connected they create preferential channels of water drainage (Fig. 1.4). Soil macrofauna, particularly earthworms, are important agents for creating macropores; and agricultural systems promoting earthworm abundance have seen significant increases in water infiltration (Capowiez et al. 2009).

Earthworms also affect soil mechanical and hydraulic properties, controlling surface runoff and erosion, through their burrowing activities (Bertrand et al. 2015). The density of burrows in temperate region soils has been estimated to range from 100 to 800 m-2 (Lavelle 1988), although higher densities have been recorded, depending on the soil type (Edwards and Lofty 1977). Furthermore, Bouché and Al-Addan (1997) found a positive relationship between water infiltration and earthworm biomass, with average estimates of 150 mm of water infiltrated per hour corresponding to an earthworm density of 100 g m-2. By using previous global biomass data on earthworm populations in conventionally tilled and no-tillage soils (Briones and Schmidt 2017), it is possible to estimate that adopting a no-tillage regime would increase water infiltration by nearly three-fold. It has been shown that 20 years of earthworm exclusion in grasslands due to additions of pesticides resulted in important reductions in infiltration rate, pH, soil moisture and organic matter contents (Clements, Murray, and Sturdy 1991). In addition

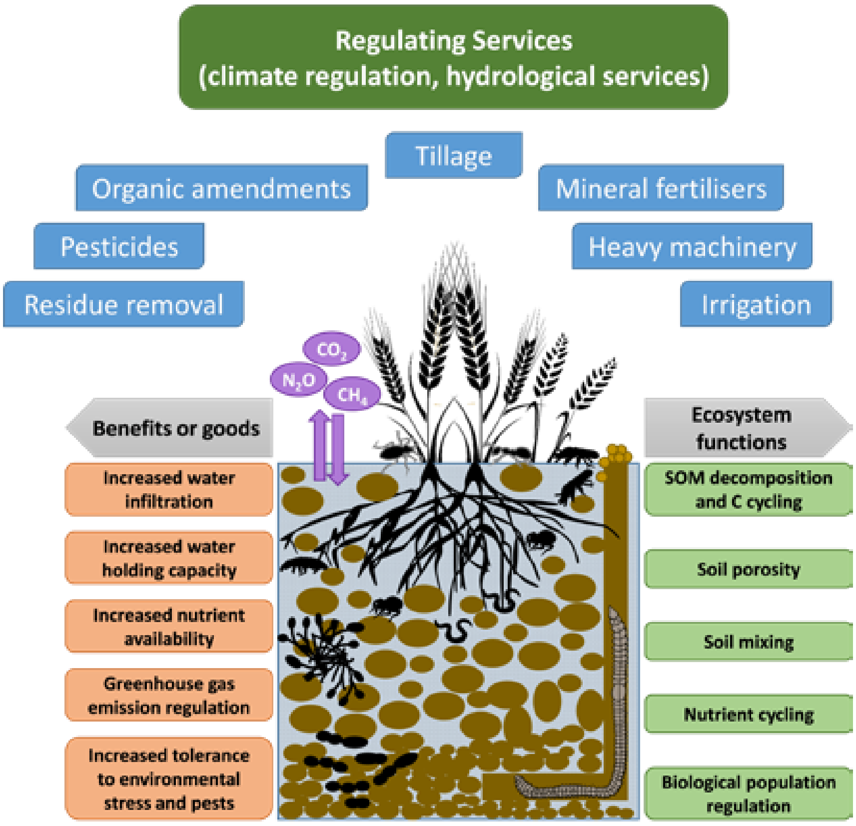

Figure 1.4. Contribution of soil biodiversity to regulating services: climate regulation and hydrological services rely on soil biodiversity activities (e.g. biopores, burrows, casts, decomposition of organic inputs, incorporation of plant residues in the soil, stimulation of beneficial symbionts and suppression of pathogens) that underpin ecosystem functioning and result and direct and indirect benefits to humans. Certain agricultural practices have adverse impacts on soil organisms and lead to soil degradation and fertility loses.

to burrowing, earthworms produce casts (Fig. 1.4), which hold more water than the surrounding soil, and up to 11-16% increases in soil water-holding capacity were observed in a microcosm experiment (Hallam and Hodson 2020). This could have important implications at the field scale since earthworms can produce several tonnes, in dry weight, of cast material per hectare per year (2-250 tonnes according to Edwards and Lofty 1972 and Bohlen 2002, or 293.6 kg year−1 ± 10%, per 100 g m−2 of earthworms according to Bouché and Al-Addan 1997).

Soil biota are essential for biogeochemical cycling which supports plant production (Bender and van der Heijden 2015). Every organism living in the soil contributes to the decomposition of organic inputs, either by fragmenting (e.g. macroarthropods such as bettles, woodlice or ants), burying plant residues (e.g. earthworms, ants, termites), degrading leaf constituents (e.g. fungi, bacteria) or by recycling detritus and grazing on microorganisms (e.g. mites, collembolans, enchytraeids) (Fig. 1.4). Some nutrients are consumed by various representatives of the soil food web and transferred between the trophic levels, while others leach into the soil, becoming available for growing crops.

By influencing nutrient dynamics, soil biota also play an important role in climate regulation. This is an essential service, since emissions from agricultural production currently account for approximately 13.5% of global greenhouse gas emissions (Mohammed et al. 2019). While both decomposition and metabolic processes of soil organisms contribute to carbon emissions, they also contribute to carbon sequestration (Fig. 1.4). The balance between carbon and nitrogen inputs and outputs determine whether soil biodiversity exerts a positive or negative feedback on greenhouse gas emissions, an issue that remains unresolved. For example, while one study has suggested that earthworm presence increases soil N2O emission by 42% and soil CO2 emissions by 33% (Lubbers et al. 2013), another has indicated that earthworms facilitate more carbon sequestration than mineralization (Zhang et al. 2013) and even offset CH4 emissions induced by rice straw amendments (John et al. 2020). These contrasting results could be a reflection of different experimental conditions, or the modulating effects of N fertilisation (de Vries et al. 2006). In contrast, there seems to be more consensus about the critical role of the ratio between fungal and bacterial communities on the carbon balance, and high ratios of fungi to bacteria usually lead to carbon accumulation and less CO2 being released into the atmosphere (Bailey, Smith, and Bolton 2002). Therefore, sustainable agricultural practices such as crop rotations, reduced or no-tillage, organic farming, and cover crops that shift the microbial community structure towards a more fungal-dominated community would enhance carbon retention (Six et al. 2006).

Aside from the positive effects on crop growth and soil fertility, soil biota can protect cultivated plants from diseases either through biological control or reduced susceptibility to pests (Fig. 1.4). For example, entomopathogenic nematodes have been successfully applied for biological control of insect pests such as mole crickets (Scapteriscus spp.), although standardised protocols are needed to predict further interactions between this inoculum and other soil inhabitants (Gaugler 1988; Helmberger, Shields, and Wickings 2017). In addition to reductions in the abundance of soil pathogens, some macrofauna may increase plant tolerance to parasites, where in one study, up to an 82% decrease in infested plants was observed when earthworms were present (Blouin et al. 2005). More interesting are tritrophic interactions, in which pest attacks on plants induce the release of secondary metabolites that attract predators of the pest (Maeda et al. 1999; Bonkowski, Villenave, and Griffiths 2009). Integrating the use of these plant compounds into current management practices may represent more sustainable crop management tools (Agut et al. 2018).

2.4. CULTURAL SERVICES DELIVERED BY SOIL BIODIVERSITY

The cultural benefits deriving from soil biodiversity are difficult to measure, as well as to implement in agricultural management and policies (Moroni, Arendt, and Bello 2011). They are considered as "non-material values" in the Millenium Ecosystem Assessment, and include spiritual enrichment, heritage inspirational and recreational experiences, health and well-being (Millennium Ecosystem Assessment and Assessment 2005). They are far less studied than the other three ecosystem services, which have associated monetary value, but recent studies have identified several cultural benefits provided by soil biota (Orgiazzi et al. 2016; Motiejūnaitė et al. 2019). According to these studies, the largest number of publications refer to the "utilitarian use" of soil organisms as sources of protein or medicine. Termites, beetle larvae and other insects are frequently consumed throughout the tropics (Anderson 2009), and it is well know that Makiritare Indians of the Alto Rio Padamo (Amazonas, Venezuela) consume giant glossoscolecid earthworms (Moreno and Paoletti 2004) (Fig. 1.5). Since the FAO (2013) indicated that consuming more insects could help fight hunger on the planet, and in 2015 Europe agreed to use insects as food, producing invertebrates, alongside with crops, could become profitable for farmers.

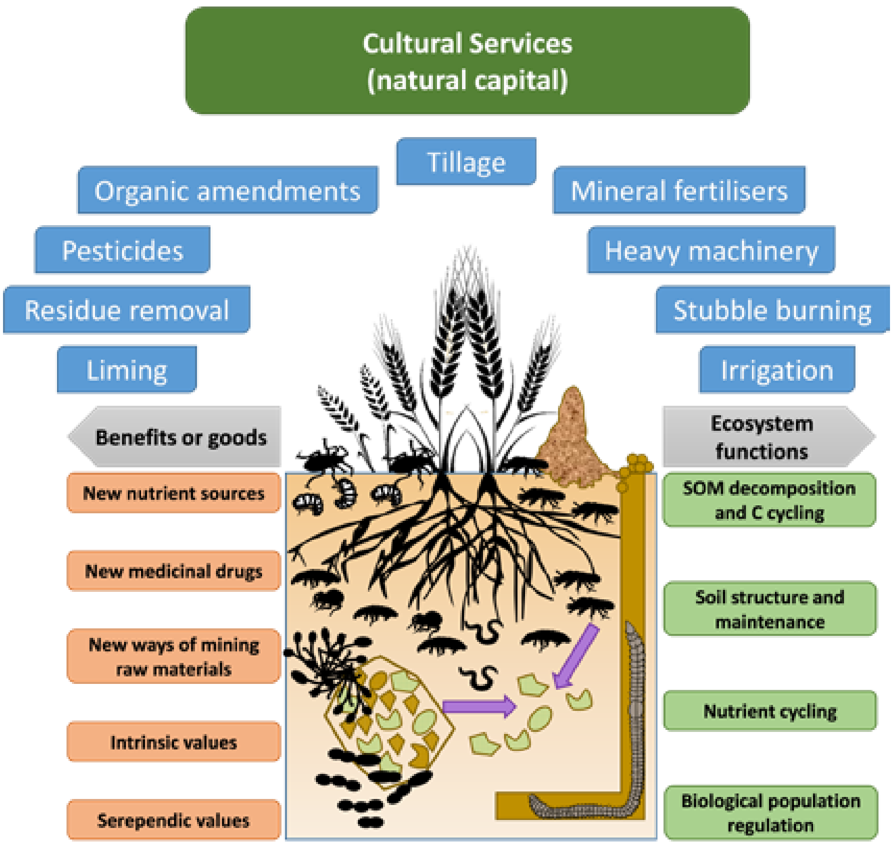

Figure 1.5. Contribution of soil biodiversity to cultural services: many other priceless values we retrieve from nature rely on soil biodiversity (e.g. protein sources, animal feed, metabolites as drugs, bioleaching of metals) and its interactions with the soil, the hydrosphere and atmosphere underpin ecosystem functioning and result and direct and indirect benefits to humans. Certain agricultural practices have adverse impacts on soil organisms and in turn, the present and future use of utilitarian and non-utilitarian goods from agricultural soils.

Aside from the well-acknowledged role of microorganisms as the main producers of half of the pharmaceuticals on the market today, there are other well-known uses of soil organisms in medicine. The remarkable spermatocidal effects of earthworm extracts have been long recognised (Fu-Xia, Bao-Zhu, and Hui-Yun 1992). However, less known are the use of microorganisms (bacteria and fungi) and termites as potential tools for “biomining”, a process that uses microorganisms to extract metals from ores through “bioleaching” (Le Roux and Hambleton-Jones 1991; Anderson 2009; Mubarok et al. 2017; Fig. 1.5). If land sparing is implemented other profitable activities by soil organisms could be operating alongside cropping systems.

“Intrinsic values” of soil biodiversity include social, spiritual, aesthetic, cultural, therapeutic and ethical benefits (Orgiazzi et al. 2016). For example, the bioturbation and burrowing activities of several soil organisms (e.g. earthworms, moles, badgers) have shown to aid the finding of archeological items, yet also contribute to the destruction of heritage sites (Motiejūnaitė et al. 2019). However, it has been argued that many of their activities have been only minorly exploited from an interpretative point of view (Canti 2003). In addition, there is a long list of linguistic and folkloric references to soil biota in many cultures, and they are commonly depicted in art, literature, cinematography, stamps, crafts, children’s literature, etc. (reviewed by Motiejūnaitė et al. 2019). Cultural events such as fungal forays organised by natural societies (e.g. British Mycological Society, Fungal Network of New Zealand), as well as public gatherings to catch earthworms at Blackawton (International Festival of Worm charming) and Willaston (World Worm Charming Championships), both in England, bring together common interest groups (families, wildlife photographers, naturalists, conservationists, etc.) as well as scientists. Certain recreational activities, such as fishing, often involve the use of earthworms and insects (grasshoppers, crickets, moth larvae) as fish baits, and have prompted a growing industry of live bait dealers for those who do not wish to gather their own bait. However, the lack of regulations on the use and disposal of unused bait has risen concerns regarding the increasing risks of species invasions (Kilian et al. 2012).

Finally, “serependic values” relate to services of soil organisms for future generations, but with thus far unknown values (Fig. 1.5). For example, organisms such as insect-associated fungi and bacteria, lichens, and many species of plants, some of wich complse the microbiomes of complex more organisms, may hold potential in drug discovery (Wright 2019). Thus, there are still many uses and non-utilitarian values to be discovered that might help us achieve UN Sustainable Development Goals (United Nations 2017).

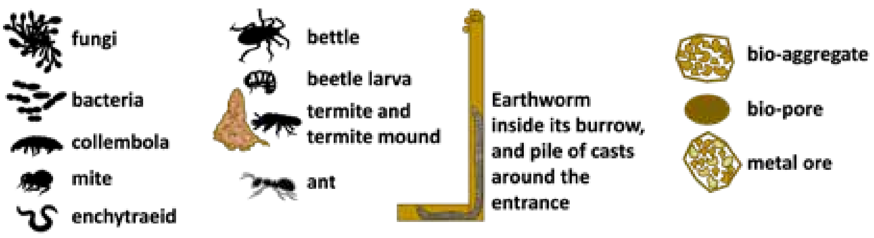

Figure 1.6. Pictorial legend

3. CONCLUSIONS

Numerous soil organisms, including various fungi, earthworms, beetle larvae, termites, and ants, are traditionally considered to be good indicators of soil fertility. This information has been known by many farmers since prehistoric times, and communities around the world use local soil knowledge to decide when to seed or how to fertilise their crops (e.g. Lauer et al. 2014). By promoting soil diversity or certain key soil organisms, farmers may benefit from enhanced soil structure, with more nutrients, while promoting crop growth and the plant tolerance to pests, and thus, become less dependent on agrochemicals. Furthermore, this understanding should increase by building knowledge exchange between researchers and practisioners (Pauli et al. 2016).

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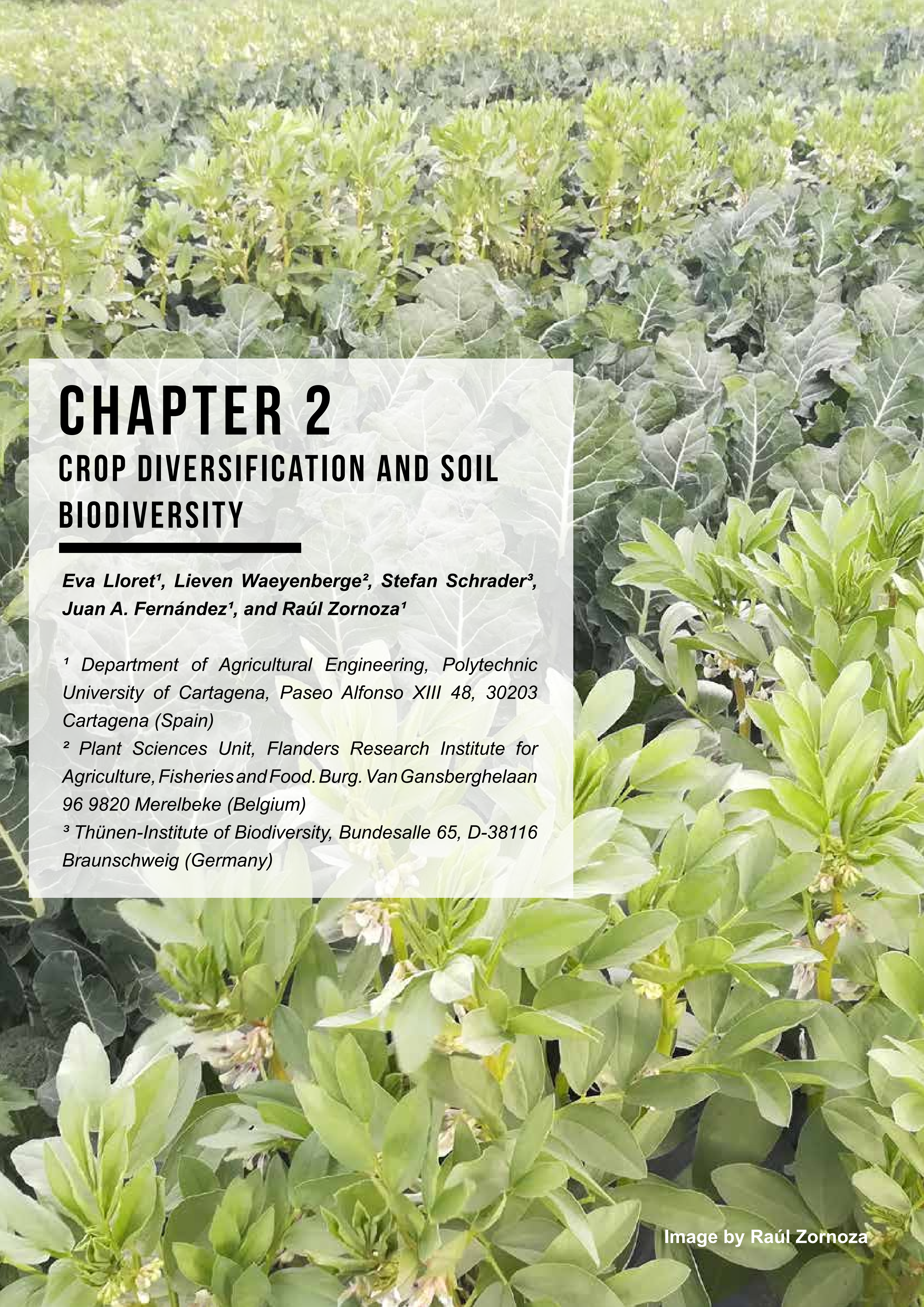

CHAPTER 2

CROP DIVERSIFICATION AND SOIL BIODIVERSITY

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Image by Raúl Zornoza

ABSTRACT

Crop diversification is an agricultural management strategy that includes practices such as crop rotation, multiple cropping, mixed cropping and agroforestry. Crop diversification may be employed by smallholder farmers in order to reduce their vulnerability in the face of a global environmental change, as well as provide economic, social, nutritional and environmental benefits. At the same time, strong links between the above- and belowground diversity have been well established. In particular, plant diversity, can influence soil conditions and have positive impacts on belowground communities and processes, while substituting for costly agricultural inputs. Meanwhile, soil biodiversity performs ecosystem services, and provides soil functions, that are essential for plant growth and agricultural productivity. Crop diversification could become an essential tool for sustaining production and ecosystem services in croplands, and should be considered an important management strategy in the context of soil sustainability and food security. However, there is still a need to identify crops and varieties that are suited to a multitude of environments and farmer preferences. To tackle this problem, participatory approaches like the initiative Agroecosystem Living Laboratories (ALL), which aims for the assessment of new and existing agricultural practices and technologies to improve their effectiveness and early adoption, should be implemented.

Keywords: crop diversification, soil biodiversity, agricultural management; soil microbial community, soil fauna, ecosystem services.

1. WHAT IS CROP DIVERSIFICATION?

Crop diversification within agroecosystems can occur in many forms, and with many levels of complexity over different spatial and/or temporal scales. Thus, diversification at the field–crop scale may refer to changes in crop structural diversity or vegetation management strategies. These strategies will allow discontinuity of monoculture by:

1. growing different crop species on the same land in successive growing seasons, via rotations;
2. growing different crop species within a growing season, using multiple cropping;
3. growing different arable crop species in proximity, in the same field, via mixed, row and strip intercropping;
4. alley cropping planting different arable or perennial species of rows of trees, via agroforestry strategies;
5. allowing non-crop vegetation within a monoculture.

Figure 2.1. shows different crop diversification strategies at the field–crop scale.

Figure 2.1. Top: Intercropped melon (Cucumis melo) with cowpea (Vigna unguiculata) (left); Agroforestry system between mandarin trees (Citrus reticulata) and fava bean (Vicia fava) (right). Bottom: Agroforestry system between almond trees (Prunus dulcis) and thyme (Thymus hyemalis) (left); intercropped broccoli (Brassica oleracea var. italica) with fava bean (Vicia fava) (right).

At the landscape scale, diversification may be achieved by combining multiple production systems, such as complex landscapes containing woodland areas, or agroforestry management with cropping, livestock, and fallow areas, in order to create a highly diverse agricultural landscape (Altieri 1999; Gurr, Wratten, and Luna 2003).

2. BENEFITS OF CROP DIVERSIFICATION

Diversification of agricultural production, via the introduction of a greater range of species or fallow periods, can lead to benefits at different levels, including both economic and social advantages. Crop diversification can increase income for small farm holdings, providing alternative ways of generating income, as well as increasing their capacity to withstand price fluctuations. Furthermore, it can result in nutritional benefits for farmers in developing countries, and can support a country or community intending to becoming more self-reliant in terms of food production. It can also reduce dependence on off-farm inputs (Clements et al. 2011; McCord et al. 2015; Makate et al. 2016).

Crop diversification also has enviromental benefits, and can be used to mitigate the effects of climate change, strengthening the ability of agro-ecosystems to respond to environmental stresses, improving resilience to drought and heat, as well as resistance to pests and diseases, and minimising environmental pollution, contributing to the conservation of natural resources (Clements et al. 2011; Degani et al. 2019).

Finally, the introduction of new cultivated species and improved varieties of crops has advantages on food production systems, enhancing plant productivity, plant and soil quality, health and nutritional value, and/or building crop resilience to diseases, pest organisms and environmental stress. For instance, the introduction of nitrogen-fixing crops, such as legumes, within a traditional cropping system, can improve the status of the soil, making atmospheric nitrogen available to other plants, thereby reducing the need for mineral fertilisers with their associated high energy costs and use of non-renewable resources (Clements et al. 2011; Isbell et al. 2017).

3. CROP DIVERSIFICATION AND SOIL BIODIVERSITY: ABOVE- AND BELOWGROUND INTERACTIONS

Agricultural practices have a profound effect on soil quality by affecting critical biological processes essential for many ecosystem functions. The agricultural management practices that have the most significant impact on soil quality are those used in intensive agriculture such as: massive diffusion and excessive use of broad-spectrum chemical fertilisers and pesticides; slash-and-burn shifting cultivation; soil tillage and compaction; reduction in crop biodiversity; and inadequate irrigation (Giller et al. 1997). The loss of soil biodiversity in intensive farming systems threatens fundamental self-regulating mechanisms such as pest control, pollination, control of soilborne diseases, organic matter mineralisation, nitrification, denitrification, etc., leading to reductions in agroecosystem functions and services, and turning farms into highly vulnerable systems dependent on external inputs (Altieri 1999; Altieri 2018; Barrios 2007). Soil biodiversity provides services that are essential for plant growth and agricultural productivity, such as maintenance of the genetic diversity essential for successful crop and animal breeding; as well as provision of nutrients, biological control of pests and diseases, erosion control and sediment retention, and water regulation (Swift, Izac, and van Noordwijk 2004). However, not only crops are strongly influenced by soil biodiversity; there is evidence that aboveground biodiversity can affect soil conditions and have positive effects on belowground communities and processes (Tiemann et al. 2015). In fact, the sustainability of soil nutrient cycles, and thus of soil fertility, depends on crop biodiversity, which leads to greater productivity and reduced nutrient losses in more diverse ecosystems (Tilman and Downing 1994; Tilman, Wedin, and Knops 1996). Thus, the greater the aboveground biodiversity, the greater the belowground biodiversity, with positive effects on crop production, soil fertility and disease control. However, despite the evidence of strong links between above- and belowground diversity, these interactions have not yet been included in the EU's Natura 2000 and the Habitats Directive, when the need for a better understanding has been recognised in the EU biodiversity strategy (van der Putten et al. 2018). Figure 2.2. depicts the interactions between below- and aboveground diversity.

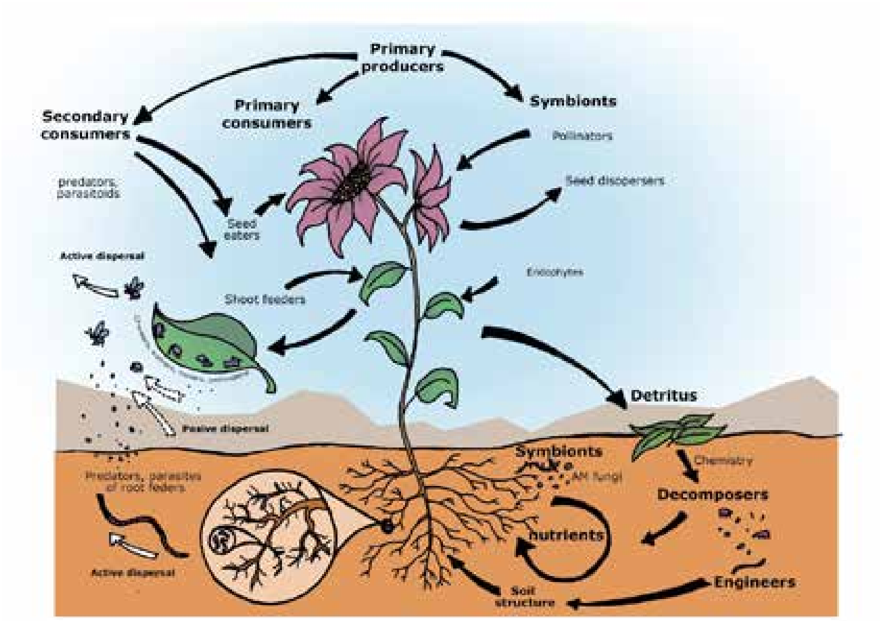

Figure 2.2. Interactions between above- and belowground biodiversity (Adapted from: De Deyn and Van der Putten 2005).

