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AGROBIODIVERSITY: CONSERVATION, THREATS, CHALLENGES, AND STRATEGIES FOR THE 21ST CENTURY

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Abstract

The conservation of agrobiodiversity begins by its characterisation to know it. On this knowledge, we must study the interactions of the different species with their abiotic and biotic context. However, as a consequence of the effects of climate change, the abiotic context is variable and extreme. Therefore, abiotic stress induced by climate change jeopardises both the biodiversity and plant genetic resources, therefore, food security. The latter is more drastic in developing communities. Thus, given the predictions of the effects of climate change at different geographical levels, it is urgent to develop strategies that might improve the management of biodiversity and promote resilience against said effects. On the one hand, preserving and describing the agrobiodiversity allows us to identify the genetic material most appropriate under different abiotic contexts. On the other hand, plants, including crops, are not isolated species and develop in a very heterogeneous biotic context that can enhance plant tolerance to abiotic stress. In this work, we review key concepts, threats, challenges, and strategies to improve agrobiodiversity management.

Key words: *Agrodiversity, climate change, conservation, abiotic stress, tolerance.*

INTRODUCTION

Biodiversity is a term coined in 1986 by Walter G. Rosen, who conceived a historical meeting, The National Forum on BioDiversity, hosting leading scientists and thinkers from different areas, and whose content was condensed in the seminal book "Biodiversity" (Wilson, 1988). Thus, biodiversity is the variety and variability of life in a given location (e.g., Earth) and it happens at the genetic, species, and ecosystem levels (Rawat & Agarwal, 2015). That is, biodiversity is the genetic variation that exists within the individuals of the populations within and across species; it is the species richness, abundance and functional roles within an ecosystem (microorganisms, plants, fungi and animals alike); and it is also the variety of biotic communities and their interactions, as well as their habitats and the ecological processes that happen in the biosphere (Rawat & Agarwal, 2015; Wilson, 1988). Furthermore, the above definition also includes the modern concepts of the microbiome - that is, all the microorganisms that are associated with a macroorganism, their host - and the holobiont, both the host and its symbionts together, which affect host behaviour, development, morphology, physiology, health and overall biological fitness (Berg et al., 2020; Rosenberg & Zilber-Rosenberg, 2016).

Nowadays, humankind has become a major driving force affecting biodiversity at the planetary scale and is responsible for initiating a mass extinction event (Elawa & Joseph, 2009; Steffen et al., 2007). The decline in biodiversity has become so drastic that it has been described as a biological annihilation (Ceballos et al., 2017), with the loss of 10% of all individuals and up to 75% of species extinct in some areas (Banks-Leite et al., 2020). Indeed, the rate of biological loss and the pressures on ecosystems are very high, e.g., with an average Living Planet Index (LPI measures the biological diversity after the trends of monitored populations of vertebrate species from all habitats; https://www.livingplanetindex.org/) of 69% decrease in wildlife populations (Butchart et al., 2010; WWF, 2022). The main threats to biodiversity are habitat and ecological connectivity loss by alteration, fragmentation, destruction or reduction in quality (e.g., deforestation, drainage of wetlands, damming rivers, land-use change), alterations in the composition of ecosystems, the introduction of invasive species, over-exploitation of biological resources (e.g., overfishing), pollution, climate change, among others (Marques et al., 2019; Rawat & Agarwal, 2015; WWF, 2022).

Agrobiodiversity is a sub-set of biodiversity, the part of biological diversity that is used directly or indirectly for food and agriculture (FAO, 2019). In the same way, as for biodiversity, agrobiodiversity occurs at the genetic, species and ecosystem levels and is affected by many of the threats listed above. Agriculture and biodiversity are strongly linked, and the former depends on the latter (e.g., pollination of crops). Moreover, we need biodiversity to minimise the impact of agriculture on the environment and, thus, to generate resilience against climate change effects. At the same time, we must maintain the production of food and other agricultural products; we need to know what we have, understand how the species interact, and develop efficient management of biodiversity.

In this review, we will explore the current situation of biodiversity, its threats and its benefits in the context of agrobiodiversity. Then, we will focus on the strategies to improve agrobiodiversity management.

HUMANKIND AND BIODIVERSITY

Development is inherent to human ecology. IUCN/UNEP/WWF (1980) defined development as "*the modification of the biosphere and the application of human, financial, living and non-living resources to satisfy human needs and improve the quality of human life*". However, as human populations grow, the need for more resources increases, and vice-versa (Malthus, 1826). Thus, the relationship of humanity with its environment is in constant deterioration unless new and sustainable modes of development are established, which lead to the definition of conservation as "*the management of human use of the biosphere so that it may yield the greatest sustainable benefit to present generations while maintaining its potential to meet the needs and aspirations of future generations*" (IUCN/UNEP/WWF, 1980). Humans, however, are also a part of the Earth's biodiversity and depend on many other species. Therefore, beyond utilitarian arguments that justify the conservation of diversity, there is a tendency to change the way of viewing biological diversity, in which genetic variability, the diversity of species and ecosystems represent an insurance to face the climate crisis and other planetary changes (Barbault, 1998). Thus, modern definitions of biodiversity emphasise the preservation of variability at the three