3.1. CROP DIVERSIFICATION AND SOIL MICROORGANISMS

Despite the fact that losses of biodiversity caused by intensive agriculture is a major worldwide concern, and that crop rotation and diversification can increase both crop productivity and diversity of soil macro- and microorganisms, the functional significance of changes in soil biological communities are still poorly understood. However, it has been observed that increasing temporal plant diversity can change soil microbial communities and enhance crop productivity through positive plant–soil feedback mechanisms mediated by soil biota (Zhou, Liu, and Wu 2017). An experiment with cucumber demonstrated that crop rotation increased cucumber yield and bacterial diversity, but decreased fungal diversity and abundance (Zhou, Liu, and Wu 2017). Furthermore, in diversified systems, the abundances of potential plant pathogens and antagonistic microorganisms are normally reduced, while potential plant-growth-promoting microorganisms increase (Kremen and Miles 2012; Leandro et al. 2018; Wen et al. 2016). For example, Tiemann et al. (2015) showed that crop rotational diversity enhanced belowground communities and functions in an agroecosystem. As crop diversity increased from one to five species, distinct soil microbial communities were related to increases in soil aggregation, organic carbon, total nitrogen, and microbial activity, while a decrease in carbon limitation was oberved. High diversity rotations, as well as intercropping or agroforestry systems, can sustain more diverse soil communities by increasing the quantity, quality and chemical diversity of plant residues and root exudates, with positive effects on soil organic matter and soil fertility.

3.2. CROP DIVERSIFICATION AND SOIL FAUNA

Aboveground diversity has been linked to soil fauna. For instance, Palmu et al. (2014) concluded that increased crop diversity was associated with increased ground-beetle activity and diversity in arable land, this beneficial effect particularly relevant in areas of intensive farming.

Nematodes are microscopic, but constitute a large proportion of the soil fauna. They are very abundant and diverse. One group in particular differs from other groups due to their specialisation in parasitising plants. Some species have only one plant family on which they can survive; other species can develop in a wider range of plants. The former group can easily be controlled by cultivating the host in a wide rotation with a low cropping frequency. The latter group can only be controlled by alternating hosts with tolerant or resistant crop varieties, preferably while monitoring the population dynamics of the pest. Unfortunately, often the farmer's knowledge on this group of nematodes and its host plants is limited, resulting in less optimal crop rotation systems (Nicol et al. 2011).

Cover crops can aid in diversifying crop rotation. However, there is no precise advice concerning the choice of cover crop, as the host status of such crops in relation to plant-parasitic nematodes is mostly lacking (Thoden, Korthals, and Termorshuizen 2011). Generally, it seems that applying a cover crop species mixture may contribute to controlling soilborne diseases like nematodes (Hajjar, Jarvis, and Gemmill-Herren 2008).

Next to plant-parasitic nematodes, other nematodes thrive in the soil. They are mostly beneficial, as they participate in improving soil fertility, soil disease suppression and soil structure. A more diverse crop rotation system seems to induce a greater overall nematode diversity (Burkhardt et al. 2019). However, other factors like the agricultural management system and soil characteristics may play a larger role (Quist et al. 2016).

A land-use change towards perennial crops is a strategy to diversify cropping systems at the landscape scale, and to reduce management intensity, which preserves the soil ecosystem, including soil-associated biodiversity. This strategy is currently the focus of discussion, especially in regions where a high ratio of maize (an annual crop) is cultivated as a renewable energy resource. Compared with maize, the cultivation of the perennial crops Agropyron elongatum (cv. Szarvasi-1) and Sida hermaphrodita, for instance, enhances earthworm abundance and species richness (Emmerling 2014). In the case of the perennial cup plant (Silphium perfoliatum), (Schorpp and Schrader 2016) found a significant increase in earthworm species richness and functional diversity from the fifth year of cultivation onwards. However, a study on the interaction between alien energy crops and native potworms and springtails elucidates the need for assessing possible allelopathic effects of these crops on soil biota (Heděnec et al. 2014).

4. A FARMER'S POINT OF VIEW

In recent decades, farmers have turned to intensive monocropping, as a result of economic incentives encouraging the production of a select few crops, the push for biotechnological strategies, and the belief that monocultures are more productive than diversified systems. However, farmers are now aware of the benefits of crop diversification, mostly through rotations; and they are including rotations in their cropping schedules, with the aims to reduce the incidence of soilborne diseases, increase soil fertility and improve soil porosity and water retention. However, intercropping and agroforestry strategies in Mediterranean climate regions are not widespread, since farmers believe that these kind of agricultural systems could negatively affect water availability to the main cash crop. Furthermore, in traditional orchards, farmers prefer the inclusion of alleys without vegetation, leading to intensive tillage and removal of cover- or alley crops, since a field in which the alleys have vegetation has traditionally been considered a "dirty" field.

5. CONCLUSIONS AND FUTURE PERSPECTIVES

Consideration of risks is pivotal for farmers when making agricultural management decisions (Chavas and Holt 1990; Leathers and Quiggin 1991). The major risks confronted include production risk due to uncontrollable events produced by climate change, and market risk due to uncertainty about future input- and output prices, and volatile global markets (Pannell, Malcolm, and Kingwell 2000; Moschini and Hennessy 2001). Both of these challenges are likely to be exacerbated in the near future. Relative risk is mitigated by the ability of soil to buffer adverse weather events, as higher abundances and diversity of soil organisms increases both the generation and reliability of soil ecosystem services (Altieri 2018; Koellner and Schmitz 2006). The increased delivery of ecosystem services can substitute costly inputs such as inorganic fertilisers, pesticides and energy (Altieri 2018; Thrupp 2000; Weitzman 2000; Figge 2004). Scientific evidence has demonstrated that crop diversification can increase expected farm profit and reduce agricultural risk in the future (Cong et al. 2014), improving stress resistance, resulting in more resilient systems (Lin 2011; Degani et al. 2019). Diversification could therefore become an essential tool for sustaining production and ecosystem services in croplands, rangelands and production forest, and should be considered an important management strategy in the context of soil sustainability and food security (Isbell et al. 2017).

There is a need to identify crops and varieties that are suited to a multitude of environments and farmers' preferences. Furthermore, the interacion between crop diversity and belowground biodiversity should be further evaluated to consider potential synergic intereactions. Participatory approaches increase the validity, accuracy and efficiency of the research process and its outputs. Researchers are better informed, and can better inform others, about traits that should be incorporated into improved cultivars. Participatory processes also enhance farmers' capacity to seek information, strengthen social organisation, and experiment with different crop species, cultivars and management practices (Clements et al. 2011). A promising approach in this context is the establishment of so-called agroecosystem living laboratories (ALLs), which aim for the assessment of new and existing agricultural pracitices and technologies to improve their effectiveness and early adoption (Anonymous 2019). An ALL implements the following components simultaneously: (i) transdisciplinary approach; (ii) co-design and co-development with participants; and (iii) monitoring, evaluation, and/or research on working landscapes.

The Global Soil Partnership and the Global Soil Biodiversity Initiative both represent outlets for further dissemination of expert-based knowledge, while a Global Soil Biodiversity Assessment is also being planned within the UN and FAO. This increased knowledge and awareness provides an opportunity for refining EU guidelines and directives, taking relationships between below- and aboveground biodiversity into account (van der Putten et al. 2018). However, economic incentives encouraging the production of a select few crops, the push for biotechnology strategies, and the belief that monocultures are more productive than diversified systems, have been hindrances in promoting this strategy (Lin 2011). Also, the majority of global agrobiodiversity is produced in smallholder food-growing systems (Zimmerer and Vanek 2016). Hence, there could be a need for governments to provide farmers with additional incentives to conserve soil capital, as a way to increase profits and reduce risks while promoting sustainable agriculture (Cong et al. 2014).

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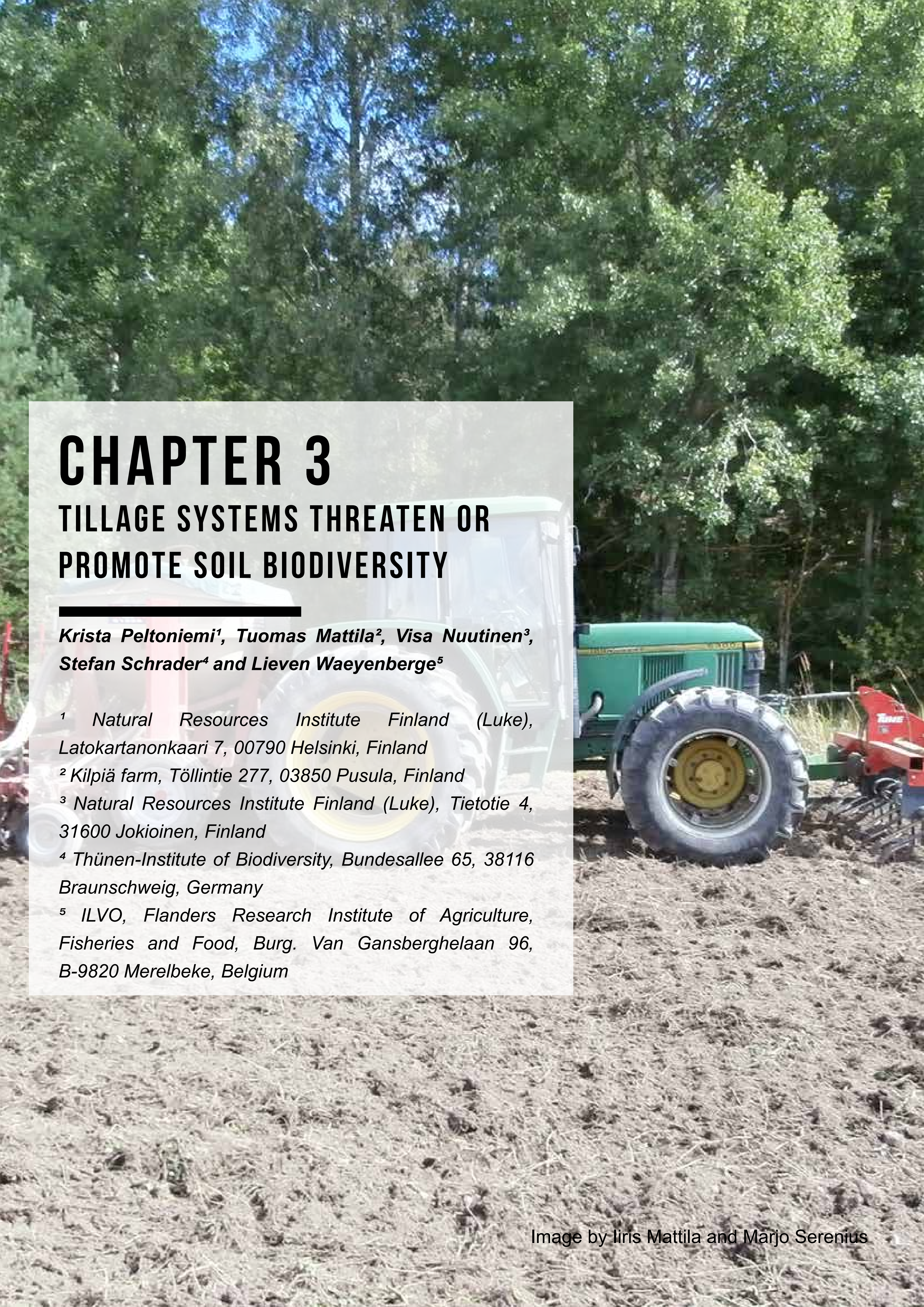

CHAPTER 3

TILLAGE SYSTEMS THREATEN OR PROMOTE SOIL BIODIVERSITY

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Image by Iiris Mattila and Marjo Serenius

ABSTRACT

Tillage is one of the most common soil management practices in agroecosystems worldwide. Conventional mouldboard ploughing is motivated by the efficient incorporation of crop residues, seed bed preparation and weed management. Ploughing induces many physical, chemical and biological changes in soil, with some well known negative effects. Reduced soil quality due to the loss of carbon and other nutrients, together with negative effects on soil structure, challenges the use of intensive and frequent ploughing as the ideal tillage regime. Ploughing also changes the composition of soil communities, and can lower both abundances and diversity of beneficial soil organisms. These include microbes and soil animals as: (i) chemical engineers in decomposing soil organic matter and recycling of carbon and other nutrients; (ii) biological regulators in controlling other soil organisms; and (iii) ecosystem engineers in forming and maintaining favourable soil structure. Their important contribution to ecosystem service provision in agricultural soils demands our understanding of the impacts of tillage on soil biodiversity. Reduced- and no-tillage systems, in conjunction with the retainment of crop residues as well as the application of diversified crop rotations, are known to promote soil biodiversity. There is a need to implement and further develop alternatives to conventional ploughing, as well as employ and preserve soil biodiversity, in order to improve the sustainability of agriculture. This chapter discusses major effects of soil tillage on soil organisms within a functional framework, in order to provide perspectives for their maintanance and enhancement in field management.

Keywords: tillage; soil biodiversity; soil quality

1. TYPES AND IMPACT OF SOIL TILLAGE

Soil tillage systems can be assigned to conventional-, reduced- or no-tillage systems (Table 3.1). Conventional tillage refers to mouldboard ploughing, which turns soil at up to depths of 15–35 cm (“inversion tillage”). Reduced tillage refers to treating only shallower soil, without turning; and no-tillage refers to direct seeding.

Tilling arable fields aims at incorporating crop residues, manure and other organic fertilisers, speeding up decomposition and nutrient cycling while controlling weeds and plant pathogens, as well as loosening, levelling and aerating the soil for seedbed preparation (Whalen and Sampedro 2010). Tillage thoroughly modifies the physical, chemical and biological properties of soil. Type and magnitude of the effects vary depending on soil properties, climate conditions and the tillage equipment used. For example, when soil is mouldboard ploughed seasonally, the topsoil organic matter content may decline, and the soil surface which is left bare by tillage becomes vulnerable to erosion and nutrient leaching (Palm et al. 2014). In soils prone to compaction, seasonal ploughing induces the development of a plough pan, separating top- and subsoil, as a barrier for root gowth and water infiltration. Furthermore, tillage can alter the inhabitable pore spaces for soil organisms, radically affecting their mobility.

Table 3.1. Tillage systems, according to mechanical impact on soil.

Tillage system	Impact on soil	Shallow (<8 cm)	Deep (~15-35 cm)
Conventional tillage	Inversion	Disc harrow, shallow plough	Plough
Reduced tillage	Mixing–no-inversion	Cultivator with sweeps, harrows (tine-, rotary-, straw-, power-)	Cultivator, spader, rotavator
No-tillage	No mixing–no inversion	No till	Subsoiler

2. STRUCTURE AND FUNCTION OF SOIL BIODIVERSITY

Soil biota can be variously grouped according to size or ecological role. Here we will use Turbé et al. (2010) classification which recognises three different guilds according to their functional role: (i) chemical engineers include decomposers such as bacteria and fungi, some protists, some nematodes, springtails, many mites, potworms and earthworms. They are responsible for decaying plant residues and controlling nutrient cycles; (ii) biological regulators are grazers on soil microorganisms, or predators of soil fauna, and thus shape soil communities in space and time. This guild includes many protists and nematodes, springtails, some mites, potworms and earthworms; (iii) ecosystem engineers modify soil structure by producing soil aggregates and pore networks, which provide habitat for smaller organisms, and control the soil water balance and soil aeration. Potworms and earthworms belong to this guild. This classification reflects the multifunctionality of soil organisms, and therefore certain soil biota may be assigned to more than one guild.

3. TILLAGE CHANGES SOIL BIODIVERSITY

Burial of surface residues during ploughing removes the living habitat of species associated with the litter layer. Natural galleries and pore spaces in the soil are disrupted, and soil temperature- and moisture regimes change. Frequent tillage may result in long term decline of soil organic matter, the resource base of decomposers; and this can reduce the soil’s ability to sustain populations. It is therfore not surprising that soil biodiversity benefits from low tillage frequency and intensity (Tsiafouli et al. 2015). In general, large bodied soil invertebrates, which are most vulnerable to physical damage caused by tillage, benefit the most from low physical disturbance (Kladivko 2001). However, not all soil organisms respond in the same way, as was shown in a literature review of 150 sources (van Capelle, Schrader, and Brunotte 2012). For instance, abundance and species diversity of springtails and mites decrease when tillage intensity is reduced; and potworms benefit from reduced tillage, though their abundance declines under no-tillage regimes (van Capelle, Schrader, and Brunotte 2012). In the following sections, we will describe tillage-induced changes in soil communities, using typical representatives of chemical engineers (bacteria and fungi), biological regulators (nematodes) and ecosystem engineers (earthworms) as examples.

3.1. CHEMICAL ENGINEERS: BACTERIA AND FUNGI

Generally, there is less microbial biomass in conventional tillage systems than in no-tillage systems (Whalen and Sampedro 2010). Based on results from more than 60 European multiyear field experiments, reduced tillage is often accompanied by a higher microbial carbon content, compared to ploughing (D'Hose et al. 2018). Bacterial potential to produce polysaccharides that promote soil aggregation, was not reduced after tillage (Cania et al. 2019); and another study reported that relative abundances of dominant bacterial phyla were similar between reduced tillage and no-tillage plots (Tyler 2019). These results suggest that bacterial communities are not strongly affected by tillage. Tillage has, however, been reported to alter the vertical distribution of soil bacterial- more than that of fungal communities (Sun et al. 2018). It is generally assumed that fungi are affected by tillage more than bacteria, since their large hyphal networks are disrupted by tillage. Fungi seem indeed to dominate over bacteria in no-tillage systems (Hendrix et al. 1986), and their hyphal length is shortened under tillage regimes (Oehl et al. 2004). In many studies, tillage has also been shown to be a major stress factor leading to a decrease in fungal inoculum potential (e.g. Jasper, Abbott, and Robson 1991; Usuki, Yamamoto, and Tazawa 2007; Al-Karaki 2013). Säle et al. (2015) found a high diversity of arbuscular mycorrhizal fungi under reduced tillage. Thus, no-tillage systems appear to be favourable habitats for both plant root-colonising mycorrhizal fungi and saprotrophs that grow on plant residues.

Often the impacts of tillage cannot be separated from the influences of other factors, such as conventional versus organic management, or the physical environment in which organisms live (bulk soil or rhizosphere). For example, Hartman et al. (2018) found that in conventional and organic management systems with different tillage intensities, soil bacterial communities were primarily structured by tillage; whereas soil fungal communities responded mainly to management type, with additional effects resulting from tillage.

Reduced tillage does not necessarily lead to a more diverse microbial community. Essel et al. (2019) suggest that changes in community composition can be explained by taxon loss, rather than taxon replacement. Therefore, microbial indicator taxa that respond to tillage methods could in some cases be more effective in detecting the direction of change than measures of overall diversity.

3.2. BIOLOGICAL REGULATORS: NEMATODES

Treonis et al. (2010) have reported increased number of decomposer microfauna after the addition of organic amendments and tillage at 0–5 cm depth, with a decline in the abundance of plant-parasitic nematodes. They observed that tillage alone reduced the relative abundance of fungus-feeding nematodes and increased the density of bacteria-feeding nematodes. Another experiment reported that tillage in general had little effect on densities of most nematode species examined, and crop rotation appeared to be more important than tillage for managing plant-parasitic nematodes (McSorley and Gallaher 1993). A study by Ito et al. (2015) reported that tillage inversion exerted stronger effects on the nematode community, compared to cover crop treatment and manure application. Organic farming is considered beneficial for soil biodiversity; however, frequent tillage operations, which are required for incorporating organic amendments or to control weeds, decreased nematode community diversity to the level observed in a conventional system (Berkelmans et al. 2003). It can be concluded that results on tillage impacts on nematodes remain inconclusive, and even contradictory. An approach that considers variation within and between different systems, soil type and climate is needed in order to reach more reliable and general conclusions. Molecular profiling of nematode communities can support these efforts (Bongiorno et al. 2019).

3.3 ECOSYSTEM ENGINEERS: EARTHWORMS

According to a recent meta-analysis, the density of earthworms was, on average, 137% higher in no-tillage soils, and 127% higher under reduced tillage, compared to ploughed soil (Briones and Schmidt 2017). Corresponding percentages for biomass in no-tillage- and reduced tillage soils were 196% and 101%, respectively. Positive effects built up over time, as effects were more pronounced in soils that had been under reduced tillage for more than ten years. Furthermore, these positive effects were relatively strong in warm temperate climates, and in fine-textured and clayey soils.

Earthworm species can be divided into three ecological groups: litter dwellers, shallow burrowers and deep burrowers. Litter dwellers and deep burrowers have been shown to benefit the most when soil is not ploughed (Briones and Schmidt 2017). This is understandable as inversion tillage turns their food source, crop residues, below the soil surface. The mentioned meta-analysis further showed that retaining crop residues on the soil surface generally amplifies the positive effects of reduced tillage. All earthworms are exposed to mechanical injuries caused by tillage implements. Ploughing can also bury them in unsuitable soil layers, an effect which may be particularly harmful for earthworm juveniles and egg capsules.

In arable soils, the impacts of earthworms are not necessarily beneficial in all instances and respects. Earthworm foraging can have detrimental structural effects in the topsoil (Shuster, Subler, and McCoy 2000); water and nutrient flow along earthworm burrows may be excessive (Shipitalo and Gibbs 2000), and earthworm activity increases gaseous emissions from soil, which may not be fully compensated by their simultaneous stabilisation of soil carbon (Lubbers, Pulleman, and Van Groenigen 2017). However, the increased abundance of earthworms under reduced tillage and no-tillage can be regarded as predominantly a beneficial change, thanks to their contribution to soil ecosystem services, such as increasing crop yield, as well as enhancing nitrogen availability (van Groenigen et al. 2015), water regulation (Andriuzzi et al. 2015), soil formation (Shipitalo and Le Bayon 2004) and biological control (Wolfarth et al. 2011).

4. A FARMER'S STORY

As a child in the 1980s, our farm landscape in Southern Finland was always black from October to April. The crop rotation consisting of spring cereals and mouldboard ploughing was the norm. In the 1990s, ploughing was gradually replaced with reduced tillage, using a tined cultivator on some of the area. When I started farming in the 2000s, I applied the knowledge learned during my years in university and had a good look at our farm's soils. Earthworms were few, soil aggregation was poor, roots were few and the soil was badly compacted. I had to do something.

My first step was to introduce grasses and legumes into the rotation, as I thought that stronger roots could improve the soil structure. I was partially right, but the soil was already compacted, and worsened with ploughing (then regarded as necessary); and terminating the grass ley made problems worse. I also had winter sown cereals, which seemed to work better than the spring sown variants. Even after ploughing down a good grass crop in autumn, our soils were hard in the spring, and required power harrowing to create a seedbed. Then, one year, I was surprised with the weather, which resulted in a big change in our tillage system.

2012 was a very wet year, and the growing season was cold. Consequently, our harvest of field beans was due to end in September, and many of the fields were already waterlogged. I had to leave the beans unharvested on one of my fields, and the undersown crop of annual ryegrass was left to grow until spring. When I started to till the soil in spring, I could not believe my eyes – the soil that was usually cloddy and hard looked like it came from a flower bed. The soil was crumbly, and easy to till and dig with bare hands. What had happened? I learned that our soils are silts, which have poor aggregate stability if the aggregates are not maintained and built over winter by living roots and soil organisms. This started our transition to using living roots as our main tillage implement (Figure 3.1a). Currently, we aim to be without plants growing in the soil for less than three weeks out of the year. We plant cover crops among each of our crops and allow the cover crops to overwinter (Figure 3.1b). The overwintered cover crops are gently mulched to the top of the soil with (low disturbance) cultivator sweeps, and the next crop is sown under the mulch layer.

Did the cover crops and continuous plant cover solve everything? Certainly not; however, our focus is now on improving soil structure and deepening the layer of active roots. We focus on good drainage and reducing compaction, through a combination of subsoiling and root activity. The combination of good soil structure, mulching and root activity has provided a beneficial environment for earthworms, which are a welcome addition to our arsenal of tillage providers. Nowadays, I'm surprised when there are less than four worms in a spadeful of soil.

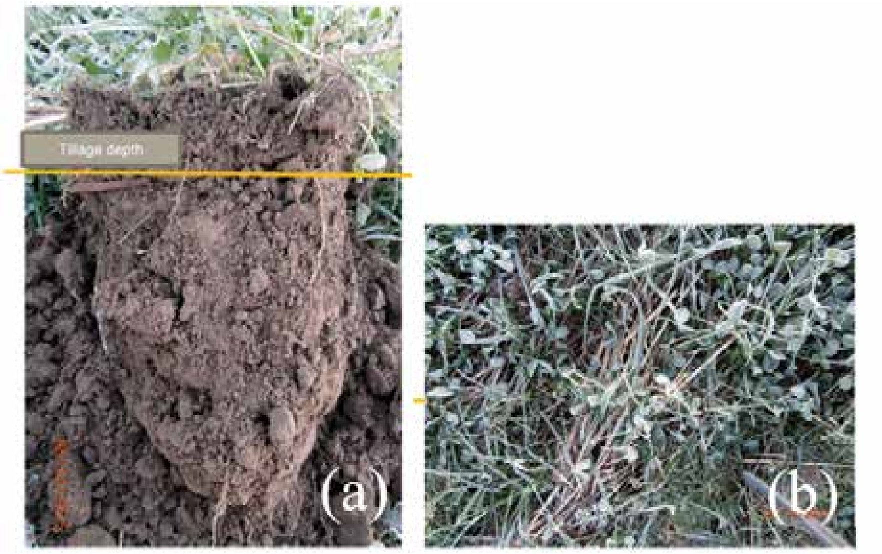

Figure 3.1. a) Soil tillage target for autumn, for silty and sandy soils: mulch cover, living roots and no compaction. b) Soil preparation in spring involves terminating the white clover cover crop with a pass of a cultivator and sweeps.

5. FUTURE PROSPECTS FOR SOIL BIODIVERSITY MANAGEMENT

Due to increasing awareness of the problems that intensive ploughing can cause, other systems such as reduced tillage and no-tillage regimes have been introduced. Conservation agriculture constitutes a set of practices where reduction in tillage is accompanied by retention of adequate levels of crop residues on the soil surface, as well as through the use of crop rotation. These practices are effective for erosion control, as well as for increasing soil organic matter content in the uppermost soil layer. The effectiveness of these practices in soil biodiversity conservation has been less consistent and needs to be more fully explored (Kleijn et al. 2019).

A diverse soil community is a key factor in preventing erosion as well as the loss of water, carbon and other nutrients; and there is a need for better understanding of how arable soil biodiversity is affected by management practices. Highly sophisticated methods for soil biodiversity studies are available, and they are continuously adjusted in order to provide the best available tools for identification- and quantification of soil life. We recommend strong collaborative research actions, in partnership with farmers from Europe in order to cope with future challenges in agriculture, which climate change will accentuate. This is necessary in order to preserve and develop a sustainable food production system for future generations.

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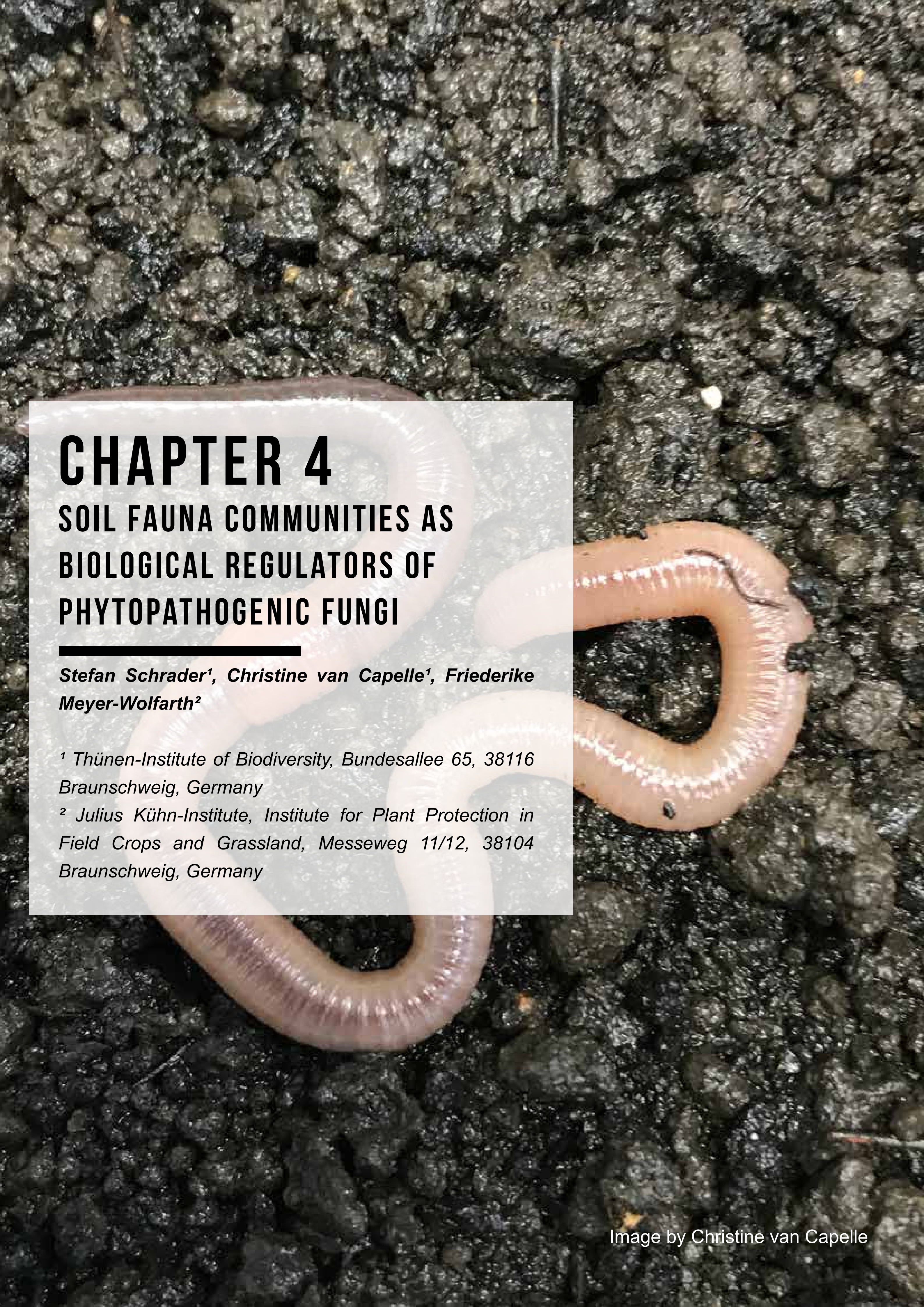

CHAPTER 4

SOIL FAUNA COMMUNITIES AS BIOLOGICAL REGULATORS OF PHYTOPATHOGENIC FUNGI

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Image by Christine van Capelle

ABSTRACT

Plant-pathogenic species of the fungal genus *Fusarium* can infect a variety of cereal crops. As they produce toxic secondary compounds (mycotoxins), infections lead to significant yearly economic losses in European arable systems. For the prevention and control of *Fusarium* and its mycotoxins, farmers can apply alternative management measures, such as the avoidance of narrow crop rotations, the cultivation of varieties of low susceptibility, and integrated fungicide treatments. However, farmers are not alone in protecting their crops and ensuring profitable and high-quality yields. There is belowground support, where the soil hosts a large diversity of fungal-feeding organisms that promote soil health. Fungivorous soil animals play a crucial role as biological regulators that significantly contribute to the provision of soil-derived ecosystem services. This chapter focusses on agricultural management measures and soil fauna-induced ecosystem services as a synergistic system, effective in combating *Fusarium* and its mycotoxins. This synergy is valuable in the context of efforts to promote soil health and improve yield and crop residue quality. It can provide an important contribution towards long-term sustainable agricultural production.

Keywords: biological regulators; crop residues; *Fusarium* infection; mycotoxins; ecosystem services; soil health.

1. SOIL BIOLOGICAL ACTIVITY SHOWS TWO FACES

Organisms are not homogenously distributed in soil, but rather concentrated in clusters, and active mainly in hotspots. Although these hotspots are estimated to account for less than 10% of total soil volume, they represent about 90% of total biological activity (Beare et al. 1995). Hotspots typically include: the soil layers surrounding plant roots (rhizosphere); the walls of earthworm burrows, including earthworm casts (drilosphere); or dead organic matter (detritusphere), such as crop residues forming a mulch layer in conservation tillage systems. Mulching promotes diversity of soil organisms, and stimulates the decomposition processes they control, which can improve the soil's humus balance.

At first glance, an increase in biological activity in soil, and the promotion of soil biodiversity, is good news. A closer look, however, shows that the promotion of biological activity is not always positive, as harmful organisms also benefit from crop residues remaining on the soil surface. Soil biological activity is thus a Janus head with two faces. A serious problem is the increasing risk of infection by soil-borne phytopathogenic fungi. Such harmful fungi survive as saprophytes, which colonise crop residues and endanger the health of the subsequent crop. Fusarium species are among the most important pathogenic fungi of cereals and maize worldwide (Yli-Mattila 2010). Since Fusaria produce toxic metabolic products (mycotoxins), infestation can reduce quality and quantity of yield, which leads to economic losses. The most common mycotoxins of Fusaria include deoxynivalenol (DON), its acetylated derivatives (e.g. 3-acetyldeoxinivalenol (3-AcDON)), zearalenone (ZEN) and fumonisins. Contamination with these toxins poses a serious health risk to humans and animals, and affects the usability of the crop for food and feed production (Ferrigo, Raiola, and Causin 2016).

One of the most important factors influencing the life cycle and population development of Fusarium species is weather. Changes in precipitation, as well as increases in both mean temperatures and carbon dioxide concentrations in the atmosphere, can increase abiotic stress, directly affecting the defense mechanisms of the crop (Vaughan et al. 2018). In addition, insect penetration of plants and plant organs can lead to higher suceptability to colonisation of toxigenic fungi, thus favoring Fusarium infections. Therefore, it is not surprising that increases in infestation rates in cereals and maize is expected in the future (Vaughan, Backhouse, and Ponte 2016). With regard to sustainable agriculture and food security, management measures that can prevent or effectively mitigate *Fusarium* infestation are greatly needed.

2. SOIL ANIMALS AS BIOLOGICAL REGULATORS

According to a common classification system (Turbé et al. 2010), the soil biodiversity pool is functionally divided into three guilds: (i) chemical engineers decompose organic residues; (ii) ecosystem engineers contribute to soil structure formation; and (iii) biological regulators shape soil biota communities. Various groups of soil fauna act as biological regulators by using phytopathogenic fungi or fungal infected plant matter as food sources, thus naturally contributing to pathogen regulation. Lagerlöf et al. (2011), for example, showed that introduced fungivorous nematodes significantly reduce the quantity of pathogenic fungi. In addition, numerous studies have shown that Fusarium species are often preferred over other soil-borne fungal species as a food source (Goncharov, Glebova, and Tiunov 2020). Fusarium infected substrates (e.g. crop residues) represent an adequate source of nutrients for soil animals due to higher nitrogen content and a narrower C:N ratio (Larsen et al. 2008). Furthermore, some studies suggest that, besides the feeding activities of single species, interactions between fungus-feeding species within soil faunal communities play a crucial role in reducing *Fusarium* biomass in agricultural soils (Sabatini and Innocenti 2001; Goncharov, Glebova, and Tiunov 2020).

In order to assess and evaluate the antagonistic potential of fungus-feeding soil animals in the context of *Fusarium* regulation, several studies have been carried out in recent years in order to unveil impacts of key organisms of various size classes (Figure 4.1), including macrofauna (e.g. earthworms), mesofauna (e.g. springtails, potworms) and microfauna (e.g. nematodes).

Figure 4.1. Key fungivorous organisms of three soil fauna size classes: macrofauna (e.g. earthworms), mesofauna (e.g. springtails, potworms) and microfauna (e.g. nematodes). Values in brackets indicate size ranges according to body diameters.

Goncharov, Glebova, and Tiunov (2020) summarised studies on the question whether soil animal communities and their interactions contribute to counteracting increasing *Fusarium* infestation and mycotoxin contamination. Results showed that soil animals significantly promote the degradation of *Fusarium* biomass and reduce the mycotoxin concentrations in crop residues (see overview by Goncharov, Glebova, and Tiunov 2020). In particular, primary decomposers within the earthworm community make an important contribution to the control of plant pathogens. These species use infected plant residues directly as a food source and incorporate them into the soil through their extensive burrow systems. This way, light-dependent formation of *Fusarium* spores (Inch and Gilbert 2003) is mitigated, and the risk of spreading is reduced even without ploughing. Figure 4.2 presents an experimental approach for studying the bioregulation potential of earthworms (*Lumbricus terrestris*) in the field.

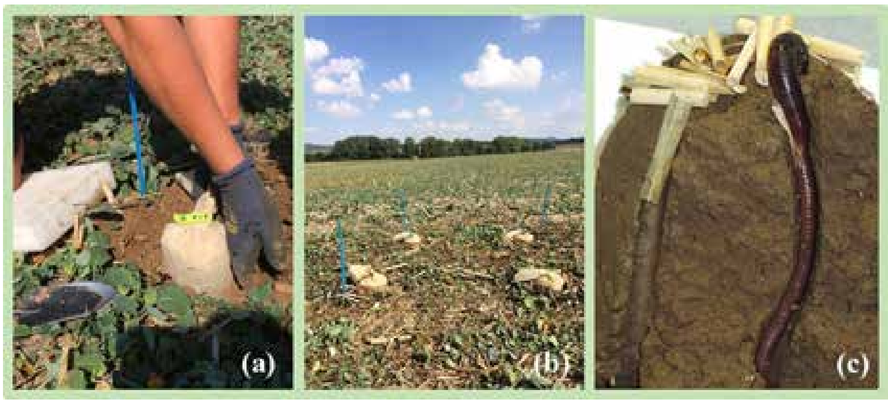

Figure 4.2. Field experiment assessing the bioregulation potential of earthworms. (a) Insertion of mesocosms into the field soil (mesh bags filled with soil, crop residues and the earthworm species *Lumbricus terrestris)*, (b) mesocosms in the field, and (c) incorporation of stubbles into the soil by earthworms in mesocosms.

With regard to smaller soil animals (meso- and microfauna), further results suggest that communities comprising different groups of organisms are highly effective in reducing *Fusarium* biomass and mycotoxin concentrations, and sustainably promote soil health. Laboratory studies indicate that interactions between representatives of the mesofauna (e.g. springtails, potworms), as well as between mesofauna (springtails) and microfauna (nematodes), are crucial for the reduction of mycotoxin concentrations in wheat and maize straw (Goncharov, Glebova, and Tiunov 2020).

3. PERFORMANCE OF SOIL ANIMALS IN COMBATING FUSARIUM

Overall, studies show that the performance capacity of soil organisms involved in bioregulation varies between size classes. The activity of larger deep-burrowing earthworms leads to the strongest reduction of *Fusarium* biomass and mycotoxin concentrations. They therefore play a key role in toxin reduction and controlling the risk of infection. Concerning micro- and mesofauna, bioregulation capacity is strongly influenced by interactions and food competition, and possibly defense mechanisms (Goncharov, Glebova, and Tiunov 2020). Thus, interactions within the soil food web can increase bioregulation (synergy effect), but also reduce it (inhibitory effect), depending on the constellations within the soil biota community. In this context, the species composition of both the fusaria and the soil animals, but also of the associated microorganisms (e.g. in gut, mucus or casts), which are significantly involved in regulating performance (Schrader, Wolfarth, and Oldenburg 2013), play an important role. In addition, the regulatory performance of soil animals varies for different toxins and depends on abiotic factors such as temperature, soil texture, moisture, nutrient content of soil and plant substrate, as well as substrate size. Based on the complexity of these relationships, we emphasise the following two points:

1. Specific soil biota communities provide great potential for natural control of *Fusarium*, and may have a wide range of regulatory capacities, depending on site conditions. The promotion of antagonistic soil animals, through adapted management, is therefore essential in order to make best use of the ecological service provisions supplied by soil fauna.
2. There are innumerable crucial correlations regarding *Fusarium* regulation by soil animals, which have thus far only been partly understood. Therefore, this topic is still of scientific interest. As part of European research projects, field and laboratory experiments are being carried out in order to close existing knowledge gaps and develop specific recommendations.

4. TEAM BUILDING FOR SUSTAINABLE AGRICULTURE: FARMERS AND SOIL ANIMALS

In summary, fungus-feeding soil animals counteract *Fusarium* infections. By promoting soil health, and reducing risk of infestation to the succeeding crop, they provide important ecosystem services, from which farmers can benefit in the context of sustainable *Fusarium* control. Thus, management that promotes fungus-feeding soil animals can benefit soil health and plant health, and provide long-term contributions to both soil protection as well as food and feed security. Conservation tillage, which takes into account the role of soil animals as drivers of self-regulation in the soil system, can be a promising alternative for ploughing. With such a mutualistic management approach, farmers and soil animals benefit from each other. As a team, they contribute to soil health and plant health through both application of “good agricultural practice” (top-down effect by the farmer) and provision of ecosystem services (bottom-up effect by the soil animals) (Figure 4.3).

In this context, a recent interdisciplinary ecological and economic evaluation of earthworm performance, with regard to the reduction of *Fusarium* biomass and mycotoxin concentrations, concludes that, under favorable conditions, the standard gross margin for wheat cultivation under conservation tillage is higher than that for conventional tillage (Plaas et al. 2019). Against the background that the soil biodiversity pool provides a whole range of ecosystem services (Lavelle et al. 2006), the resilience of an agricultural production system increases with the application of soil-conserving management measures. Future advisory services require knowledge-transfer in order to protect, promote and utilise functional soil biodiversity in agricultural practice and policy-making.

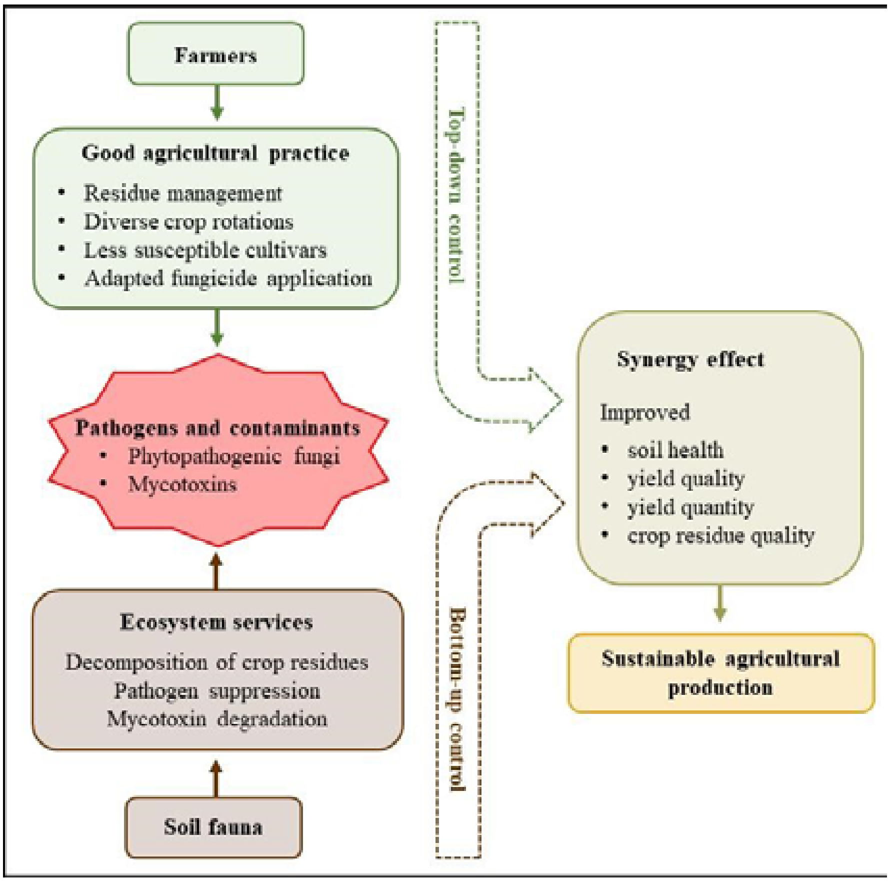

Figure 4.3. Synergy effect between farmers' top-down control (anthropogenic) and soil fauna bottom-up control (natural) in agroecosystems, for sustainable management of soil-borne plant pathogens and associated contaminants.

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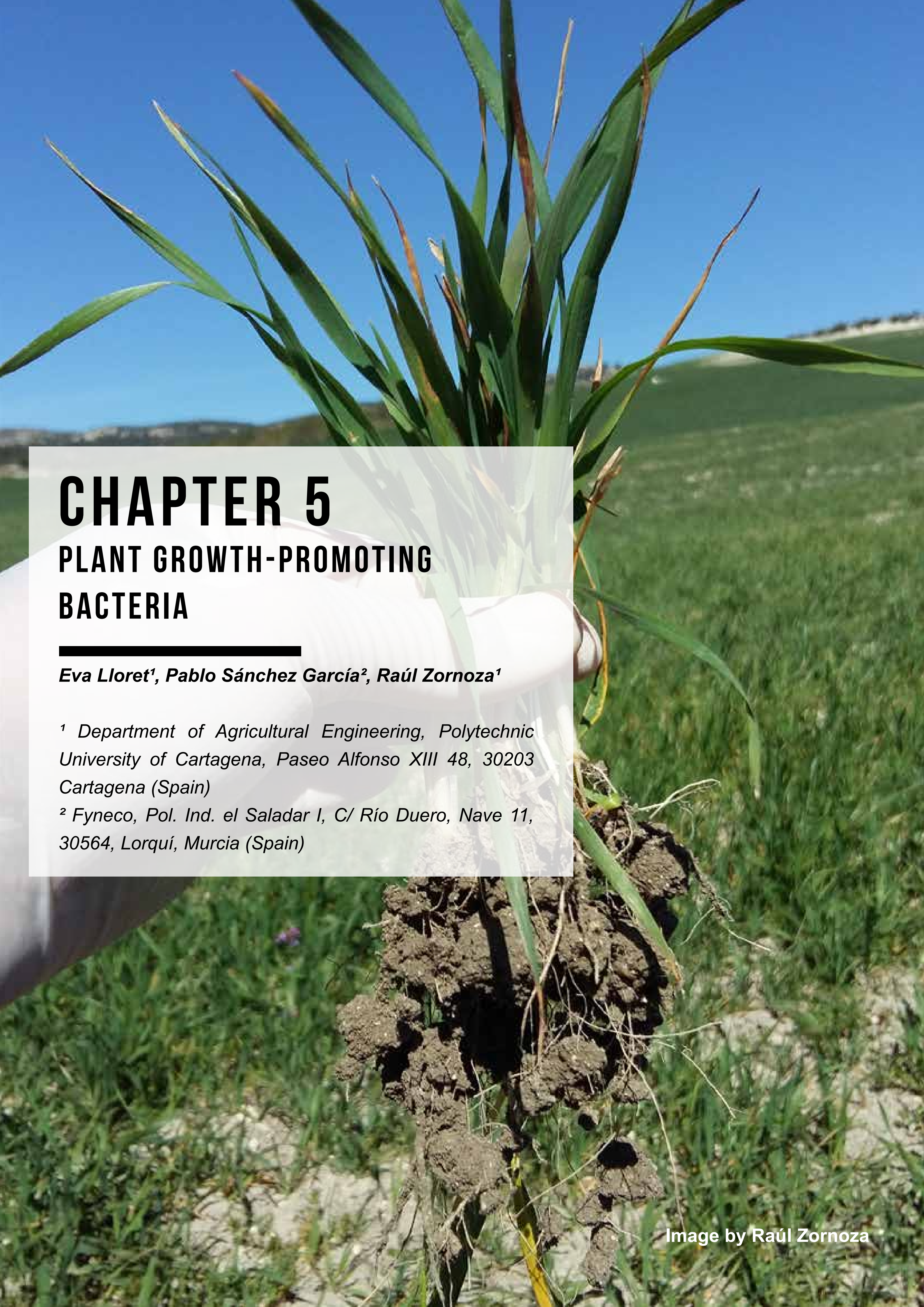

CHAPTER 5

PLANT GROWTH-PROMOTING BACTERIA

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Image by Raúl Zornoza

ABSTRACT

Plant-microbe interactions in the soil are the determinants of plant health, productivity and soil fertility. Plant growth-promoting bacteria (PGPB) are plant-associated bacteria that can enhance plant growth and protect them from diseases and abiotic stresses. While plant growth promotion is based on direct mechanisms, such as improved nutrient acquisition and hormonal stimulation, reduction of diseases is achieved by indirect mechanisms like induced systemic resistance, the production of antifungal or antibacterial agents and the production of siderophores. Members of the bacterial genera Azospirillum, Rhizobium, Bacillus, Pseudomonas, Serratia, Stenotrophomonas, and Streptomyces are well-studied PGPB. Based on the beneficial plant–microbe interactions, it is possible to develop microbial inoculants for agricultural application that, depending on their mode of action and effects, can be used as biofertilisers, biopesticides, phytostimulators and bioremediators. Nowadays, there is a strong growing market for microbial inoculants worldwide with an annual growth rate of approximately 10%. Bacterial inoculants are a promising and environmentally friendly strategy to increase agronomic efficiency by reducing production costs and environmental pollution, once the use of chemical fertilisers can be reduced or eliminated. The future success of these inoculants, however, will benefit from further research to improve the development of more efficient inoculants that can successfully colonise host rhizosphere and consistently promote the growth of host plants.

Keywords: plant growth promoting bacteria; microbial communities; plant fitness; soil diversity; sustainable agriculture.

1. DEFINITION OF PLANT GROWTH-PROMOTING BACTERIA

Plant growth-promoting bacteria (PGPB) include: a) naturally occurring free-living soil bacteria, b) bacteria that form specific symbiotic relationships with plants, c) bacteria that live in the rhizosphere (the narrow region of soil directly influenced by root secretions and associated microbial activity), d) endophytes (bacteria that can colonize plant's interior tissues), and e) cyanobacteria. PGPB colonize plant roots and have beneficial effects on them (Glick 2012; Lugtenberg and Kamilova 2009). As the root tissues of soil-dwelling plants are unable to relocate, they are dependent on soil microorganisms in their immediate surroundings, such as bacteria and fungi, for nutrient- and water acquisition. Therefore, together with other soil microorganisms, PGPB play an important role in regulating soil fertility, nutrient cycling and maintaining plant diversity (Fitzsimons and Miller 2010). In fact, plant–microbe interactions in the rhizosphere largely determine plant health and productivity, as well as soil fertility (Souza, Ambrosini, and Passaglia 2015).

Multiple factors such as temperature, pH and plant root exudates (mainly organic compounds) shape the soil microbiome (Lakshmanan, Selvaraj, and Bais 2014). Moreover, microbial communities associated with plants and soil have shown specificity to particular plant species, which can be attributed to secondary metabolites released by root exudates. Thus, the shaping of the soil microbial community depends on the nature and concentrations of organic constituents of exudates, and the corresponding ability of microbes to use these as energy sources (Ramakrishna, Yadav, and Li 2019).

The major groups of PGPB belong to Proteobacteria and Firmicutes (Jiang et al. 2008; Chen et al. 2010; Rojas-Tapias et al. 2012). In the phylum Firmicutes, Bacillus sp. are the predominant bacteria with plant growth promoting activity. In the phylum Proteobacteria, class Gammaproteobacteria includes the genera Pseudomonas, Acinetobacter, Serratia, Pantoea, Psychrobacter, Enterobacter and Rahnella; and class Betaproteobacteria includes the genus Burkholderia and the bacterium Achromobacter xylosoxidans (Batista et al. 2018). Host plants associated with PGPB include those belonging to the families Fabaceae, Poaceae, Asteraceae, Brassicaceae, Asteraceae, Crassulaceae and Solanaceae (Ramakrishna, Yadav, and Li 2019).

2. MECHANISMS OF ACTION AND BENEFITS OF PGPB

The use of naturally occurring PGPB in sustainable agriculture has grown in importance in the past decade, due to their beneficial effects on soil and crop productivity. In addition to enhancing plant growth, PGPB help plants to cope with biotic and abiotic stresses, resulting in better crop yield and soil fertility (Singh and Jha 2017). Regarding the mechanisms of action of PGPB, plant growth promotion and other benefits may be achieved either directly or indirectly (Ramakrishna, Yadav, and Li 2019) (Figure 5.1.). The direct promotion of plant growth entails providing the plant with a compound that is synthesised by the bacterium, or facilitating the uptake of certain nutrients from the environment (Yadav 2017). The indirect promotion of plant growth occurs when PGPB decrease or prevent the deleterious effects of one or more phytopathogenic organisms (Yadav 2017). The main direct and indirect benefits of PGPB are described below.

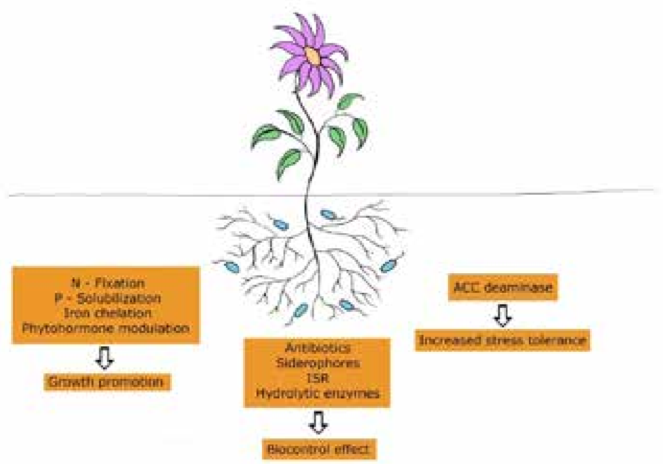

Figure 5.1. Main mechanisms used by PGPB to promote direct or indirect plant growth.

2.1. ATMOSPHERIC NITROGEN FIXATION

Atmospheric nitrogen fixation is performed by bacteria that convert atmospheric nitrogen into a form of nitrogen available to living organisms. Since nitrogen is the major limiting factor for plant growth, the application of nitrogen-fixing microbes as biofertilisers has emerged as one of the most efficient and environmentally sustainable methods for increasing the growth and yield of crop plants. Bacteria such as Rhizobium and Bradyrhizobium can establish symbiosis forming nodules on roots of leguminous plants like soybean (Glycine max), pea (Pisum sativum) and alfalfa (Medicago sativa), among many others (Murray 2011). Free-living bacteria such as Azospirillum, Azoarcus, Azotobacter, Bacillus, Burkholderia, Gluconoacetobacter and Herbaspirillum also have the ability to fix nitrogen and can fertilise several important crops, such as wheat, sorghum, maize, rice and sugarcane (Pérez-Montaño et al. 2014).

2.2. PHOSPHORUS SOLUBILISATION

Phosphorus is a major essential macronutrient for biological growth and development. However, phosphorus in soils is immobilised or becomes less soluble either by adsorption, chemical precipitation, or both, making only 0.1% of the total phosphorus present available to the plants (Tilak et al. 2005; Yadav 2017). Phosphate solubilising bacteria (PSB) such as Azospirillum, Bacillus, Burkholderia, Erwinia, Pseudomonas, Rhizobium and Serratia, convert insoluble phosphates into soluble forms, thereby increasing the availability of this essential nutrient for plant growth and development (Richardson et al. 2009; Pérez-Montaño et al. 2014).

2.3. POTASSIUM SOLUBILISATION

Potassium is the third major essential macronutrient for plant growth. However, concentrations of soluble potassium in the soil are usually very low, and more than 90% of potassium in soil exists in the form of insoluble rocks and silicate minerals. Moreover, due to an imbalanced fertiliser application, potassium deficiency is becoming one of the major constraints in crop production. In this sense, potassium-solubilising bacteria (KSB) are able to solubilise potassium rock through production and secretion of organic acids. Potassium-solubilising, plant growth-promoting rhizobacteria, such as Acidothiobacillus ferrooxidans, Bacillus edaphicus, Bacillus mucilaginosus, Burkholderia, Paenibacillus and Pseudomonas have been reported to release potassium, in accessible forms to plants, from potassium-bearing minerals in soils (Yadav 2017).

2.4. PHYTOHORMONE PRODUCTION

Plant hormones play key roles in plant growth and development, as well as in the response of plants to their environments (Davies 2010). PGPB can produce or modulate phytohormone levels, thereby affecting the plant´s response to environmental stressors. Among the phytohormones modulated by PGPB are auxins, cytokines, gibberellins and ethylene. Indole-3-acetic acid (indoleacetic acid, IAA) is the most common and most studied auxin. IAA affects plant cell division, extension, and differentiation; stimulates seed and tuber germination; increases the rate of xylem and root development; controls processes of vegetative growth; initiates lateral and adventitious root formation; mediates responses to light, gravity and florescence; and affects photosynthesis, pigment formation, biosynthesis of various metabolites, and resistance to stressful conditions (Spaepen and Vanderleyden 2011; Tsavkelova et al. 2006). Cytokines and gibberellins stimulate shoot development (Kloepper 1994). Ethylene can affect plant growth and development in a large number of ways, including promoting root initiation, inhibiting root elongation, promoting fruit ripening, promoting flower wilting, stimulating seed germination, promoting leaf abscission, activating the synthesis of other plant hormones, inhibiting Rhizobia spp. nodule formation, inhibiting mycorrhizae–plant interactions, and responding to both biotic and abiotic stresses (Abeles, Morgan, and Saltveit 1992). PGPB regulate ethylene levels, and prevents them from becoming growth-inhibitory, through the synthesis of 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase (Glick 2012).

2.5. BIOCONTROL EFFECT

PGPB have shown biocontrol effects against multiple plant diseases (Liu et al. 2017). The biocontrol effects shown by some PGPB are achieved through numerous ways, such as production of antifungal or antibacterial agents, production of siderophores, nutrient competition, ethylene regulation through the synthesis of ACC deaminase, activation of induced systemic resistance, and hyperparasitism against pathogens via the excretion cell wall hydrolases. This can lead to the suppression of pathogenic fungi including Botrytis cinerea, Sclerotium rolfsii, Fusarium oxysporum, Phytophthora sp., Rhizoctonia solani, and Pythium ultimum (Arora 2013; Kim et al. 2017; Wang, Yan, and Cao 2014). In recent studies, Streptomyces sp. has proven to modulate defence-related metabolism in tomato plants infected with Pectobacterium (Dias et al. 2017). Tomato wilt was mitigated using Bacillus subtilis, Bacillus amyloliquefaciens, Pseudomonas fluorescens or Pseudomonas aeruginosa (Abo-Elyousr et al. 2019), and Paenibacillus polymyxa NSY50 application reduced Fusarium oxysporum infection in cucumber (Shi et al. 2017), making PGPB a viable alternative to pesticides (Rey and Dumas 2017).

2.6. SIDEROPHORE PRODUCTION

Despite the fact that iron is the fourth most abundant element on earth in aerobic soils, it is not readily assimilated by either bacteria or plants. To tackle this problem, bacteria synthesise siderophores (molecules that bind and transport iron), increasing the provision of iron to plants (Glick 2012). In addition, some bacterial strains can act as biocontrol agents using the siderophores that they produce. In this case, siderophores from PGPB can prevent some phytopathogens from acquiring a sufficient amount of iron, resulting in PGPB outcompeting fungal pathogens for available iron, hence limiting the ability of fungal pathogens to proliferate (Kloepper et al. 1980).

Despite the iron is the fourth most abundant element on earth in aerobic soils, it is not readily assimilated by either bacteria or plants. To tackle this problem, bacteria synthesize siderophores that solubilize and sequester iron, increasing the provision of iron to plants (Glick 2012). In addition, some bacterial strains can act as biocontrol agents using the siderophores that they produce. In this case, siderophores from PGPB can prevent some phytopathogens from acquiring a sufficient amount of iron, outcompeting fungal pathogens for available iron, hence limiting their ability to proliferate (Kloepper et al. 1980).

2.7. SOIL BIOREMEDIATION

PGPB can be used to remediate contaminated soils in association with plants. Of all the contaminants, heavy metals and organic pollutants have attracted the most attention. Hyperaccumulating- and/or high biomass plants have the capability to ameliorate heavy metal contamination in soil, which can be enhanced by PGPB like Pseudomonas spp., Bacillus spp. and Burkholderia spp. (Dhawi, Datta, and Ramakrishna 2015, 2016; K. Li et al. 2014; Ma et al. 2017; Pidatala et al. 2016, 2018). Furthermore, organic compounds like crude oil, polycyclic aromatic hydrocarbons (PAHs), total petroleum hydrocarbons (TPHs), and polychlorinated biphenyls (PCBs) have been degraded and even mineralised by PGPB in association with plants (Huang et al. 2004; 2005; Muratova et al. 2005; Villacieros et al. 2005).

2.8. REDUCTION OF WATER STRESS

Studies in Sorghum have shown that resistance to water stress was conferred by Actinobacteria due to the bacterial production of certain genes (Xu et al. 2018). In tomato and pepper plants, however, resistance to drought stress was increased by Achromobacter piechaudii through the production of ACC deaminase, restraining the production of ethylene, which is known to increase under stress conditions (Mayak, Tirosh, and Glick 2004).

3. A FARMER’S POINT OF VIEW

In Southern and Eastern Spain, farmers are concerned about the difficulties in maintaining high crop yields due to soil nutrient depletion, pests, and diseases. They are also aware of how fertilisers and pesticides should be replaced by other products or management practices in line with agroecological principles. Currently, there are two main farmers’ positions in relation to PGPB use. On one hand, some farmers have been using PGPB from many years, mostly from companies with highly qualified technicians who understand the different types of metabolic processes in soil and how they influence the mobility of nutrients and subsequent crop health. On the other hand, most traditional farmers vaguely attribute the use of PGPB to soil health and fertility, since they are lacking in sufficient knowledge. They know that they must enhance and protect soil health, but conventional practices have led many to prefer chemical applications. Nonetheless, when they notice the dramatic decrease in soil fertility, they are willing to try new alternatives, since they find it is increasingly expensive to maintain production at the expense of a larger volume of inputs.

4. CONCLUSIONS AND FUTURE PERSPECTIVES

Global population increases, together with climate change and environmental pollution, require the use of alternative strategies to increase agricultural production in a sustainable way that reduces damage to the environment and human health.

The numerous benefits that PGPB can confer to their host plant suggests their promise as a green technology, as well as a potential alternative for chemical fertilisers and pesticides; and this can result in the improvement of soil health, as well as a reduction in production costs. In terms of PGPB commercialisation, the PGPB market is expected to increase at an annual growth rate of 9.9% (Timmusk et al. 2017). Figure 5.2. depicts the current biofertiliser market by product.

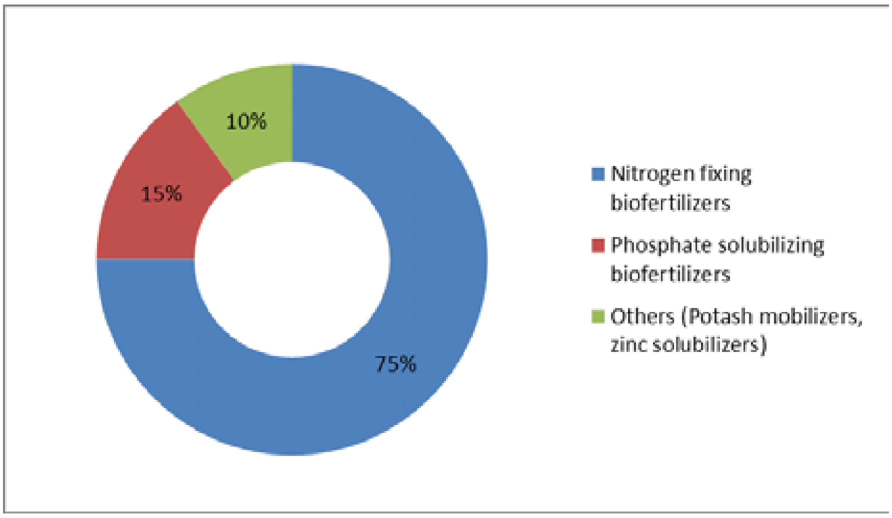

Figure 5.2. Market share of different types of biofertilisers at global level (Grand View Research 2015).

However, there are several drawbacks and challenges that must be considered for optimal agricultural use of PGPB. The main bottlenecks are shelf-life-, reliability- and consistency of microbial inoculants under field conditions (Ramakrishna, Yadav, and Li 2019). The success of PGPB inoculation depends on several factors such as plant root exudates, soil microbial community and soil health (Souza, Ambrosini, and Passaglia 2015). Since associative interactions of plants and microorganisms must have come into existence as a result of coevolution, the use of the latter as bioinoculants must be pre-adapted, so that it fits into a long-term sustainable agricultural system.

Regarding their effect on indigenous microbial communities, studies have shown that PGBP altered resident microbial community structure, but that these alterations had temporary, spatially-limited and transient effects on the resident microbial population. In fact, factors such as plant species, environmental stressors and agricultural practices appear to influence community structure more than an exogenous active PGPB introduced at high levels (Castro-Sowinski et al. 2007; Qiao et al. 2017).

Another factor to consider prior to application of PGPB is that they tend to harbour antibiotic resistance genes (ARGs). This is due to the overuse of antibiotics in both animal husbandry and the pharmaceutical industry, which results in the spread of ARGs in soil and the environment (Riber et al. 2014).

There is very little information on the biological significance of antibiotic resistance conferred by PGPB, and there is an urgent need to consider the negative aspects associated with these beneficial microbes before inadvertently introducing them in-field (Kang et al. 2017). Furthermore, some PGPB have been reported to be opportunistic human pathogens, such as Burkholderia cepacia and P. aeruginosa (Kumar et al. 2013; Li, Wu, and Ye 2013), which pose ecological and human risks that should be addressed properly before their commercial production. Reassessment of the biosafety of PGPB products is in process in Europe, USA and other countries (Ramakrishna, Yadav, and Li 2019).

In conclusion, PGPB (as biofertilisers, biopesticides, phytostimulators and bioremediators) render beneficial services for sustainable crop production by improving soil fertility, plant resistance to diseases, and maintaining balanced nutrient cycling. At the same time, further studies must be conducted to improve the development of more efficient inoculants that can successfully colonise the rhizosphere of host plants, and consistently promote the growth of host plants, as well as guarantee its safe in-field application.

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CHAPTER 6

MYCORRHIZAL FUNGI IN AGRICULTURE

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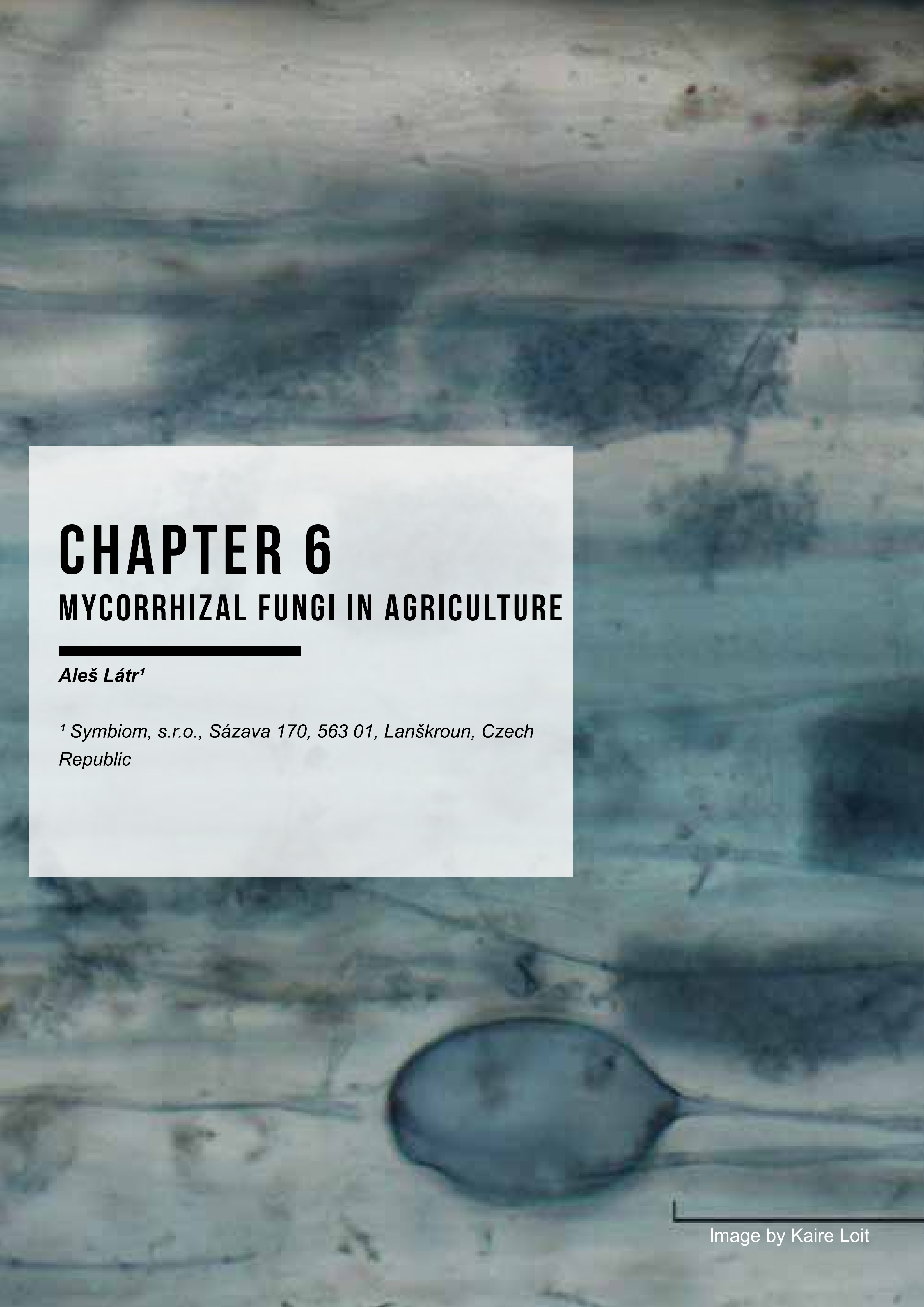

Image by Kaire Loit

ABSTRACT

Arbuscular mycorrhizal symbiosis is a naturally occurring relationship between beneficial soil fungi and plant roots. Mycorrhizal symbiosis plays an important role in plant–soil interactions in both natural and agricultural ecosystems, although the diversity and abundance of mycorrhizal fungi is greatly affected by climate, agricultural management, and soil parameters. As a ubiquitous symbiotic relationship between arbuscular mycorrhizal fungi and the majority of vascular plant species, its beneficial effect represents a valuable tool for cultivation of a wide range of crops in agriculture, horticulture and forestry, as well as for phytoremediation and landscaping. Mycorrhizal symbiosis brings the possibility to economise plant production in an environmentally friendly way. Regarding the practical advantages of using mycorrhizae, it can be concluded that mycorrhizae represent not only a sustainable strategy for plant fertilisation, but also increases tolerance to adverse environmental conditions like water stress, supports plant biodiversity and soil stability, decreases vulnerability of plants to root pathogens, and consequently reduces post-planting maintenance and management costs. The overall objective of this chapter is to raise awareness about mycorrhizal technology as an ecological tool for facilitating sustainable increases in plant production.

Keywords: arbuscular mycorrhiza; ERM; tillage; fertilisation; diversity; erosion

1. GENERAL CHARACTERISTICS OF MYCORRHIZA

Arbuscular mycorrhizal fungi (AMF) form symbiotic relationships with 72% of the vascular plant species worldwide (Brundrett 2017) with the exception of some families like Amaranthaceae, Brassicaceae, Caryophyllaceae, Juncaceae, etc., whose members have lost their mycorrhiza-forming capacity, either permanently or intermittently (Brundrett 2017; Brundrett and Tedersoo 2018). AMF have also been described in bryophytes, ferns, groups of gymnosperms including some conifers (e.g. Thuja, Sequoia, Metasequoia) and cycads. The fossil record shows that the evolutionary history of AMF goes back at least to the Ordovician (460 million years ago), coinciding with the colonisation of the terrestrial environment by the first land plants (Redecker 2002).

AMF are ubiquitous in almost all terrestrial ecosystems occupied by plants, including extreme environments such as cold-, saline-, heavy metal contaminated- or submarine habitats (e.g. Hildebrandt et al. 2001; Sudová et al. 2011; Oehl and Körner 2014). AMF colonise the root cortex, forming haustoria-like structures called arbuscules in the cortical cells, where the symbiotic interface between fungus and plant develops. The fungus facilitates uptake of water and soil nutrients, in return for plant carbon assimilated through photosynthesis (Smith and Read 2008). In natural ecosystems, plants obtain up to 90% of their phosphorus (P) requirement from AMF (Jakobsen, Abbott, and Robson 1992; Leake et al. 2004; Smith et al. 2011). The contribution of AMF to facilitating the acquisition of nitrogen (N) requirements in plants may be less pronounced, and is affected by various soil factors such as soil type, water content and pH (Mäder et al. 2000; Hodge and Storer 2015).

Approximately 270 fungal species of the order Glomerales form arbuscular mycorrhiza (Schüßler, Schwarzott, and Walker 2001; Castillo et al. 2016). Fungal mycelium grows from microscopic spores in the soil, and are typically 20–400 µm in diameter. The germinating hypha penetrates the host plant's rhizodermis by forming an appressorium, and thereafter intraradically colonises the root cortex, forming arbuscules and, in some cases, oval storage vesicles filled with lipidic bodies. Root morphology does not change remarkably; sometimes the root is more branched and can exhibit reduced frequency of root hairs in comparison with non-mycorrhizal roots. Extraradical mycelium (ERM) grows into the soil, forming a vast network of hyphae reaching a distance of up to 20–40 cm from the root. One gram of dry soil may contain several- or tens of metres of ERM (Jakobsen, Abbott, and Robson 1992). Growth rate of ERM in soil is species-dependent and reaches values of 0.7–3.1mm per day (Jakobsen, Abbott, and Robson 1992). The ERM thus increases the absorptive surface of a plant's root system, as well as the volume of soil available for nutrient acquisition.

Generally, AMF perform key ecosystem services such as promoting plant growth (Gianinazzi et al. 2010; Njeru et al. 2015; Cozzolino et al. 2016). They facilitate soil aggregation (Rillig and Mummey 2006), protect plants from various diseases (Solaiman, Abbott, and Varma 2014), and help plants to withstand periods of temporary or persistent water deficit (Bowles et al. 2016). Thus, AMF may play an important role in agricultural production (Jeffries et al. 2003; Avio et al. 2013).

2. EFFECTS OF MYCORRHIZAL FUNGI ON PLANT GROWTH, PLANT HEALTH AND SOIL QUALITY

AMF alter host plant physiology in a manner that typically results in positive changes in plant nutrition, growth, and overall health and vigour. The key role of mycorrhizae lies in increasing plant mineral-nutrient acquisition via the extensive development of ERM that branches into the surrounding soil matrix. In general, AMF hyphae transport both macronutrients (i.e. phosphorus, nitrogen, potassium) (Delavaux, Smith-Ramesh, and Kuebbing 2017) and micronutrients (e.g. copper, iron, zinc, manganese) (Lehmann and Rillig 2015). The mycorrhizal relationship may also help the plant to withstand environmental stressors such as drought, salinity, soil contamination, erosion, heat, pathogens, etc. (Augé 2001; Cabral et al. 2016; de la Peña et al. 2006; Yang et al. 2014). AMF represent a fraction of the ecosystem; however, they can be a driving force in nutrient cycling dynamics. Plants associated with AMF exhibit increases in carbon fixation, photosynthetic rate, leaf water potential, transpiration rate, stomatal conductance, and relative water content, as well as lower leaf temperature, as was shown for citrus (Wu and Xia 2006).

High AMF diversity can facilitate ecosystem functioning, such as maintaining plant biodiversity, ecosystem variability, and productivity, implying the need to protect AMF and to consider them in future management practices in order to maintain diverse ecosystems (van der Heijden et al. 1998). The phenomenon underlying the above statement is that the ERM hyphae can mediate contact between roots of neighbouring plants, and even facilitate both intra- and interspecies transport of nutrients and assimilates (Simard et al. 1997). Linkage of plants via ERM can influence community structure (O'Connor, Smith, and Smith 2002; Reynolds et al. 2003; van der Heijden and Horton 2009). For example, Bray, Kitajima, and Sylvia (2003) suggested that competitive interactions between exotic invasive plants and native plants are dependent on the mycorrhizal associations present. Linkage of plants via ERM can influence ecosystem processes including indirect- (through changes in plant- and soil microbial community composition) and direct pathways (effects on host physiology and resource capture, and direct mycelium effects) (Rillig 2004a). This has an important implication on production of bare-root plants in nursery beds, as by sharing resources via the ERM network, plant size would equalise and uniformity of crop would therefore be enhanced.

Mycorrhizal diversity and abundance have been found to be negatively correlated with intensity of agricultural production (Smith and Read 2008). Low plant diversity (König et al. 2010), abundance of non-host plants (Vestberg et al. 2005; Mathimaran et al. 2005), tillage (Jansa et al. 2002; Castillo et al. 2006; Brito, Goss, and De Carvalho 2012; Alguacil et al. 2008; Wetzel et al. 2014; Oehl and Koch 2018; Baltruschat et al. 2019), high levels of N and P fertilisers (Wang et al. 2009; Jansa et al. 2014; Baltruschat et al. 2019), fungicides (Castelli et al. 2014) and frequent or long fallow periods (Thompson 1987) have been found to negatively affect the absolute abundance of viable mycorrhizal spores and infective ERM in the soil.

Tillage can be considered as the primary negative factor of human-mediated activity on AMF and the soil microbial community in general (Mathew et al. 2012). Conventional tillage typically disrupts the upper 20–35 cm of soil and causes changes in the physicochemical properties of soil (Peigné et al. 2007) by inversion via mouldboard ploughs, disc ploughs or spading machines. In contrast, reduced- or no-till farming practices use shallow- or no ploughing, which results in reduced soil erosion, greater macroporosity in the soil surface (e.g. from greater earthworm abundance), increased microbial activity and carbon storage, and reduced run-off and nutrient losses (Peigné et al. 2007).

Soil tillage is not tolerated by all AMF species equally (Köhl, Oehl, and van der Heijden 2014). Some AMF species appeared as 'generalists' (Oehl et al. 2003), occurring in different soil types (sandy or clay soils, fertile or infertile soils), climates (dry and wet), and land-use intensities (natural and intensively managed ecosystems). Some species are more sensitive, have low fitness in intensively managed agroecosystems, and may thus be found exclusively in soils with reduced- or no-tillage (Castillo et al. 2006, 2016; Oehl et al. 2003, 2010; Oehl and Koch 2018; Baltruschat et al. 2019). A predominant feature of no-till AMF communities is that they produce more ERM (Z. Kabir et al. 1998; Borie et al. 2006) and usually colonise the host plant roots to a greater extent than those AMF exposed to soil tillage (Schenk et al. 1982; Mcgonigle and Miller 1996; Brito, Goss, and De Carvalho 2012). The disruption of the hyphal networks and dilution of AMF propagules in a greater volume of soil through deep ploughing reduces the chance of plant root colonisation (Zahangir Kabir 2005). As a consequence, the nutrient uptake (mainly of P) is lower for plants with AMF communities from tilled soils, rather than from non-tilled soils (Köhl, Oehl, and van der Heijden 2014).

Generally, excessive use of chemical fertilisers in intensive agriculture significantly contributes to the contamination of potable water sources and represents an important contribution to environmental pollution. Cordell, Drangert, and White (2009) estimated, that the current global phosphate reserves will be depleted in 50–100 years, and may reach peak P production around 2030. However, the quality of mining phosphate rock (source of concentrated P) is decreasing, while the production costs are still increasing. In the future, there will be an increasing demand for new approaches in fertilising crops with phosphorus. Increased P uptake from the soils with large amounts of P in unavailable forms (e.g. adsorbed to clay minerals; Fe-, Al-, or Ca-phosphates; or in organic complexes) (Bünemann and Condron 2007) may be one way. However, as Köhl, Oehl, and van der Heijden (2014) showed, the manipulated microbial communities (e.g. via adaptive agricultural management) may also help enhance P availability to plants by using inherent phosphorus pools in soil, thus reducing need for P fertilisers.

3. EFFECTS OF MYCORRHIZA ON PLANT PATHOGENS AND SOIL QUALITY

Mycorrhizal symbioses often result in increased resistance, or decreased susceptibility, of plants to soil-borne pathogens (e.g. Dassi, Dumas-Gaudot, and Gianinazzi 1998; Brimner and Boland 2003; Dalpé 2005). The potential of mycorrhizae as a biocontrol agent covers several known mechanisms of interaction with other components included in the “plant–mycorrhizae–pathogen–environment” complex. The following mechanisms can be considered: improved plant nutrition; the anatomical and morphological transformation in the root system; activation of plant defence mechanisms (mainly at the enzymatic level); direct competition, between mycorrhizal fungi and root pathogens, for plant host assimilates or infection/colonisation sites; and the modification of soil microbial communities (Azcón-Aguilar and Barea 1997; Brimner and Boland 2003; Dalpé 2005).

Soil biota, and in particular mycorrhizal fungi, play an essential role in erosion control and can influence soil quality as an integral indicator of sustainable ecosystems (Herrick 2000). One of the most important features of soil is its stability against erosion. Aggregation of water-stable components seems to be one of the most important effects of mycorrhizae in soil (Caravaca et al. 2002; Rillig 2004b). The soil with mycorrhiza was shown to have significantly more water-stable aggregates than the nonmycorrhizal soils (Augé 2001). Apart from physical entanglement of soil particles by fungal hyphae, AMF hyphae produce glomalin, a glycoprotein, quantified operationally in soils as glomalin-related soil protein (Wright and Upadhyaya 1996), which is able to aggregate soil particles and act as an anti-erosion agent (Rillig 2004b). Glomalin enters the soil mainly by releasing from decomposing hyphae, rather than from active secretion (Driver, Holben, and Rillig 2005). Its concentration mainly depends on vegetation cover and soil management (Mirás-Avalos et al. 2011), and decreases with the soil depth (Harner, Ramsey, and Rillig 2004).

4. CONCLUSIONS AND FUTURE PERSPECTIVES

As awareness of the benefits of mycorrhizal symbiosis increases among farmers, commercial products containing AMF are increasingly used in crop production. There is no universal method of application; however, the product must reach the vicinity of the developing plant root, either via seed treatment, irrigation system, furrow application or by mixing with cultivation substrate at plant nurseries. The efficiency of mycorrhizal inoculation will depend on soil and crop management, product quality, application method, and other factors (e.g. ecological).

The majority of crops cultivated in agriculture, horticulture or forestry are dependent, to some extent, upon a certain type of mycorrhizal relationship with soil fungi. The importance of AMF increases in environments that lack essential nutrients, with water stress or other environmental constraints present. They are valuable for optimal soil functioning and overall ecosystem stability and sustainability. Appropriate management of soil AMF may lead to significant reductions in the amount of applied fertilisers, without lowering plant productivity, simultaneously enabling more sustainable crop production.

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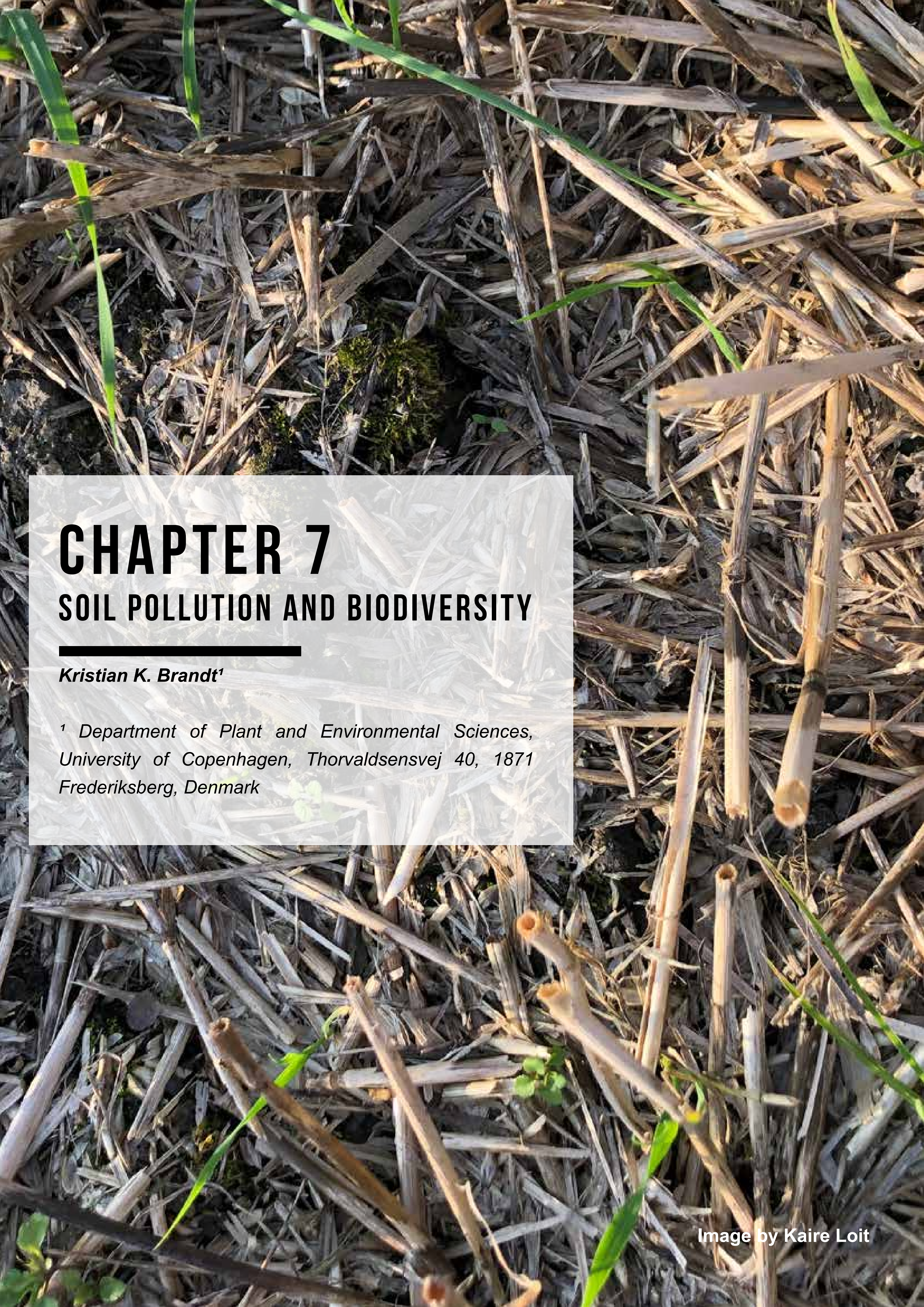

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CHAPTER 7

SOIL POLLUTION AND BIODIVERSITY

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ABSTRACT

Healthy soils support an immense diversity of soil microorganisms and a rich soil fauna of pivotal importance for provision of agroecosystem services, but chemical pollution can compromise these services. A brief overview of some of the most important classes of chemical pollutants, and their possible adverse impacts on biodiversity and associated ecosystem services, are reported. The term 'pollutant' is here used to indicate a chemical substance that has undesired, adverse effects on environmental quality or human health following its release into agricultural soil. Main pollutants in agricultural soils include a range of inorganic toxic elements (heavy metals and metalloids), fertilizer nitrogen (N) and phosphorus (P) not taken up by crop plants, pesticide residues, and a range of so-called emerging pollutants such as pharmaceuticals and antibiotic resistance genes. Due to the persistent nature of metals and their common accumulation in agricultural soils, metals are probably the class of pollutants that is most likely to exert long-term effects on soil biodiversity. Pesticides are also likely to exert effects on non-target organisms, especially on those closely related to the organisms deliberately targeted by these agrochemicals, and can affect biodiversity also in adjacent aquatic and terrestrial environments. Likewise, an excess of N and P supplied by inorganic fertilisers can detrimentally affect plant diversity at the landscape scale, and cause collapse of heavily eutrophicated aquatic ecosystems. Agricultural practices that reconcile crop productivity and biodiversity to ensure food production, while counteracting current losses in biodiversity and associated ecosystem services, are needed. To this end, we need progressive farmers and scientists working together to understand the full complexity of soil pollution effects in agroecosystems and beyond.

Keywords: biodiversity; ecosystem services; microbiome; pollutants; soil.

1. INTRODUCTION

Agricultural soils are fundamental for human welfare and provide several ecosystem services of crucial importance for mankind (MEA (Millennium Ecosystem Assessment) 2005; see Chapter 1). For millienia, farmers have worked to harness one of these ecosystem services; namely agricultural crop production providing food for humans and domestic animals. There is still a need for optimising crop management practices, but by now most ‘low-hanging fruits’ have been ‘picked’ by farmers in Europe. In addition to crop production, agricultural soils also provide a wide range of other ecosystem services that should be protected and ‘managed’ in order to ensure sustainable agriculture and maximise benefits for mankind (MEA (Millennium Ecosystem Assessment) 2005). Farmers are increasingly urged to protect this wider set of ecosystem services within agroecosystems. To a large extent, these ecosystem services can be linked to the presence or functions of soil biota, such as microorganisms and invertebrate animals (Brandt et al. 2015; Power 2010).

Soil bioversity is therefore of pivotal importance for provision of agroecosystem services. Healthy soils are supporting an immense diversity of soil microorganisms as well as a rich soil fauna. Indeed, a single gram of soil contains several billions of microorganisms belonging to thousands of different species, and only a tiny fraction of these have yet been characterised and described by microbiologists (Curtis, Sloan, and Scannell 2002; Delmont et al. 2011; Fierer et al. 2007). Microorganisms include prokaryotes (i.e. bacteria and archaea) and eukaryotes (e.g. fungi and protozoa), collectively of vital importance for farmers via their impacts on soil fertility and pest regulation. However, these microorganisms also provide a rich source of biochemicals for biotechnological and pharmaceutical industries, and have profound impacts on climate, environmental quality and human health (Brandt et al. 2015). Likewise, soil animals have important roles in maintaining healthy soils and agroecosystems. Earthworm activity, for instance, is important for sustaining optimal soil structure for plant growth, and for stimulating microbial processes in soil (Power 2010). Likewise, nematodes represent a dominant and highly diverse group of soil animals that stimulate microbial processes (e.g. via their ecological role as grazers of microorganisms, and as vehicles of microbial transport in soil) (van den Hoogen et al. 2019).

In a recent comprehensive report, it was estimated that 33% of all land is moderately to highly degraded due to the erosion, salinisation, compaction, acidification and chemical pollution of soils, representing a major threat to sustainable agriculture and global food security (FAO 2015). According to this report, chemical pollution was ranked as the third most important threat to soil function (broadly translating into ecosystem services provided by soil) in Europe. Indeed, concerns about soil pollution are growing worldwide (Rodríguez-Eugenio, McLaughlin, and Pennock 2018). The following text provides a brief overview of some of the most important classes of chemical pollutants and their possible adverse impacts on biodiversity and associated ecosystem services provided by agricultural soils.

The term 'pollutant' is here used to indicate a chemical substance that has, over a specified concentration, undesired, adverse effects on environmental quality or human health following its release into agricultural soil. This definition includes agrochemicals such as inorganic fertilisers and pesticides, as these compounds, when not well managed, may have adverse effects on non-target organisms both within the agroecosystem and beyond. This definition also includes several natural substances such as trace elements, which may exert toxic effects on soil biota if allowed to accumulate in agricultural soils. Main pollutants in agricultural soils include a range of toxic elements (heavy metals and metalloids), nitrogen (N) and phosphorus (P) from excessive fertilisation, pesticides, polycyclic aromatic hydrocarbons (PAHs), persistent organic pollutants (POPs), radionuclides, emerging pollutants (e.g. pharmaceuticals), pathogenic microorganisms, and antimicrobial resistant bacteria/genes (Rodríguez-Eugenio, McLaughlin, and Pennock 2018). The focus of this chapter is on heavy metals, pesticides, emerging pollutants, and fertilisers.

While these compounds are all considered pollutants, most of them are actually used by farmers to increase agricultural productivity and profitability. Essential metals like copper and zinc and veterinary pharmaceuticals are for instance used for animal growth promotion in animal husbandry, but will end up in agricultural soils following manure application. Likewise, pesticides and fertilisers are essential for maximising yields in most cropping systems.

2. HEAVY METALS

The term 'heavy metals' is increasingly omitted from scientific literature as the term is somewhat vague and even misleading (Hodson 2004). However, the term is understood by most people and here it indicates a group of environmentally problematic toxic metals and metalloids such as mercury, cadmium, lead, copper, zinc, chromium and arsenic. Some of these elements (notably chromium, copper and zinc) are essential elements in most organisms and are considered micronutrients for crop plants. However, all of these elements, when present in excess, can be toxic to humans and other living organisms, including those residing in agricultural soils. Anthropogenic sources of heavy metals may include atmospheric deposition (e.g. via mining or other industrial activities) or introduction via irrigation waters, fertilisers (both inorganic and organic) or copper-based fungicides.

Heavy metals have been found to accumulate to toxic levels in some agricultural soils, such as old vineyards following extensive use of copper-based fungicides (Komárek et al. 2010), or agricultural soils receiving poor quality sewage sludge over extended periods (McGrath, Chaudri, and Giller 1995). However, in general, current European Union (EU) policy and regulation have reduced the 'heavy metal problem' during recent decades, and today we are dealing to a large extent with legacy heavy metal pollution impacts from old contamination events. Nevertheless, soil metal concentrations are still increasing in cropping systems that rely on copper-based fungicides or application of manure from pigs that routinely receive excessive levels of copper and zinc as feed additives (Jensen, Larsen, and Bak 2016; Magid et al. 2020). In addition, soil metal levels may increase in areas with high rates of atmospheric metal deposition (e.g. from metal smelters or other industrial activities) (Ettler 2016).

3. PESTICIDES

Pesticides are widely applied to agricultural soils with the delibarate aim of reducing crop losses due to insects, weeds or microbial plant pathogens (mainly fungi), and any non-target effects of pesticides on biodiversity or associated ecosystem services should be evaluated accordingly (EFSA Panel on Plant Protection Products and their residues (PPR) 2010). Apart from the copper-based fungicides mentioned above, pesticides represent a wide diversity of synthetic organic chemicals with contrasting environmental fates and effects. Some are easily mineralised in soil, whereas others are quite persistent, or may give rise to problematic compounds through their degradation.

Pesticide use can adversely affect biodiversity in some cases, and target organisms can develop pesticide resistance, thereby rendering the pesticides less effective in their designated function (Fisher et al. 2018). Pesticide resistence may also confer a human health risk in some cases. Indeed, fungal resistance to azole fungicides is widespread in some areas of Europe, and has been implicated to confer a risk for treatment failure in immuno-compromised humans infected with certain fungal pathogens (Berger et al. 2017; Fisher et al. 2018).

Pesticides may also be transported to adjacent terrestrial or aquatic ecosystems, and thereby exert adverse effects on non-target organisms (EFSA Panel on Plant Protection Products and their residues (PPR) 2010; Schwarzenbach 2006). Therefore, it is clear that sustainable agriculture should move in the direction of lower reliance upon these toxic agrochemicals.

4. EMERGING POLLUTANTS

Emerging pollutants refer to a growing number of synthetic or naturally occuring chemical substances that are not commonly monitored, yet are of emerging concern with regard to environmental quality or human health. Thus, the term covers both hazardous man-made chemicals introduced into the environment, as well as naturally occuring chemical substances previously thought to be of low risk to the environment or humans.

Pharmaceuticals and personal care products (PPCPs) comprise two broad categories of emerging pollutants that can reach agricultural soils, especially via application of manure, sewage sludge or irrigation water (Rodríguez-Eugenio, McLaughlin, and Pennock 2018; Smith 2009). They are bioactive compounds meant to affect the human body, and therefore should be monitored closely for any adverse effects in soil biota (Magid et al. 2020). In addition, antimicrobial pharmaceuticals (antimicrobials) are designed to kill or inhibit activity of bacteria (antibiotics), fungi (antifungals) or other microorganisms, and may consequently have adverse effects on soil microorganisms (Brandt et al. 2015).

Plasticisers (e.g. phthalates and bisphenol A) represent another category of emerging pollutants that may reach agricultural soils via the same waste streams as PPCPs, as well as via the widespread use of plastic materials in some farming operations (Rodríguez-Eugenio, McLaughlin, and Pennock 2018; Nizzetto, Futter, and Langaas 2016). Plasticisers are used to increase the flexibility of plastics, and are known to be potential endocrine disruptors in humans. More recently, researchers have started to investigate effects of whole plastic materials and microplastics in agricultural soils. However, very little is known about the effects of (micro)plastics on soil biota (Boots, Russell, and Green 2019), but a recent study concluded that high doses of some microplastics clearly have the potential to negatively affect plant growth and cause significant shifts in the size, activity, structure, and functioning of the soil microbial community (Zang et al. 2020).

Even some genes (i.e. DNA) have been categorised as emerging environmental pollutants. Hence, antibiotic resistance genes (ARGs) and other antibiotic resistance determinants (e.g. mobile genetic elements involved in transfer of ARGs among different species of bacteria) are now widely recognised to confer human health risks (Ashbolt et al. 2013; Larsson et al. 2018; Laxminarayan et al. 2020). Thus, the environmental dimension of antibiotic resistance has been incorporated into current EU- and national action plans in the global fight against antibiotic resistance in pathogenic bacteria. Studies indicate that ARGs have accumulated in soils during the antibiotic era (i.e. since ~1940), when humans started to use antibiotics in human medicine, and later also in animal farming (Graham et al. 2016; Knapp et al. 2010; Zhao et al. 2020). The drivers behind this expansion of the soil reservoir of ARGs are not fully understood, but dispersal of ARGs from human- and animal sources probably play a major role, as well as environmental selection of ARGs.

5. FERTILISERS

Fertilisers are essential for most crop production systems, and are thus of critical importance for food security. Organic farming practices rely exclusively on organic fertilisers (mainly animal manure), whereas inorganic fertilisers are commonly used in conventional farming. Plants compete for nutrients with soil microorganisms, and are therefore unable to take up all N and P input from fertilisers. When applied in excess, or when inputs do not match the needs of crop plants, this can give rise to a series of problems such as eutrophication of adjacent aquatic environments (via leaching or runoff), increased atmospheric deposition of ammonium, and release of nitrous oxide (N2O), a potent greenhouse gas. Reported detrimental consequences of agricultural fertiliser use include reduced biodiversity in both aquatic and terrestrial ecosystems, oxygen depletion zones in freshwater and coastal marine ecosystems, and global warming (Erisman et al. 2013; Gleeson et al. 2020; Robertson 2000). Thus, farmers and society as a whole have a strong joint interest in optimising plant nutrition by maximising nutrient uptake efficiency in crops.

Organic fertilisers represent an avenue for recirculating nutrients in areas with animal farms, and may even offer a chance to recirculate nutrients from urban to rural areas via the application of sewage sludge (biosolids). However, animal manure and sewage sludge can also contain a wide range of the pollutants mentioned above, such as metals, PPCPs and ARGs. Organic fertilisers can also be a source of pathogenic and/or antimicrobial resistant microorganisms that may reach consumers via multiple environmental pathways (e.g. contamination of food, soil, water and air). Recently, the environmental and human health risks associated with sewage sludge and animal manures were reviewed and systematically compared in a Danish context (Pedersen et al. 2019; Magid et al. 2020). It was concluded that sewage sludge from contemporary Danish society does not constitute a higher risk to soil biota or human health, compared to cattle or pig manure. Such comparisons are rare, but the reported study indicates that farmland application of high-quality sewage sludge may constitute negligible risks when compared to the much higher amounts of animal manures used for fertilisation on farmlands.

6. CONCLUSIONS AND FUTURE PERSPECTIVES

Soil pollution clearly confers a risk to soil biodiversity and associated ecosystem services. However, it must be emphasised that agricultural soil biotic communities (especially microorganisms) often display remarkable resilience to disturbances associated with soil pollution. Soil microbial communities can thus recover quickly following disturbances associated with agricultural management practices such as repeated application of fertilisers or pesticides (Petersen et al. 2003; Puglisi 2012; Poulsen et al. 2013; Rutgersson et al. 2020).

Due to the persistent nature of metals, and their past- and present accumulation in agricultural soils, metals may be considered the class of pollutants most likely to exert long-term effects on soil biodiversity and ecosystem services provided by soil biota. Metal pollution in soil has been found in many vineyards (e.g. copper), and has been associated with long-term adverse effects on soil biota (Fernández-Calviño et al. 2011). Other metals (e.g. zinc) have also been implicated to confer significant risks (Jensen, Larsen, and Bak 2016). Apart from directly reducing soil biodiversity, metals may also negatively affect earthworm burrowing activity, leading to soil compaction and subsequent biodiversity declines (Arthur et al. 2012; Thorsen, Brandt, and Nybroe 2013). Metals have also been found to co-select antibiotic resistance and ARGs (Berg et al. 2010; Zhao et al. 2019), and are likely to exert a more significant selection pressure for antibiotic resistance, compared to antibiotic residues in many agricultural soils (Song et al. 2017).

Pesticides are likely to exert effects on non-target organisms, especially those closely related to the target organisms (Thiour-Mauprivez et al. 2019), and can affect biodiversity in adjacent aquatic and terrestrial environments. Likewise, excess N- and P fertilisation can detrimentally affect plant diversity at the landscape scale, as well as cause collapse of aquatic ecosystems via eutrophication and subsequent formation of oxygen-depletion zones. Sustainable agricultural practices must be ensured in order to avoid, or at least mitigate, problems like these in the future. We require agricultural practices that reconcile crop productivity and biodiversity, in order to ensure food production while counteracting current losses in biodiversity and associated ecosystem services.

To this end, there is great need for progressive farmers and scientists to work together to understand the full complexity of the impact of soil pollution, both in agroecosystems and beyond. We need to understand the resilience of soil biota during and after exposure to pollutants, especially in the context of a changing climate. Specifically, there is a need for research looking into a greater number of factors (e.g. pollutants, climate, crop management, etc.) and their interactions, in order to better reflect a field-realistic context in agricultural research (Rillig et al. 2019).

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CHAPTER 8

EFFECT OF ORGANIC BY-PRODUCTS USED IN AGRICULTURE ON BIODIVERSITY

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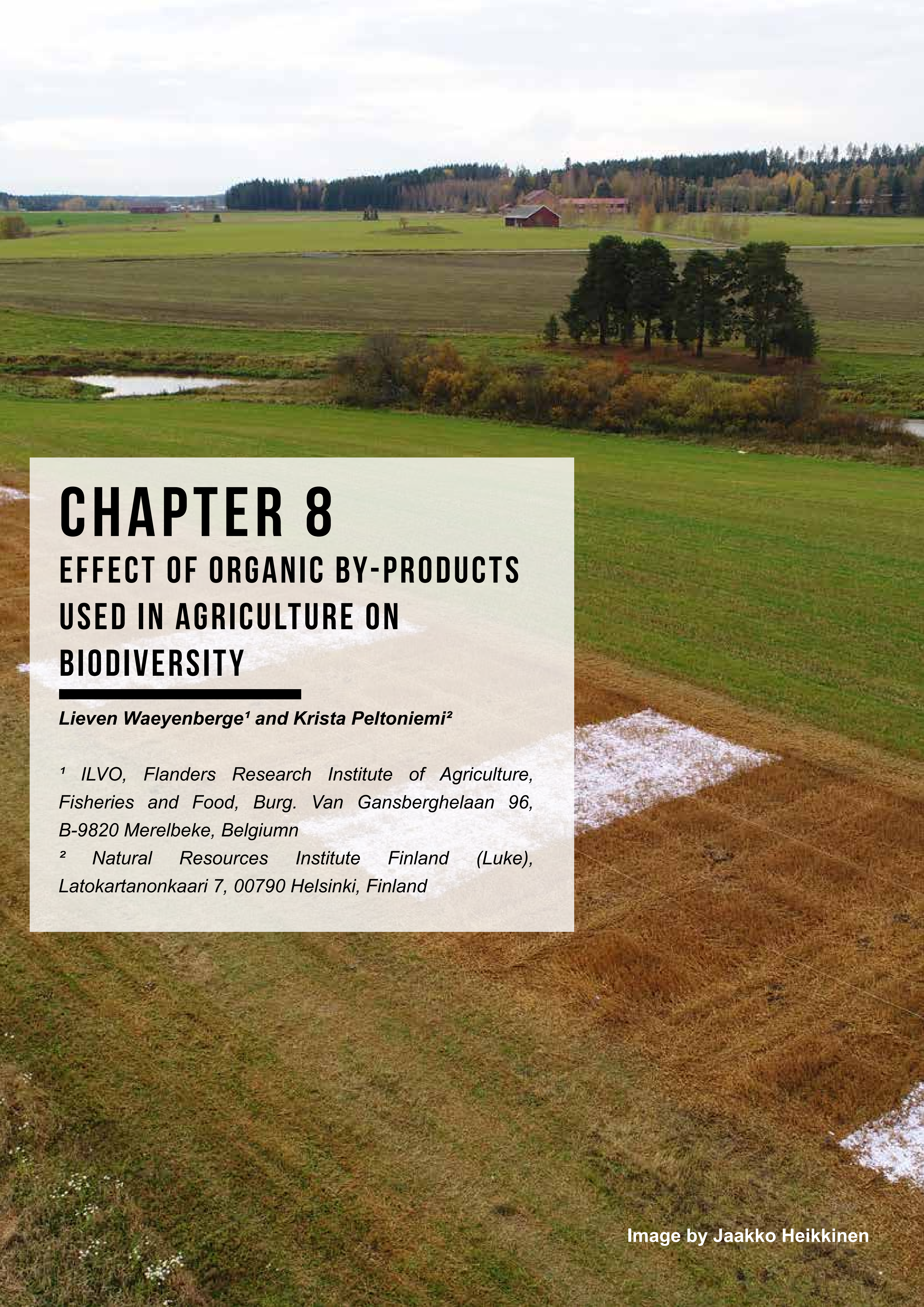

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ABSTRACT

Soil fertility is a primary concern for farmers. As crops grow, nutrients become depleted, and thus need to be supplemented regularly to the soil. Synthetic fertilisers are increasingly being replaced with organic fertilisers. Organic fertilisers can be upgraded with co-substrates like biochar or digestate. Next to organic fertilisers, cover crops and crop remnants are being incorporated into agricultural fields in order to increase organic matter content. Generally, increased applications of organic by-products into agricultural fields enhances biodiversity and associated provision of ecosystem services, such as soil fertility, disease suppression, soil structure, water holding capacity, erosion reduction and aeration. Humans can indirectly benefit from the re-use of organic waste, as well as the use of industial by-products, on agricultural fields, as it can facilitate climate mitigation by influencing carbon sequestration. However, there are several factors still to be addressed. The effects of different by-products on soil organisms is unknown. Some by-products contain pollutants that are toxic to soil organisms; others contain phytopathogens that reduce crop yield. Economic aspects are not fully considered when using organic amendments. Some of them are quite expensive because they have limited availability, or need to be processed before use. Insufficient data are available for evalutaing the influence of the agricultural management system, soil type and climate on the use of organic by-products. A holistic approach, considering biological, economic and social aspects is required for proposing actions that can be implemented within European directives, in order to make European agriculture more sustainable.

Keywords: climate mitigation; disease suppression; soil biodiversity; soil fertility; organic matter; sustainable agriculture.

1. INTRODUCTION

Agricultural food production directly or indirectly (via consumption or processing) leads to a significant amount of by-products. Part of these by-products are still marketable as input for another industrial process, the largest part being biowaste. Researchers are increasingly exploring ways to use biowaste as an alternative for synthetic fertilisers, or as a source material for manufacturing new, environmentally-friendly products such as bioplastics, nutraceuticals, biofuels and compost. The latter is another product under investigation as a soil amendment to substitute synthetic fertilisers.

This chapter will address the effects on biodiversity due to the use of by-products by farmers, as a replacement for synthetic fertilisers for maintaining soil health. Can it be a solution towards sustainable food production, compatible with biodiversity conservation or restoration?

2. ORGANIC BY-PRODUCTS USED IN AGRICULTURE

2.1. SYNTHETIC VERSUS ORGANIC FERTILISER

Fertilisers can have a natural or synthetic origin. Synthetic fertilisers such as ammonium nitrate, ammonium phosphate and potassium sulfate are inorganic salts typically derived from by-products of the petroleum industry. Organic fertilisers are by-products from plant and animal parts or residues typically from agricultural activities, the food industry and bioenergy production plants.

On the contrary to organic material, synthetic fertilisers only add certain nutrients (especially nitrogen (N), phosphorus (P) and potassium (K)) to the soil for crops to grow. However, they usually do not contain micronutrients. Moreover, synthetic fertilisers release nutrients so rapidly that some of it is leached into surface waters or groundwater. In contrast to organic fertilisers, synthetic fertilisers do not add organic matter; organic matter improves soil structure, water retention and resistance to soil erosion. Concerning biodiversity, synthetic fertilisers do not support soil microbial biodiversity. Thus, microbial biomass does not increase, but the microbes can immobilise large amounts of the added nutrients, increasing nutrient activity (Jonasson et al. 1996). Moreover, synthetic fertilisers select by killing a significant percentage of the soil organisms, while organic fertlisers introduce a wide range of organisms, including several that control plant pathogens or break down environmental pollutants (Timilsena et al. 2015).

2.2. SOURCES OF ORGANIC BY-PRODUCTS USED IN EUROPEAN AGRICULTURE

The use of organic fertilisers, crop residues or cover crops enriches soil organic matter content, which improves soil structure and enhances soil fertility through the provision of valuable nutrients like N, P, K, sulfur (S) and micronutrients (Diacono and Montemurro 2010). The main sources of organic fertlisers are different types of manures or composts. Manures from cattle, pigs and poultry are collected from animal husbandries and used on the field, generally without further processing. Biowaste from the food industry, agriculture, forestry, and most of all from municipal organic waste collection, is the major source for the production of compost (Meyer-Kohlstock, Schmitz, and Kraft 2015). Cover crops (Figure 8.1) diversify crop rotation and help reduce soil erosion (Panagos et al. 2015). They can also add nitrogen the surrounding soil through biological nitrogen fixation, or function as catch crops that store the remaining nitrogen after the main crop is harvested, thereby preventing leaching (Abdalla et al. 2019).

Figure 8.1. Wheat field in Belgium a few weeks after harvest and sowing of a cover crop. The incorporation of crop remnants and cover crops is scheduled for after winter (Source: ILVO).

Other sources of organic fertilisers were recently introduced. Biochar is the char material left behind after biomass pyrolysis during bioenergy production. Biochar preferably is used as a co-substrate during composting because it contains little amounts of nutrients, and can even immobilise them when added to soil, resulting in crop losses and declines in microbial diversity. Biochar-compost (Figure 8.2), however, reduces some of the N and carbon (C) losses, and accelerates the composting process (Meyer-Kohlstock, Schmitz, and Kraft 2015). Digestate is the material remaining after anaerobic digestion of biomass, and consisting mostly of organic waste. In this way, digestate is not the same as compost, which is a product from an aerobic, oxygen-dependent process. Similar to biochar, it is not always ideal to use digestate directly on land as fertiliser; composting before application is recommended (Teglia, Tremier, and Martel 2011).

Industrial by-products of the forest- and paper mill industry, such as pulp and paper mill sludges, as well as sludge composts, as soil amendments and plant nutrient sources, are suggested to promote arable soil health (Camberato et al. 2006). Promising results from the use of the pulp and paper mill biosolids as soil amendments increased their popularity. They improve organic matter content-, water holding capacity-, structure- and bulk density of soils (Rashid, Barry, and Goss 2006). Paper mill biosolids, however, may contaminate soil with heavy metals as well as organic compounds, which consequently need to be monitored carefully.

Figure 8.2. Field experiment in Belgium using application of biochar-compost (Source: ILVO).

3. EFFECTS OF AGRICULTURAL ORGANIC BY-PRODUCTS ON SOIL ORGANISMS AND ASSOCIATED PROVISION OF ECOSYSTEM SERVICES

3.1. SOIL ORGANISMS

Globally, soils have been proposed to contain one quarter to one third of all living organisms (Jeffery et al. 2010). We are only beginning to comprehend the complexity of soil interactions. Turbé et al. (2010) distinguish three 'all-encompassing ecosystem functions', each fulfilled by a functional group of organisms: (i) Transformation and decomposition of organic material is performed by 'chemical engineers' (especially bacteria and fungi, but also collembolans, mites, some nematodes, ants, enchytraeids, and earthworms); (ii) management of the food web structure is performed by 'biological regulators' such as protists, collembolans, mites, many nematodes, ants and microarthropods; (iii) soil utilities like water retention, habitat construction, aeration, etc. are performed by 'soil ecosystem engineers' like earthworms, enchytraeids, ants, isopods, and moles. The effect of organic by-products on three important groups of organisms will be highlighted, namely microorganisms, nematodes and earthworms.

Microorganisms and earthworms generally are known by farmers and the public. This is not the case for nematodes, with a possible exception of plant-parasitic species because of their detrimental effects on crop yield. Nematodes or roundworms are a diverse, highly specialised group of organisms. They inhabit virtually all ecosystems. In the soil, they occur across multiple trophic levels and frequently are the most abundant and diverse invertebrates present. Consequently, nematode composition contains high intrinsic information value for each soil sample (Yeates et al. 1993).

3.2. IMPACT OF ORGANIC BY-PRODUCTS ON BIOLOGICALLY-MEDIATED ECOSYSTEM SERVICES

3.2.1. CHEMICAL ENGINEERS AND SOIL FERTILITY

Long-term experimental field studies have demonstrated that microbial biomass significantly increases after application of farmyard manure, as well as all types of compost (Diacono and Montemurro 2010). When organic amendments contain easily accessible nutrients, bacteria actively develop. This is especially the case when N-rich (liquid) manure or digestate is used. As a consequence, bacteria-feeding nematodes develop as well. When less-easily decomposed organic amendments are used, such as different types of compost containing woody components, fungal populations also increase significantly (Güsewell and Gessner 2009), with subsequent increases in fungivorous nematodes. Bacterivorous and fungivorous nematodes benefit from increases in decomposer microbes, as these microbes represent a primary food source. By grazing on them, bacterivorous and fungivorous nematodes contribute considerably to nutrient mineralisation, not only by releasing ammonium through their faeces, but also by rejuvenating old (inactive) bacterial and fungal colonies via spreading bacteria and fungi to newly available organic residues, and by promoting rhizosphere colonisation of beneficial bacteria (Ferris et al. 1998; Gebremikael et al. 2016; Knox et al. 2004). The abundance and activity of these microbivorous nematodes may, in turn, also be regulated by predatory nematodes and other fauna, further modulating nutrient availability (Wardle and Yeates 1993).

In contrast, removal of organic by-products, such as crop residues, can result in a degraded soil ecosystem. Karlen et al. (1994) found that ten years of corn residue removal under no-tillage resulted in reduced soil quality, where soil carbon, microbial activity, fungal biomass and earthworm populations were all reduced, compared to sites where residues were not removed. The impact of earthworm decline can be substantial, since earthworms contribute significantly to decomposition and distribution of organic material (2–20 tons per hectare per year), as well as (up to five-fold) increases in nutrient availability (https://orgprints.org/30567/1/1629-earthworms.pdf).

From a soil microbiological perspective, the fields are simplified “ploughed up wood-wide-web” systems (Helgason et al. 1998) lacking complex forest-derived carbon compounds. Forest soil organic matter largely consists of slowly decaying wood and microbial residuals (Clemmensen et al. 2013).

Therefore, industrial by-products of forest origin are thought to promote arable soil health by maintaining soil nutrient balance and soil structure (Camberato et al. 2006), and by diversifying the soil substrate, thereby leading to a more diverse microbiome. One benefit of more variable substrate selection could be less-optimal growth conditions for harmful microbes, due to increased microbial competition. Indeed, addition of forest litter recently was shown to decrease the susceptibility of wheat to pathogenic Fusarium infections (Ridout and Newcombe 2016). Organic humic acids have been proposed to act as a two-way biofertiliser in sustainable agriculture; plants treated with humic compounds interact with the surrounding microbes; and humic compounds may also modify the structure, and activate the microbiome, of the rhizosphere (reviewed by Canellas and Olivares 2014).

3.2.2. DISEASE SUPPRESSION

Organic amendments also can have a disease suppression effect. Soil fertility management by incorporation of organic by-products, like manure and compost, enhances soil microbial activity and subsequent suppression of soilborne plant pests and diseases by favoring antagonists (Mehta et al. 2014). However, it is unclear which type of organic amendment is most efficient against particular pests or diseases, and how weather conditions or soil characteristics can influence this effect.

Cover crops are increasingly being used to control plant-parasitic nematodes. Still, there are no straightforward recommendations, as the effect depends on whether or not a cover crop is a host plant for one or more nematode species (Thoden, Korthals, and Termorshuizen 2011). The same applies for soilborne diseases; however, Hajjar, Jarvis, and Gemmill-Herren (2008) has suggested that a mixture of cover crops may contribute to controlling both soilborne diseases as well as pests, as a result of cover crop genetic diversity (including pest- or disease-resistant genes).

Biochar or biochar-compost (Figure 8.2) is able to aid in the control of pests and diseases. Possible explanations are that biochar: (i) improves colonisation of mycorrhizal fungi that protectant plants against pathogens; (ii) enriches the diversity of the soil community, which can increase the presence of biocontrol agents (e.g. the fungal genus Trichoderma); or (iii) induces a low-level defense mode in plants, due to the presence of low concentrations of phytotoxins (Huang et al. 2015).

3.2.3. SOIL ENGINEERING

The incorporation of organic by-products such as compost, cover crops and crop residues, or the cultivation of crops leaving behind substantial amounts of C-rich residues in fields, facilitates the development of earthworm populations. However, earthworm development is even more stimulated by farmyard manures or partially composted organic material, as this contains more food for them (Leroy et al. 2008). On the contrary, root crops of which most of the crop is harvested, discourage the development of earthworm populations (Edwards and Bohlen 1996).

Earthworms are especially known to improve soil structure and stability. Their behaviour creates pores, improving aeration and water distribution. Earthworms also create microhabitats for other organisms to develop (Edwards and Bohlen 1996), which boost the provision of other ecosystem services.

3.2.4. CLIMATE CHANGE MITIGATION

It has already been mentioned that biochar enhances soil disease suppression. However, the use of biochar has also attracted interest due to the fact that biochar is more resistant to microbial degradation and chemical transformations, compared to other organic by-products. These characteristics endow biochar with a greater potential to become a highly useful source of soil amendment for improving agricultural productivity through soil quality enhancement, while simultaneously sequestering carbon dioxide from the atmosphere, mitigating climate change (Mulabagal et al. 2017).

Organic material stored or applied on the field comes in contact with the atmosphere and releases powerful greenhouse gases, such as methane (CH4) and nitrous oxide. The digestion of organic material reduces these gas emissions (Greenhouse gas emission statistics, Eurostat 2014). Furthermore, a recent study showed that the addition of organic residues to agricultural soil has the potential to enhance soil CH4 uptake (Ho et al. 2015).

4. CONCLUSIONS AND FUTURE PERSPECTIVES

Modern agricultural management systems are particularly detrimental to biodiversity and can lead to reductions in ecosystem service provision. A range of drastic and synergistic actions is needed to make agricultural food production more sustainable.

The use of organic amendments, such as composts and manures, in agriculture, can be traced back to at least the 3rd millennium BC (Wilkinson 1982). Historical scrolls describe the use of cereal by-products, such as straw and chaff, in composts and soil amendments for crop production in ancient Greece and Rome (Foxhall 1998). In modern agriculture, the use of organic amendments was significantly replaced by synthetic fertilisers. However, numerous reports describe, as a consequence, reductions in soil quality, including: soil acidification, reduced amounts of soil organic carbon, deteriorated soil structure, heavy metal contamination, losses of biodiversity and an increase in greenhouse gas emissions. Therefore, the reintroduction of biomass is ongoing, but it is a slow process. This could be due to a number of factors, such as (i) uncertainties around precise ecological and economic benefits; (ii) the influence of soil types, environmental conditions and management practices; and (iii) the importance of long-term studies to elucidate ecosystem mechanisms and biological interactions. Moreover, several studies report on the impact of organic by-products on biodiversity of the complete ecosystem. However, most of them only address plants and aboveground organisms. Less is known regarding the impact on belowground organisms. This is probably due to the fact that most soil organisms are microscopic and difficult to collect, making them more difficult to study. Modern techniques in diagnostics like next-generation sequencing, remote sensing or fourier-transform infrared spectroscopy could solve this problem.

Scientific research should provide data indicating clear directives at the European level. These directives may not be straigthforward, as demonstrated by the fact that several studies report that organic amendments to soil contributes to greater soil biodiversity in organic farming (Mäder et al. 2002), while for a farmer other factors such as lower yields and higher consumer prices are of more importance and thus should be considered as well (Seufert and Ramankutty 2017). Another example concerns the use of cover crops. Cover crops are largely constrained by climate; low temperatures in northern regions, after the main crop harvest, gives these crops little time to grow, while the same crops compete with the main crop for water in southern regions. Selective breeding towards cold tolerant varieties, or varieties that quickly develop a surface cover, and then halt further growth, preserving soil water, can be a possible solution. Additionally, selective breeding should also aim for a low host-suitability of cover crops, regarding plant pathogens. However, the presence of different species of plant pathogens among different regions of Europe makes selective breeding for this purpose a challenge. A third example concerns the accessibility of manure or compost. Excess manure is available in certain regions but is of limited availability in other regions due to local regulations or other specialisations in livestock management systems. Compost, on the other hand, is currently limited throughout Europe, and therefore costly. Finally, caution is required with the implementation of new organic amendments. Biochar and digestate composition can alter soil communities, and can even contain pollutants detrimental to soil organisms, depending on the source of biomass used in the production system.

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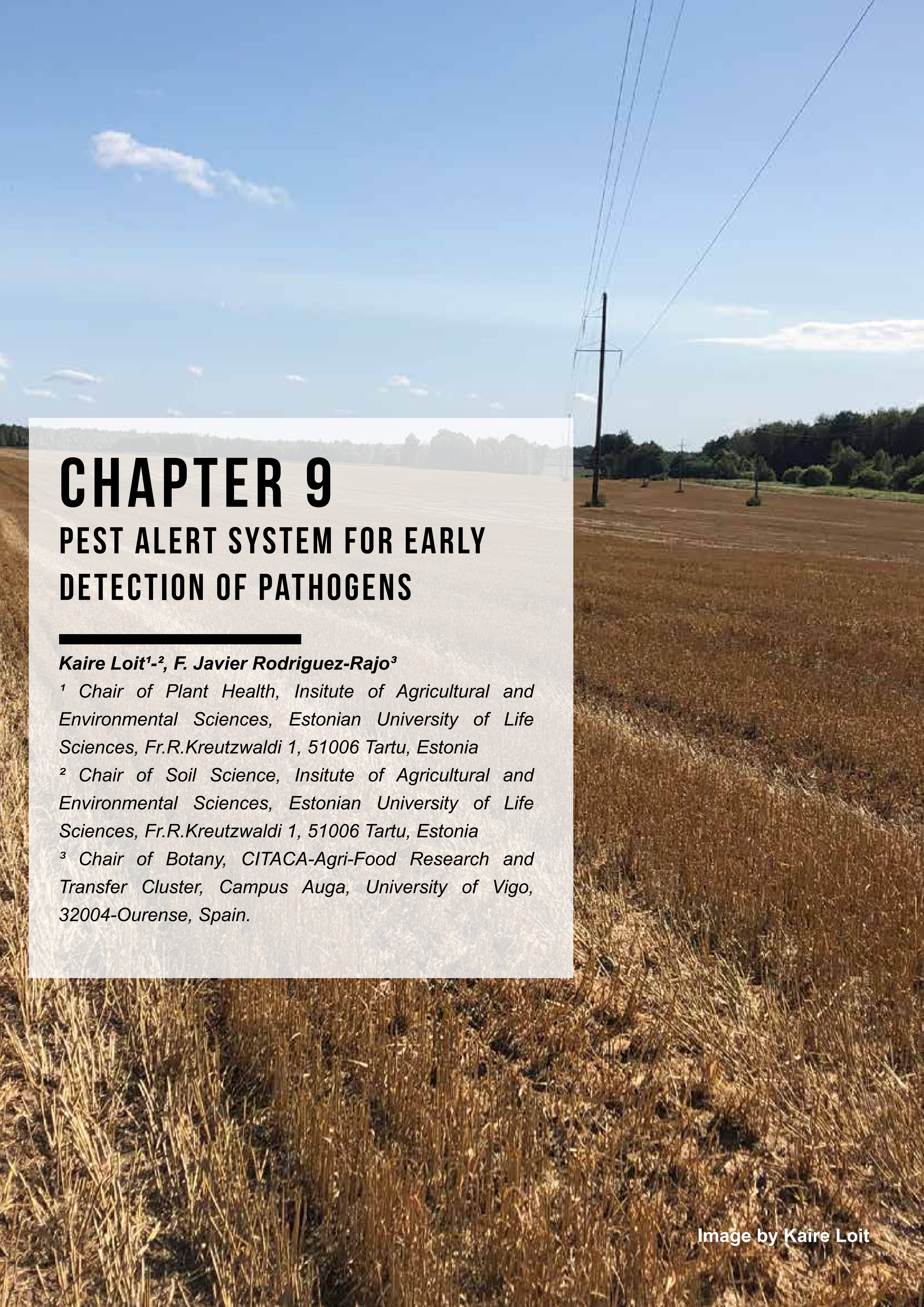

CHAPTER 9

PEST ALERT SYSTEM FOR EARLY DETECTION OF PATHOGENS

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Image by Kaire Loit

ABSTRACT

Fungicide use plays an essential role in agriculture, benefiting crop health, yields and quality. Unfortunately, the current trend is to apply fungicides on a routine basis, and not according to actual need. Every year, large quantities of foliar fungicide treatments are applied in an inadequately-timed manner. Unnecessary fungicide applications are detrimental for both economic and environmental reasons. Many crop diseases are dispersed via airborne spores (Almquist and Wallenhammar 2015), which can vary in space and time. Treatment schemes for controlling such pathogens provide need-based scheduling, using appropriate diagnostic techniques. For airborne pathogens, it is possible to use air sampling for immediate detection of inocula presence (West et al. 2017). A range of air sampling methods, as an alert system for rapid detection of airborne diseases of different pathogens, is in use globally.

Keywords: airborne inoculum, environmental impact, spore traps

1. INTRODUCTION

Fungicide use plays an essential role in agricultural production, bringing the primary benefit of crop health and higher yields.The management of polycyclic diseases that have several infection cycles per season often relies on unnecessary routine pesticide application schedules. Air sampling techniques for airborne pathogenic fungal spore collecting have been widely used in studies of plant diseases. In this chapter, we identify the key bottlenecks and opportunities of air sampling as a promising approach in the early detection of airborne pathogen load. Also, we intend to demonstrate that this disease decision support system could help reduce unnecessary fungicide applications in order to help maintain economic and environmental benefits. Various responses in plants – from changes in leaf colour, shape or size, to disturbances to the plant – can each be incorporated, via spectroscopy and imaging methods, to map diseases in fields (West et al. 2017). However, these methods are not useful for mapping early detection. For example, Head blight on wheat, when the disease has already erupted, is too late detected to allow disease control. Moreover, studies have shown that different forecasting models that provide fungicide treatment recommendations based on climate, crop rotation, field information, and economy are not competent as forecasting tools. If the timing of spore release can be determined, fungicides can be applied more efficiently when the pathogen is not present or is present in low numbers (Almquist and Wallenhammar 2015).

2. MANAGEMENT OF AIRBORNE DISEASES

It’s generally well known that disease control depends highly upon agronomic practices such as adjustment of sowing or planting dates, as well as strategic application of foliar fungicides, to minimise infection. Still, management of pathogens that produce more than one infection cycle per growth period often relies on calendar-based fungicide application schedules. Usually, the pathogen species present in a region, and their inoculum availability during different growth stages, are affected by environmental conditions (Hardwick 2002; Del Ponte et al. 2009; Almquist and Wallenhammar 2015), crop in the rotation sequence, as well as other factors that affect inocula production and infection success (Blandino et al. 2010; Davidson et al. 2013; Qiu and Shi 2014; Thiessen et al. 2016).

Many studies (Blandino et al. 2010; Qiu et al. 2016; Edwards and Jennings 2018) have shown that increasing trends towards non-inversion or minimal-tillage, as well as short rotations, have led to increased inocula availability of pathogens because the crop residues persist for a long time and produce large amounts of inocula. Studies also show that regional inocula levels also play an important role in local disease epidemics. For example, the study of Blandino et al. (2010) with maize residue density showed that ploughing to a 30 cm depth significantly reduced Fusarium head blight (FHB) severity and mycotoxin deoxynivalenol (DON) occurrence in each year and site. FHB severity and DON contamination both significantly increased with the density of the residues left by the preceding crop. The importance of infected crop stubble from previous seasons in local disease epidemics have also been shown by Fitt et al. (2006), who explained that the infection of blackleg or stem canker of brassicaceous plants, in most cases, initiated in autumn via ascospores, which originate from fruiting bodies of the sexual stage, and are produced on oilseed rape stubble from previous seasons. In addition, Davidson et al. (2013) showed the importance of daily rainfall and temperature in influencing the timing of ascospore release from infested field pea stubble.

Prediction infection models, based on the main risk factors that leave crops vulnerable to epidemic diseases, are important for integrated management strategies. Traditionally, the main infection risk factors were associated with agriculture practices (e.g. crop rotation, planting dates, tillage practices), environmental conditions (e.g. climate, weather), and different host susceptibilities according to the plant phenological stage (De Wolf and Isard 2007). The disease triangle is one of the paradigms in plant pathology (Stevenson 1960), claiming that the existence of a plant disease absolutely requires the interaction of a susceptible host, a virulent pathogen and favourable environmental conditions for disease development (Stevenson 1960; Agrios 2005). Knowledge of pathogen biology and disease cycles, including interactions between pathogen, environment and host, is essential for avoiding or reducing the consequences of a given plant disease (De Wolf and Isard 2007). Therefore, plant disease is prevented with the absence of any one of these three causal components. Moreover, the combination of: i) the identification of a given plant phenological stage propitious for disease infection; ii) the observation of pathogen presence in the field; and iii) the identification of suitable environmental conditions for pathogen via agrometeorological models are important components predicting disease outbreaks. Despite the fact that we do not have control over the weather, we still have tools that can effectively be used to rapidly measure the spore load in air. To avoid unnecessary fungicide applications, as well as to prevent or to reduce the lesions appearance, fungicide sprays should be applied at a time prior to the visibility of lesions in plants. Some studies noted a 25–35% reduction in fungicide treatments in vineyards by means of monitoring spore loads in the air (González-Fernández et al. 2019).

3. AIR SAMPLING TECHNIQUE USED IN STUDIES OF CROP DISEASES

Since many authors have related fungal disease levels at a given time with airborne spore concentrations from previous periods, airborne spore concentrations can be used as biosensors of pathogen development (Carisse, Savary, and Willocquet 2008). Identification of the main infection risk periods, based on spore thresholds of the crop in the air, makes disease detection possible prior to the appearance of symptoms (González-Fernández et al. 2019). Rapid air sampling methods, for monitoring the presence of fungal spores in the air, can bring enormous benefits to farming. Several studies have concluded that using air sampling for early detection of pathogens during the plant growth cycle may result in more accurate conclusions regarding the need for localised fungicide applications. West et al. (2008) showed that the timing of spore release for some species coincides with a growth stage of the plant that is susceptible to the disease. Brachaczek, Kaczmarek, and Jedryczka (2016) showed that, in a case of high disease pressure, fungicide treatment against stem canker was most effective when applied 4–11 days after the highest concentration of airborne pathogenic ascospores, and under a no-tillage regime. Once the spores are present in the air over the crop at concentrations higher than a given threshold, they still need 4–6 more days (depending on the phenological growth stage), under suitable weather conditions, to develop fungus and lesions. Carisse, Savary, and Willocquet (2008) also found a significant correlation between airborne spore concentration on a given date, and lesion density one week later, for both unmanaged and managed sites in their study.

To determine the incidence of airborne pathogens of crops, a variety of air sampling techniques have been used in studies of crop diseases, including downy mildew of hops (Gent et al. 2009), Sclerotinia stem rot of oilseed rape (Almquist and Wallenhammar 2015), blackleg or stem canker of brassicaceous plants (Fitt et al. 2006), and grape powdery mildew (Thiessen et al. 2016; González-Fernández et al. 2019). Moreover, inocula-based forecasts are best suited to sporadic crop diseases, particularly those that infect during early- or late crop growth stages, when farmers do not routinely spray fungicides (West et al. 2017).

Another practical aspect discussed is the location of the air sampler. Heard and West (2014) and West et al. (2017) have demonstrated that spore concentrations depend on the sampler location. In some crops, close row spacing can reduce spore movement and the ability to detect potential inocula (Thiessen et al. 2016).

For strategic fungicide application decisions, PTA-ELISA or DNA-based diagnostics are designed to detect specific pathogen species that can infect a particular crop. Some studies confirm the utility of recent PTA-ELISA protocols to quantify fungal germinative protein concentrations in the air over the crop, based on recognition of specific antibodies. Several studies have shown that PCR or qPCR assays, for the detection or quantification of inocula, can be implemented to improve ecological sustainability of disease management, through more targeted fungicide applications. For example, Almquist and Wallenhammar (2015) clearly showed that qPCR quantification of the airborne inocula of Sclerotinia sclerotiorum represents a reliable tool for predicting the potential disease risk. A study using PCR to detect Pseudoperonospora humuli in air samples showed that the use of PCR to determine the timing of the first fungicide application led to a reduction in fungicide use. A review paper by West et al. (2008), regarding the practical application of DNA-based technologies for disease forecasting, suggested that the combination of molecular diagnostics with strategic sampling of airborne inocula can be exploited in order to more accurately predict the risk of severe disease epidemics in agroecosystems, regarding diseases with outbreaks limited by amount of inocula.

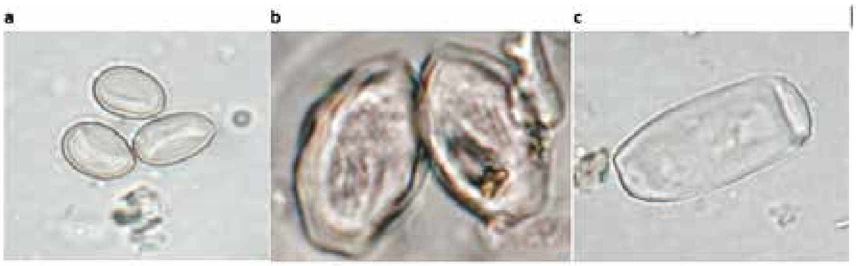

Figure 9.1. Botrytis cinerea- (a), Plasmopara viticola- (b) and Uncinula necator (c) spores sampled in the air over an agroecosystem.

Figure 9.2. a) Seven-day recording volumetric spore trap (Burkard Manufacturing, Rickmansworth, UK) in the wheat field. b) Seven-day recording volumetric spore sampler and Ciclone sampler (Burkard Manufacturing, Rickmansworth, UK) for airborne spore protein detection.

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CHAPTER 10

IMPROVING SOIL QUALITY WITH COVER CROPS

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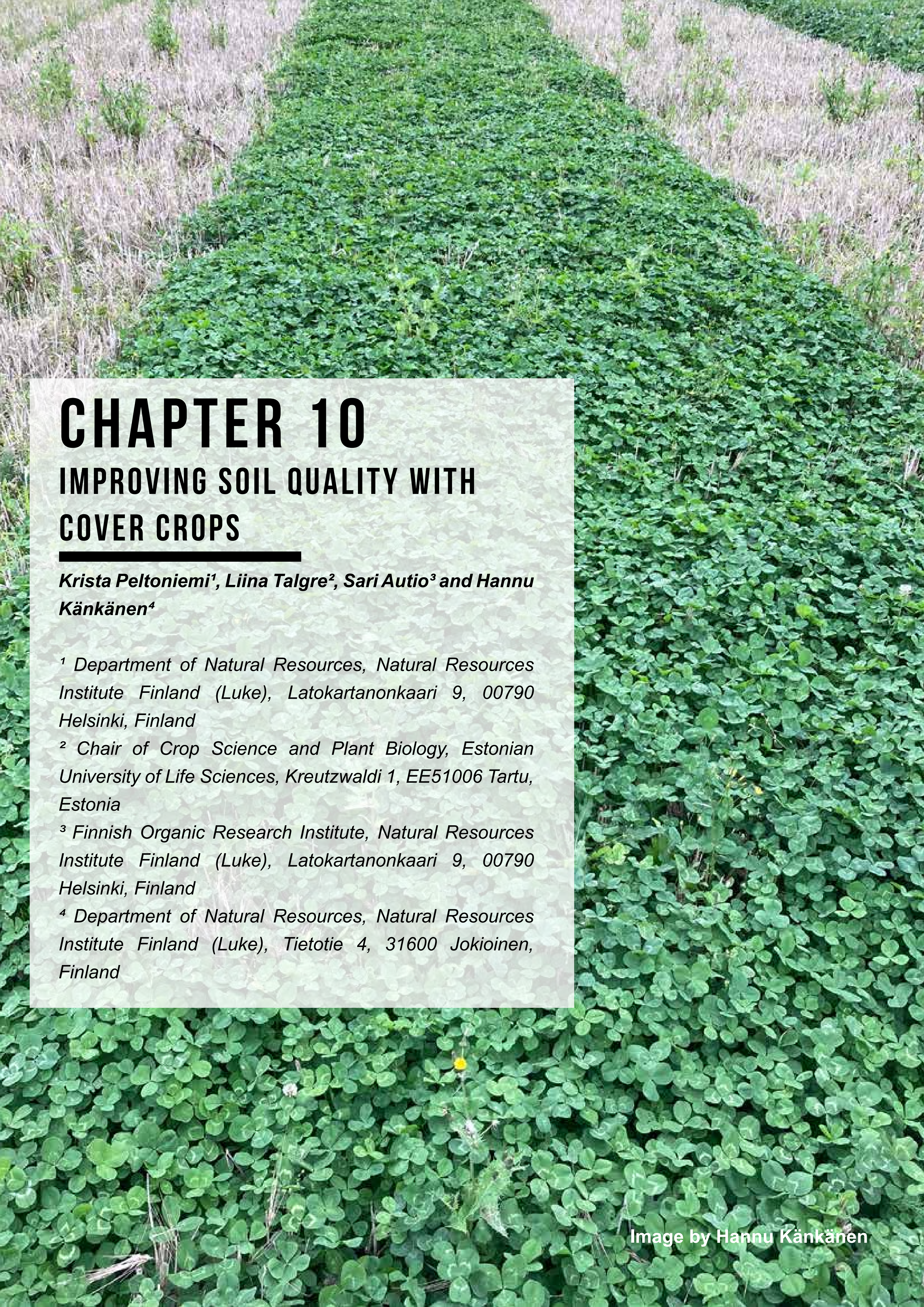

Image by Hannu Känkänen

ABSTRACT

The growing of cover crops or catch crops (terminology depends on the context and region), undersown or sown after the main crop harvest, is a beneficial agricultural practice generally applied to improve physical, chemical and biological properties of soil. For instance, cover crops are used to prevent nutrient leaching, retain water holding capacity, protect soil from erosion, and control weeds and plant pathogens. Depending on the species, cover crops may increase carbon and nitrogen inputs from plant residues, root exudates or via symbiotic nitrogen fixation. Cover crops are also able to utilise and increase the proportion of phosphorus in the soil. How cover crops interact with soil microbial communities has not been systematically assessed, and thus is not well understood. Organic matter provided by cover crops are assumed to stimulate microbial activity in soil. A few studies suggest that cover crops enhance soil microbial communities by increasing mycorrhizal fungal abundance, phosphorus in microbial biomass or enzyme activity. In addition, specific cover crops have been suggested to benefit specific microbial groups, especially arbuscular mycorrhizal fungi. The question of whether cover crops induce changes in functional community composition of soil microbes needs further investigation. Cover crops could be part of the solution for more sustainable agriculture in a future challenged by climate change and loss of carbon from arable soils.

Keywords: cover crop; catch crop; soil biodiversity; soil fertility

1. INTRODUCTION

The negative effects of invariable cropping and lack of vegetation after main crop harvest can be mitigated by growing cover crops, also called catch crops (CCs). CCs refer to plants that take up nutrients left in the soil by previous crops and green manure and protect the soil by increasing plant cover. CCs have a variety of ecological functions: aiding in the conserving of water and nutrients; protecting soil from erosion; controlling weeds and soilborne pathogens; and improving the physical, chemical and biological properties of soil (Smolinska and Horbowicz 1999; Fageria 2009). Also, leguminous CCs may increase the yield of succeeding crops, as a result of their nutrient cycling capabilities (Talgre et al. 2012; Hallama et al. 2019; Li et al. 2015).

Depending on the choice of CC species and the sowing time, we can influence the amount of biomass, as well as root depth. Selection of plant species with rapid growth and deep root systems are usually a good choice to facilitate nutrient uptake to main crops, as CCs with deep roots take nutrients from deeper soil layers, and the nutrients are mobilised into the topsoil after crashing of CC populations (Thorup-Kristensen 2001; Thorup-Kristensen, Magid, and Jensen 2003). CCs increase carbon (C) and nitrogen (N) inputs through plant residue decomposition, root exudates and symbiotic N fixation. The winter-cereal CCs, when applied in Mediterranean horticultural rotations, modulate agroecosystem interactions in response to environmental conditions, thereby managing weed selection and growth (Ciaccia et al. 2015; Campanelli et al. 2019). Grasses and cruciferous crops absorb N from soil, whereas legumes can take N from atmosphere via biological N fixation. Legumes have been widely reported to be superior in providing N to the subsequent crop, even when the CC is undersown (Vyn et al. 1999; Garand et al. 2001; Talgre et al. 2009). Similarly, like N mineralisation differs between legumes (Müller and Sundman 1988; Kirchmann and Marstorp 1991), there are great differences in N release between non-legume species, both when material is incorporated in the soil (Jensen 1992)and when crops are allowed to overwinter (Sturite, Henriksen, and Breland 2007).

CCs are able to utilise moderately labile phosphorus (P) and increase the proportion of labile P fractions in the soil (Soltangheisi et al. 2018). Interactions between CCs and the soil microbial community, which is a key driver of P cycling, have not yet been systematically assessed. Hallama et al. (2019) concluded that CCs may enhance the soil microbial community by providing a legacy of increased mycorrhizal abundance, microbial biomass P, and phosphatase activity.

Temperatures during autumn often are insufficient for satisfactory post-harvest growth of CCs in northern parts of Europe, whereas undersowing has been shown to be a suitable method for establishing CCs. Moreover, undersowing is not restricted to cool climate regions, but can be a beneficial tool for diversifying crop rotations in other regions as well (e.g. Kunelius, Johnston, and MacLeod 1992; Singer and Cox 1998; den Hollander, Bastiaans, and Kropff 2007; Baributsa et al. 2008).

The growth of undersown CCs is preferred to be moderate until cereal harvest, in order to keep competition against the main crop low. Undersowing has shown to decrease yield of the main crop greatly (Kunelius, Johnston, and MacLeod 1992; Känkänen and Eriksson 2007; Arlauskiene and Maiksteniene 2008), slightly (Solberg 1995; Ohlander et al. 1996; Garand et al. 2001; Känkänen and Eriksson 2007) or not at all (Solberg 1995; Känkänen and Eriksson 2007; Talgre et al. 2009), depending on the species of both the main crop and CC, as well as on circumstances (Känkänen 2010). After harvest, CCs should grow vigorously and have good frost- and winter hardiness, together with a well-developed root system (Karlsson-Strese, Umaerus, and Rydberg 1996). Furthermore, CCs should not easily become weeds, or transmit- or multiply pests and pathogens that attack the main crop in rotation.

Climate change further increases the need for using CCs in northern Europe, as under conditions of higher precipitation, as well as longer, warmer winters, there is expected to be an increased risk of leaching of both plant protection chemicals and fertiliser nutrients, as well as soil erosion (Peltonen-Sainio et al. 2009). Replacing winter fallows with CCs may contribute to climate change mitigation through the sequestration of soil C and N (García-González et al. 2018).

In Finland, the total CC area in 2018 was approximately 123,000 hectares, most of which was undersown among cereal crops. Approximately half of the total CC area was represented by legumes (mainly white- and red clover, Trifolium repens L. and T. pratens L.) (Figure 10.1a), and the other half represented by grasses (mainly Italian ryegrass Lolium perenne L.) (Figure 10.1b; approximately one third of these grasses were perennial species). Mixtures of legumes and grasses were seldom used. Sowing CCs after main crop harvest, or using cruciferous species, was rare. In Estonia, the total CC area was increased in 2018, this increase mostly represented by legume undersowing in cereal crops. Since organic production in Estonia has grown in recent years, the interest in growing CCs after main crop harvesting, in order to maintain soil fertility, has also increased. Adding plant material into soil can increase activity of microorganisms, which is critical for sustaining fertility and productivity of agricultural soils. According to Lupwayi et al. (2004), legumes with high N content increase soil microbial activity and functional diversity, whereas residues with high C content improve soil quality by increasing soil organic matter content. Consequently, long-term use of CCs has been reported to enhance soil productivity (Hansen, Kristensen, and Djurhuus 2000; Blombäck et al. 2003).

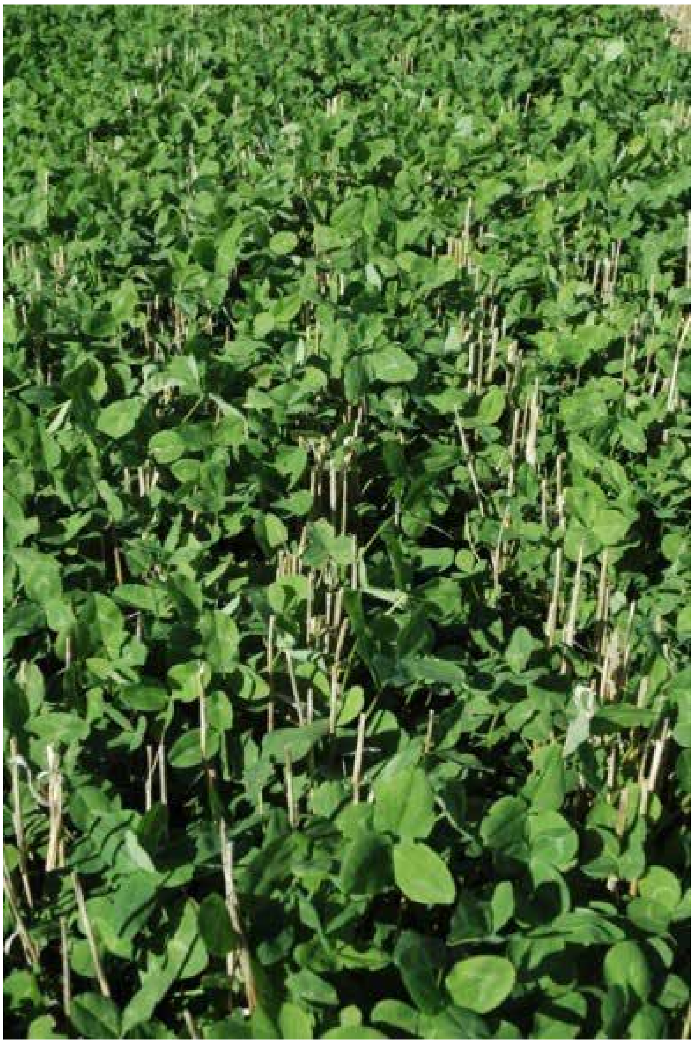

Figure 10.1a. Mixture of undersown white- and red clover (Trifolium repens L. and T. pratens L.), a couple of weeks after barley (Hordeum vulgare) harvest.

Figure 10.1b. Italian ryegrass (Lolium perenne L.) (light green leaves) sown in spring under winter wheat (Triticum aestivum) (straw and darker leaves).

1.1. BIOMASS PRODUCTION AND NITROGEN BINDING OF COVER CROPS

Of the undersown legumes studied in Estonia, red clover (Trifolium pratense), hybrid lucerne (Medicago sativa) and white melilot (Melilotus albus) produced the greatest biomass. Growth period, aftermath formation (i.e., regrowth of CCs after harvest of the main crop) and competitiveness had an influence on the biomass production of the undersowings. When CCs are undersown, total amounts of dry matter (roots, leguminous biomass and cereal straw) varied between 6.4–9.4 t ha–1 (Talgre et al. 2009); and 93–177 kg N ha–1, 16–20 kg P ha-1 and 98–153 kg K ha–1 returned to soil (Talgre et al. 2012). Undersown legumes improve the C:N ratio in organic matter, creating better conditions for organic matter decomposition in soil (Dordas and Lithourgidis 2011; Talgre et al. 2012). Particularly sensitive were lucernes and white melilot; a delay in main crop (cereal) harvest reduced the biomass of these undersowings. Red clover is more stable and resistant to unfavorable conditions than other legumes (Talgre 2013). In Finland, the dry matter (shoots and roots) yields of undersown legumes and Italian ryegrass (Lolium multiflorum) were 1.1 and 3 t ha-1, respectively (Känkänen and Eriksson 2007). N yield of legumes was, on average, 30 kg ha-1 (Känkänen 2010), which is low compared to that in Estonia, although cereal straw was not included. Furthermore, yield of undersown CCs vary greatly (Känkänen 2010).

When CCs are sown after a cereal harvest, the quantity of CC biomass produced depends on the sum of effective temperatures during the growing season. Therefore, sowing of CCs early in midsummer ensures good growth. If sowing is delayed until the end of summer, there is increased risk that CCs are no longer able to grow and absorb nutrients properly, depending on CC species (Iivonen, Kivijärvi, and Suojala-Ahlfors 2017; Toom et al. 2019). Depending on the CC species and sowing time, the biomass of CCs ranged from 2.2–4.9 t ha–1 (Toom et al. 2019). Iivonen, Kivijärvi, and Suojala-Ahlfors (2017), Talgre et al. (2012) and Toom et al. (2019) investigated the biomass production of Italian ryegrass, phacelia (Phacelia tanacetifolia), white mustard (Sinapis alba) and buckwheat (Fagopyrum esculentum). All these researchers found that white mustard had the highest aboveground dry matter yield, compared to that of other investigated species.

The N accumulation of CCs is largely dependent on the amount of biomass they can produce by the termination time. N retention capacities of CCs are species-specific; an early developing, deep root system with high root density has been shown to aid in taking up leachable N from deeper soil layers (in 't Zandt, Fritz, and Wichern 2018).

2. CURRENT KNOWLEDGE ON THE IMPACTS OF VARIOUS COVER CROPS ON SOIL BIODIVERSITY

Soil quality may be described as the ability of soil to support biological activity and promote the health of the soil community; and soil microbial activity is much more sensitive to changes than physical or chemical parameters (Odlare, Pell, and Svensson 2008). Diverse sources of organic matter may stimulate microbial activity in the soil (Tejada et al. 2008). Long term simulations have shown that CC cultivation could drastically increase soil organic C and total N, especially in reduced-tillage treatments (Büchi et al. 2018). Thus, increases in soil organic C content would likely stimulate both the abundance and diversity of microbial communities; however, little is known about how CCs and tillage systems affect the composition of soil microbial communities (Schmidt et al. 2018).

A well-studied mechanism through which plants affect the soil microbial community is via the effect of root exudates (Buyer et al. 2010; Maul and Drinkwater 2010). Since exudate composition, quantity and seasonality depend on host plant species, a CC that includes a variety of plants should be able to maintain greater diversity of root-associated microbes, conferring greater overall benefits to crops. Through strategic choice of CC species and sowing time, it is possible to influence the amount of biomass, as well as root depth. According to Vukicevich et al. (2016), there are several impacts of root exudates to microbes in the rhizosphere. Root exudates attract and sustain arbuscular mycorrhizal (AM) fungi, entomopathogens and N-fixing bacteria (Akiyama, Matsuzaki, and Hayashi 2005; Rasmann et al. 2005; Long 2001). However, root exudates also attract host-specific pathogens (Nicol et al. 2003; Hamel et al. 2005; Hofmann et al. 2009), and thus can lead to both positive and negative feedback mechanisms within soil communities. In contrast, Schreiner and Koide (2006) found that brassicaceous plants may inhibit AM fungal spore germination due to the antifungal volatiles produced by their roots.

Plant residues and soil organic matter are energy sources for microbial processes. Fanin, Fromin, and Bertrand (2015) found that the quality of plant residues had a strong effect on shaping soil microbial communities. For example, lower C:N ratios in plant residues promote faster-growing copiotrophic microbes, including disease-suppressive microbes. Tein et al. (2014) demonstrated that glucosinolate content in CC residues can reduce soilborne pathogens of potato.

Talgre et al. (2019) found that microbial activity was higher in organically managed soils, compared to conventionally managed soils. The highest microbial activity was observed in an organically amended system containing CCs, and with cattle manure incorporated into the soil. The lowest microbial activity occurred in conventionally managed soil where no mineral fertilisers had been used, evidently because of low input of organic matter, the use of pesticides and low soil pH. A study by Martínez-García et al. (2018) confirms that both organic soil management and CCs enhance the activity and abundance of soil microbial groups (e.g. bacteria, saprotrophic fungi). However, the impact of CCs on microbial communities may be difficult to distinguish from the effects of other soil management practices. For instance, Romdhane et al. (2019) found that modifications of soil properties due to CC management, rather than the composition of CC mixtures, were related to changes in the abundance of ammonia-oxidizing and denitrifiying bacteria, while there was no effect on total bacterial abundance. Finney, Buyer, and Kaye (2017) found that CCs generally promote microbial biomass and activity, and that specific CCs are associated with increase in the abundance of specific microbial groups (e.g. increased positive associations of AM fungi with oats and rye, and of non-AM fungi and hairy vetch, Figure 10.2). It was also shown that the introduction of a mixed living mulch advantageously promoted artichoke (Cynara scolymus) mycorrhization (Trinchera et al. 2017); while in an organic horticultural rotation, spelt (Triticum dicoccum), when cultivated as a winter cereal CC, boosted colonisation of AM fungi to coexisting plants (Trinchera et al. 2019). Therefore, selection of CC species may be an appropriate management strategy for increasing targeted fungal groups.

Figure 10.2 Mixture of hairy vetch (Vicia villosa L.) and winter rye (Secale cereale L.) (sown after cereal harvest).

Schmidt et al. (2018) studied the effect of reduced tillage, tillage depth and cultivation of CCs on soil microbial functional diversity in irrigated Mediterranean agroecosystems. Their results suggested that implementing CCs led to a significant increase in total bacterial numbers, compared to no-till treatments, at all soil depths examined. Increased diversity and supply of nutrients provided by CCs was likely responsible for the observed increases in microbial abundance and community diversity.

Promoting CC variety and diversity can be an efficient way to increase soil microbial diversity while suppressing soilborne pests that cause crop losses (Garbeva, van Veen, and van Elsas 2004; Raaijmakers et al. 2009). Peralta et al. (2018) investigated the effects of different crop rotations on soil microbial diversity and disease suppression-capacity, through increased abundance of disease-suppressive microorganisms. They concluded that CCs in crop rotation did not increase soil bacterial diversity. Also, they found that the composition of soil microbial communities, rather than simply a greater soil microbial diversity, may be more important to soil disease suppression.

3. CONCLUSIONS AND FUTURE PERSPECTIVES

CCs have been used for a long time in organic farming. In the future, the use of CCs will likely be considered an essential part of integrated agricultural management. Benefits from growing CCs, sown after the main crop harvest or undersown, for improved quality and health of cultivated soils, are unquestionable. However, the choice of CC species, timing of sowing, how much biomass it produces, and other management practices (e.g. tillage regime) likely determines the overall impact on the soil. Impacts of CCs on the activity and composition of soil microbial communities are not well understood and require further investigation. C loss from arable soils, together with predicted drier and warmer weather conditions, remains a challenge for food production. CCs could be part of the solution for more sustainable agriculture.

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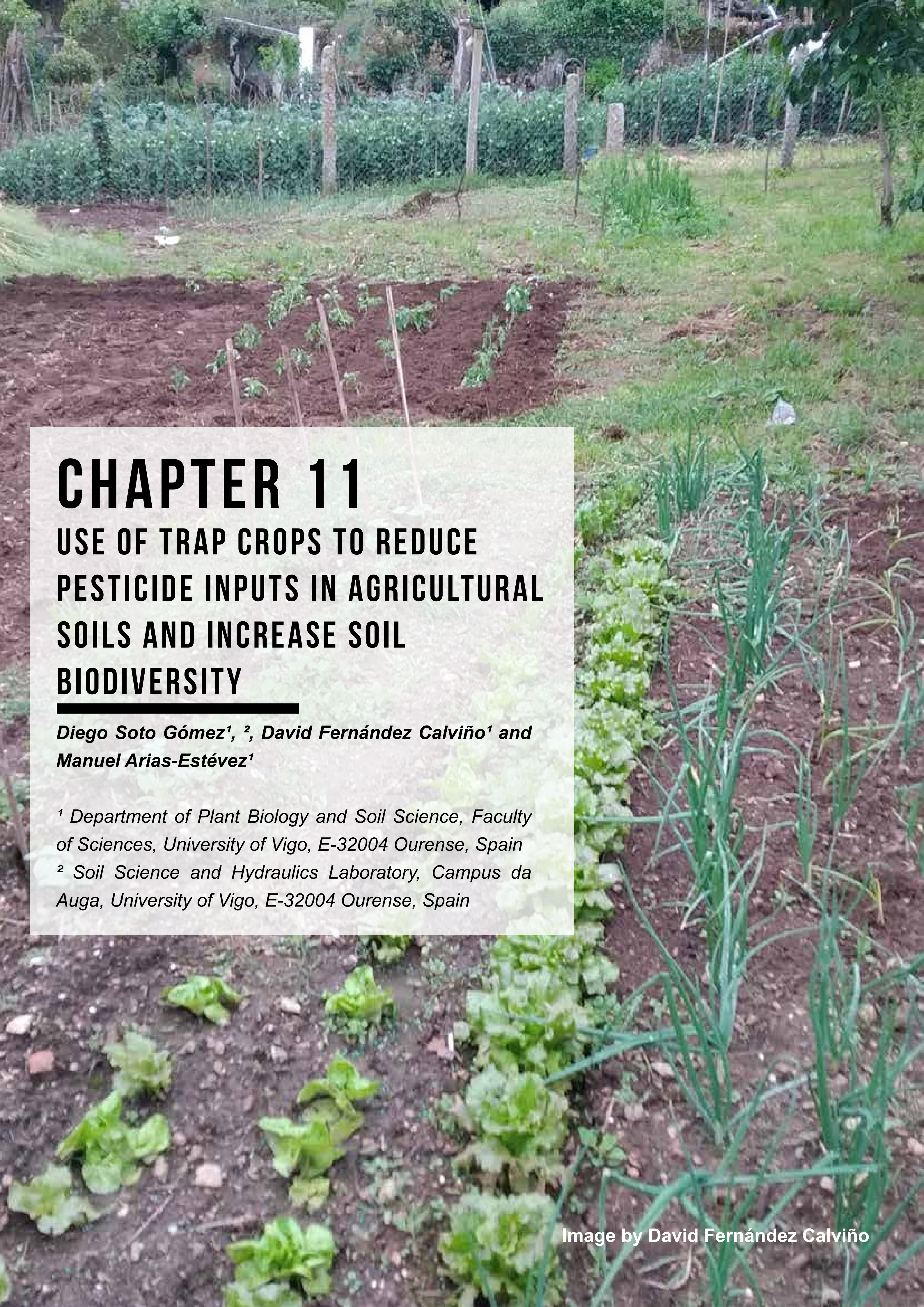

CHAPTER 11

USE OF TRAP CROPS TO REDUCE PESTICIDE INPUTS IN AGRICULTURAL SOILS AND INCREASE SOIL BIODIVERSITY

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Image by David Fernández Calviño

ABSTRACT

Trap crops are those cultivated to protect another crop (main- or cash crops), since they are capable of attracting or repelling certain pests. Trap cropping is a traditional method based on plant diversification, the use of which is booming in integrated pest control given the problems associated with other types of management that are less environmentally sustainable. The use of trap crops is highly complex and admits many possibilities, since there is a wide variety of trap crops, each having different effects on pest species. There are plants that not only attract, but disrupt, the life cycle of some pests, or eliminate viral vectors present in some insects (e.g. in the stylet of aphids). Besides, concerning the main crop, these techniques can be used at various times in the growing season, and with different distributions, thus increasing control opportunities, as well as possible combinations of trap crops. In this chapter, we present this method and its use nowadays, through different examples of effective trap croppings. Moreover, we also included the known effects of the trap crops on agroecosystem biodiversity.

Keywords: trap crop; integrated pest management; pests; organic agriculture; push and pull; biodiversity.

1. INTRODUCTION

One alternative to the use of chemical pesticides is the use of trap crops, an environmentally sustainable method that was often used in traditional agriculture before the appearance of chemical pesticides (Shelton and Badenes-Perez 2006). Trap crops are those selected to attract and retain certain organisms, preventing attacks on the main crop of greater interest to farmers. For one reason or another, the pests that are intended to be controlled can have an equal- or greater affinity for trap crops than for the cash crops, concentrating the pests at certain locations, distracting them or making their extermination easier. Trap crops can also have other effects on crop pests; they are capable of attracting predators and parasitoids of pest species (Sarkar et al. 2018), as well as disrupt the life cycle of some insects, and produce adverse effects on viruses present in some organisms (Gonsalves and Ferreira 2003).

There is a wide range of techniques related to trap cropping, and it is important to understand the relationships that occur between trap crops, target pest species and other organisms (e.g. natural enemies), in order to determine the best strategy for each case, which factors influence its effectiveness and, and what are the results of each technique.

2. TRAP CROPS: A BROAD APPROACH

To establish a trap crop, a series of factors that will determine the effectiveness of the method must be taken into account. To begin with, the trap- and the main crop must have similar requirements (e.g. temperature, daylight hours, soil pH), since they will be cultivated in the same area (Shelton and Badenes-Perez 2006). The spatial location of the trap crop, relative to the main crop, is important; as is the period, as many pests occur at a specific time of the year. In addition, trap crops can have different effects that must be considered; among others, they can attract a pest or alter its life cycle, as well as lure natural predators.

2.1. EFFECT OF LOCATION AND PLANTING TIME

When designing the spatio-temporal margin of a trap crop, there are multiple options. Using the trap crop on the perimeter of the main crop is a technique that has given good results. For example, it is a system that has been used lately to protect sugar cane from Chilo sacchariphagus, using Erianthus arundinaceu as a trap crop (Nibouche, Tibère, and Costet 2019). C. sacchariphagus females prefer this latter crop for oviposition, but larval survival rate and subsequent development is much lower than in sugarcane. Another option is an intercropped crop, where the two crops develop in parallel, as shown in Srinivasan and Moorthy (1991). In this case, Indian mustard is used to protect cabbage crops from diamondback moth. The growth cycle of cabbage is shorter, so there is the possibility of planting mustard several times, increasing the effectiveness of this trap crop. Another option that offers good results is to use the trap crop before or after the main crop. This type of sequential crop has worked, for example, in the control of nematode cysts by rotating potato (Solanum tuberosum) with trap crops of the same family, such as S. nigrum or S. sisymbriifolium (Scholte and Vos 2000). These crops produce a series of compounds that cause the cysts of the nematodes to hatch (Devine et al. 1996), but do not provide support for oviposition of the pest, reducing its presence in the soil.

2.2. EFFECTS ON PESTS

The attractive effect that some crops have on certain pests has been known for years, and one of the most functional examples is the system used in California to separate Lygus bugs from cotton using alfalfa as a trap crop (Stern et al. 1969). However, every year new applications of this technique are developed, as is the case of the use of orange jasmine (Murraya paniculata) at the edges of citrus orchards to attract Asian citrus psyllid (Diaphorina citri) (Tomaseto et al. 2019). In this case, orange jasmine was treated with thiamethoxan, reducing the population of the pest, and transforming these perimeter crops into sinks for psyllid populations. This can be considered an artificial dead-end for the target pest species; however, a similar effect can be achieved if the trap crop has the capacity to eradicate or reduce the population of the pest species, as in the case of a dead-end trap crop (Solanum sisymbriifolium) used to control nematodes in potato crops; here, the root exudates of S. sisymbriifolium cause nematode cysts to hatch, but do not offer space for oviposition. Therefore, when rotated with potatoes, this trap crop is able to reduce the population density of nematodes (Dias et al. 2017).

There are also trap crops, known as insectary plants, that can help reduce pest populations by attracting natural predators and providing them with food (Shrestha, Finke, and Piñero 2019). For example, the effectiveness of sweet alyssum (Lobularia maritima) has been proven in attracting syrphid flies to lettuce crops, where they prey upon aphids (Hogg, Bugg, and Daane 2011). If predatory species attack pests at different stages of development, or during different times, biological control becomes more efficient (Snyder 2019). The combination of various types of trap crops can be very effective in controlling some pests. Shrestha, Finke, and Piñero (2019) successfully used different crops to protect Brassica oleracea. To this aim, on one hand, the authors used several Brassica species, and on the other hand, insectary crops (sweet alyssum and buckwheat, Fagopyrum esculentum). The concentration of herbivores (e.g. Evergestis rimosalis, Trichoplusia ni, and Plutella xylostella) in the trap crops was higher than in the main cabbage crop, and the presence of the braconid wasp Cotesia orobenae, an endoparasitoid of E. rimosalis, increased as a result of the presence of insectary plants. Furthermore, there was an increase in the presence of eggs of Coleomegilla maculata, an aphid predator, in the trap crops that were established jointly with insectary plants. This is a fairly complex system, and the possibility that certain natural enemies of a pest can also affect populations of other natural enemies of the same pest should be taken into consideration.

Trap crops can also be used to control the spread and incidence of certain viruses. An effective trap crop to control viruses is one that cannot host the virus but is attractive to the vectors and their natural enemies (Hull 2014). There are a number of cases that support the effect of trap crops on virus control (Hooks and Fereres 2006), and a clear example is the control of PVY (the Y potato virus) and CMV (cucumber mosaic virus) using sorghum (Avilla et al. 1996); by using sorghum as a barrier, vectors (e.g. aphids) lose part of their ability to infect before reaching the main crop.

2.3. PUSH AND PULL

There is a particular trap crop technique based on mechanisms of repulsion and attraction, termed push and pull. This system manipulates the behaviour of pests, causing them to move them away from the main crop, through the use of a crop that repels the pest, and another one that is attractive to it (Cook, Khan, and Pickett 2007). The synergies between both crops produce a greater control effect on the pest. A recent example of this type of strategy was employed to control lepidopteran stem borers in cereal crops in sub-Saharan Africa (Khan et al. 2016). Inserting unattractive plants for moths (e.g. Melinis minutiflora; Figure 11.1) reduced the presence of these pests, since this crop is very attractive to Cotesia sesamiae, a parasitoid of stem borers. Also, moths feel a predilection for the oviposition in Napier grass (Pennisetum purpureum), a plant that can be grown as an attractant and also serves as a dead-end for stem borers, as it secretes a gummy substance that immobilises stem borer larvae. The combination of both crops significantly reduced the presence of moths in cereal crops.

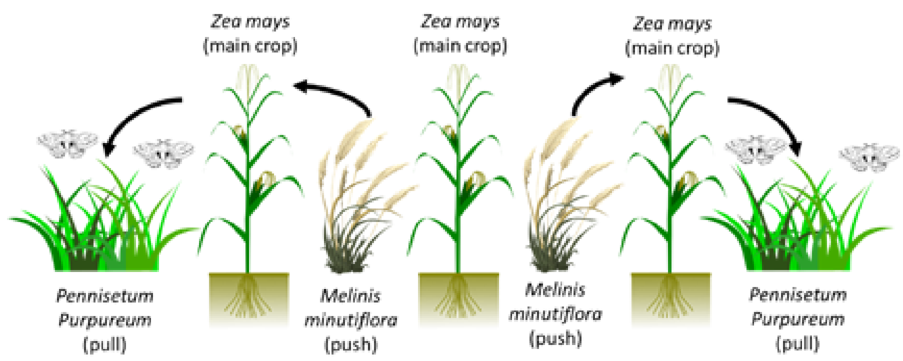

Figure 11.1. Push and pull technique: moths (e.g. Striga spp.) are attracted (pull) to Napier grass (Pennisetum purpureum) planted in the perimeter of maize crops (Zea mays), while being repelled (push) by Melinis minutiflora cultivated between rows (Adapted from: Khan et al. 2010).

3. TRAP CROPS AND BIODIVERSITY

The establishment of intensive agriculture, with a production based on the use of chemical pesticides, brings a decrease in biodiversity, which can be restored through the use of a more environmentally friendly type of management, organic agriculture (Letourneau and Bothwell 2008). A consistent technique with this type of agriculture that can contribute to the increase of biodiversity is the use of trap crops. Parker et al. (2016) found that, to protect broccoli from the crucifer flea beetle, the use of several trap species together (Brassica juncea, Brassica napus and Brassica rapa subsp. Pekinensis) was more efficient than each of them separately. As explained in previous sections , some trap crops increase the biodiversity of the ecosystem by attracting natural predators of the pests (Hogg, Bugg, and Daane 2011; Snyder 2019). It has also been shown that some push and pull systems improve soil biodiversity by increasing the abundance and diversity of arthropods (Khan et al. 2011). However, the effect of trap crops in the biodiversity of edaphic microbiota has not been studied yet.

4. CONCLUSIONS AND FUTURE PERSPECTIVES

Trap crops are environmentally friendly, and there are numerous examples of their functionality in both developed- and developing countries. In the long term, these techniques are much more interesting, and less devastating, than the chemical pesticides used in conventional agriculture. Given the versatility of these types of crops, and the rise of genetic manipulation techniques that are currently being developed (e.g. CRISPR/Cas9) (Gurr and You 2016), trap crops may become one of the pillars of organic agriculture in the coming years. However, an in-depth investigation is required in order to determine the optimal application of this type of crop (e.g. which planting patterns are more effective, and what percentage of trap culture should be planted with respect to the main one). It is also necessary to determine the economic efficiency of this type of management (Sarkar et al. 2018). Moreover, research tasks should also include other aspects related to the effects trap crops have on soil or the diversity of species present in it.

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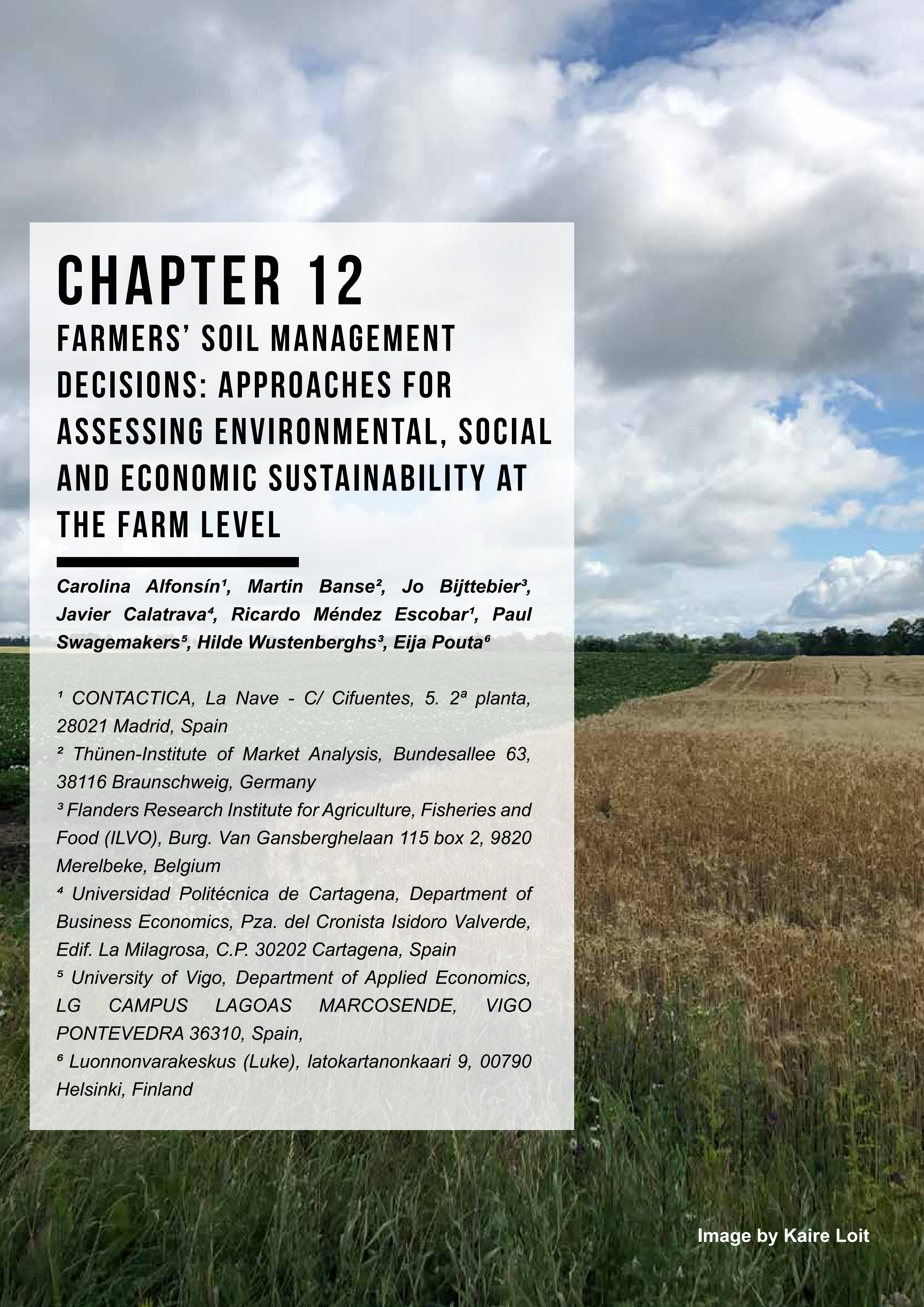

CHAPTER 12

FARMERS' SOIL MANAGEMENT DECISIONS: APPROACHES FOR ASSESSING ENVIRONMENTAL, SOCIAL AND ECONOMIC SUSTAINABILITY AT THE FARM LEVEL

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Image by Kaire Loit

ABSTRACT

Farmers are the key decision makers in soil management. In their decisions, they can take into account the multiple dimensions of sustainability: monetary revenue that farm production generates; protection and enhancement of natural resources, such as soil quality; and social and cultural aspects of farming. In this chapter, we briefly discuss the approaches that can be used to understand, predict and facilitate farmers' decision-making: economic approach; theory of planned behaviour from social psychology; and lifecycle analysis, focusing on environmental aspects of production and sustainability assessment that integrates various aspects of sustainability.

Keywords: land owners; farmer behavior; economic decision; sustainability; life cycle assessment.

1. INTRODUCTION

Sustainable agriculture "conserves land, water, and plant- and animal genetic resources, and is environmentally non-degrading, technically appropriate, economically viable and socially acceptable" (FAO 1989). The concept of sustainability thus integrates multiple dimensions. In this chapter, we shortly review which approaches can support farmers' decisions to adjust their farms to increase sustainability through soil management.

From a socio-economic perspective, farmers most often perceive farm optimisation in terms of the monetary revenue that farm production generates. Farmers have to earn a living, but some of their activities protect and enhance natural resources (e.g. improving soil structure or biodiversity), while certain ways of farming have a more negative impact on the environment (e.g. fertilisers and pesticides polluting soils and water resources, resulting in externalised costs such as contaminated drinking water). Current and future adaptations to emerging environmental and resource vulnerabilities, supported by agri-environmental policies, may lead to adjustments in land use and farm practices that restore soil biodiversity.

One can identify three distinct, yet mutually interdependent, aspects that shape how farmers optimise their farming system, and in turn, farm management and decision making (van der Ploeg and Ventura 2014):

1. Notions or ideas about 'how to farm', i.e. the drivers and motivations for farming that are based on a farmer's reality and needs, and his or her cultural beliefs;
2. Actual farm practices, i.e. the strategic actions which are an expression of those beliefs;
3. Different kinds of internal and external relationships, such as those with markets, technology, and administrative- and policy frameworks.

Farmers are increasingly challenged to include environmental, economic and social aspects of sustainability in designing their farming systems. This affects the three mutually dependent aspects of farmers' decision making, and calls for assessment of farming systems via indicators. These in turn can help farmers in reorienting their farm production towards environmental, social and economic sustainability at the farm level.

In the following sections, we briefly review theoretical approaches to understand- and facilitate farmers' decision making towards sustainability. These approaches can help to evaluate management practices and cropping systems from an environmental and socioeconomic point of view through the construction of a framework that enables assessing the cost and benefits of management practices to improve soil quality and enhance soil biodiversity.

2. FARMER'S ECONOMIC DECISION

Farmers are a heterogeneous group whose values, objectives and practices differ. They have to earn a living, and their farming strategies are often based on an economics, which implicitly or explicitly results in trade-offs between economic- and environmental assets. Farmers usually optimise their farm production according to what 'adds up' and to what 'remains below the line'.

Different farmers optimise farm production differently; they align their farming practice with their ideas and motivations. The way they produce food is influenced by markets and policies; and so is how farm production results in farm income. Decisions most often represent the way farmers see themselves, their technological farm production, and what they perceive others (expressed through markets and policies) want them to produce, and in turn how they behave. Costs and risks (regarding both harvesting and selling farm produce) influence how farmers optimise their farming systems, and in turn the decisions farmers make. In sustaining their farming businesses, farmers' differing ideas and motivations influence their decisions about farm management, leading them to adopt diverging farming practices. For example, farmers can convert the risk on environmental degradation from an externalised cost into a valuable farm asset. The optimisation of soil biodiversity and its productive capacity, as well as the value added for more environmentally sound food produce, can, on one hand, reduce costs (buying less inputs from the market); and, on the other hand, improve farm income (improved prices paid for quality produced, in combination with payment schemes).

Questions for economic analysis to be answered include: How important is healthy soil for the farm's economic performance? What practices result in healthy soil? How do farmers assess soil health? What can they learn about achieving better soil health? Could soil health and more specifically soil biodiversity be relevant indicators for assessing farm performance? How can farmers sustain the economy of farm production?

3. DRIVERS AND BARRIERS IN FARMERS' DECISION MAKING

The theory of planned behaviour (TBP) from social psychology can be used as a framework for revealing drivers and barriers, for adoption of soil management practices by farmers (Ajzen 1988, 1991). In this theory, farmers' intentions to adopt a practice is determined by the degree to which implementing it is positively or negatively evaluated by the farmer (attitude), the feeling of social pressure from others (called referents) to adopt the practice (subjective norm), and the beliefs of the farmers about the ease or difficulty of successfully applying it (perceived behavioural control) (Figure 12.1). Combining attitude, subjective norm and perceived behavioural control, results in a positive or negative intention to actually perform the behaviour. According to the theory of planned behaviour, the greater the farmer's intention to adopt the practice, the more likely they are to act on it as well.

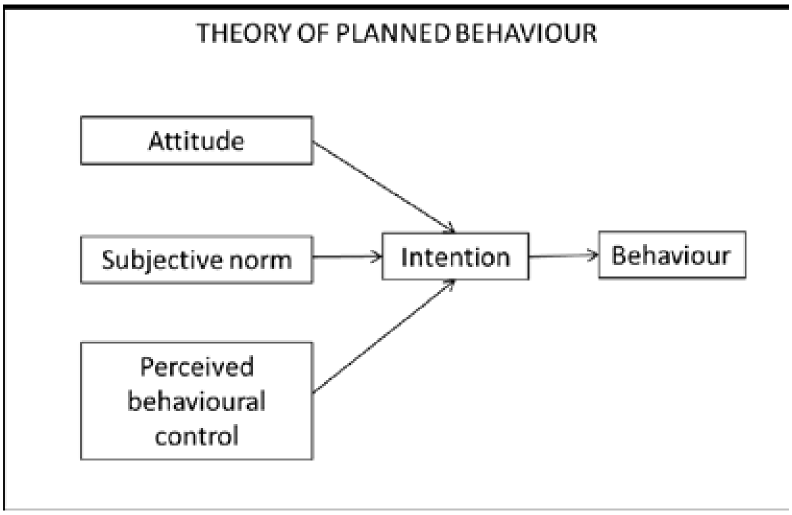

Figure 12.1. Theory of planned behaviour

Attitude is formed by the belief that the behaviour is associated with a set of outcomes, weighed by an evaluation of these outcomes. The latter is the value given by the farmer to this outcome, e.g. how important it is to him/her to have good soil structure. Subjective norm is determined by how much the farmer perceives that others (referents) think he/she should adopt the practice, and by a farmer's motivation to comply with these referents. Finally, perceptions of behavioural control are determined by the belief that a set of control factors facilitate or obstruct the behaviour, weighed by the expected impact that these factors would have if they were to be present. All these underlying subjective beliefs influence a farmers' intention to adopt a practice, and are acting as cognitive drivers or barriers which encourage or discourage the farmer to adopt it.

The application of TPB consists of different stages. Semi-structured interviews identify outcomes, referents and control factors for each management practice, followed by a large-scale survey that assesses farmers' beliefs on the control factors, outcomes and referents related to each of the practices. The results can reveal insights into what drives- and prevents farmers from applying particular practices.

4. ENVIRONMENTAL ASSESSMENT – LCA

Life Cycle Assessment (LCA) can be used to quantify many of the environmental impacts of economic activities. When farmers adopt new farming practices, this may alter the farm's impact on the environment. LCA takes into account the full cycle, from raw material extraction, through transformation, manufacturing and transport, to the use of the end product. The interpretation of the assessment must follow a multi-criteria and multi-category baseline in order to avoid burden shifting when studying the consequences of innovative farm management approaches (Wegener et al. 1996).

According to the international standard ISO 14040:2006, LCA studies are divided into four interconnected stages, and consist of the definition of goal and scope of the assessment, the collection of relevant data, the life cycle impact assessment, and the interpretation of the findings.

The results of LCA rely significantly on the quality of data used and the choice and quality (completeness and robustness) of the life cycle impact assessment method. In complex fields, such as the agro-food sector, including all the relevant variables and their correspondent impacts into the study is a complex task. Different methodologies have been developed to minimise uncertainty of the results, and to harmonise the procedure to perform an LCA study in the sector. The right selection of methodology and impact assessment method, and the right definition of goal and scope, are determinant to obtain meaningful conclusions.

5. INTEGRATED SUSTAINABILITY ASSESSMENT AT THE FARM LEVEL

Sustainability assessment aims to direct decision-making either at policy or farm levels (Sala, Ciuffo, and Nijkamp 2015; Pope et al. 2017). The FAO 2013's Sustainability Assessment of Food and Agriculture systems (SAFA) (FAO 2013) provides a holistic framework to assess all four dimensions of sustainability, i.e. environmental integrity, economic resilience, social well-being and good governance, in 21 themes and 58 subthemes (Figure 12.2).

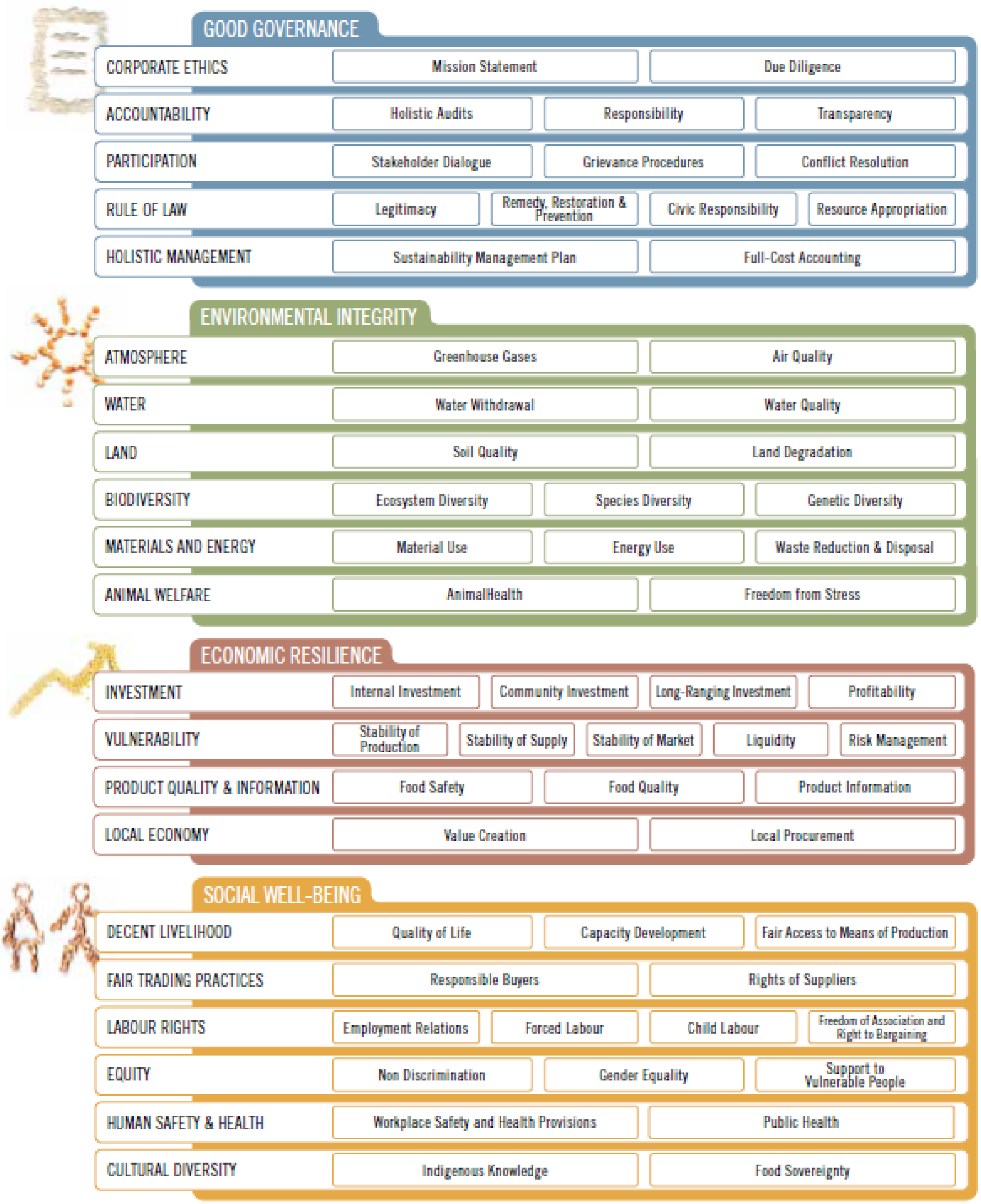

Figure 12.2. SAFA framework with the four dimensions of sustainability, and the themes and subthemes in each dimension.

In the implementation of this framework, first one determines the assessment level or operational boundaries (FAO 2013; Rogasik et al. 2014). As the optimization of practices to enhance soil structure or soil biodiversity is situated at the farm level, the integrated sustainability assessment is performed at that level, with the farm gate serving as the system boundary. The direct effects from farming practices are assessed, as well as the indirect effects resulting from the use of external inputs. The effects beyond the farm gate, caused e.g. by transport or further processing of farm outputs, are not taken into account.

The conceptual framework then needs to be translated into indicators. Indicators are variables, which points to, provide information about, or describe the state of phenomena, which are difficult to measure directly (for example, soil life). They measure performance or reflect changes in activities, projects or programs. Indicators are considered easy-to-use tools for farmers, because they simplify the complex system, inform and encourage decision-making (Girardin, Bockstaller, and Werf 1999; Hák, Moldan, and Dahl 2007; UNAIDS 2010). Three types of indicators can be distinguished: (1) target-based indicators, assess whether plans or policies are in place; (2) practice-based indicators, also called means-based, refer to indicators that assess farm practices or technical means; (3) performance-based indicators, also called effect-based, are used to assess the impact of practices (FAO 2013). From (1) to (3) indicators become more relevant (in the sense of coming closer to the reality of the impact they aim to assess), but also require more data and more complex models, decreasing feasibility of measurement (Payraudeau and van der Werf 2005).

Choosing a relevant and feasible indicator set for farm level sustainability assessment is a challenge. Even more so, as they as they need to support the farmers' strategic decision-making, which plays a central role in the adoption of sustainable practices. Sufficient interaction between farmers, advisors and experts therefore is key in the implementation process of a sustainability assessment (Coteur et al. 2020).

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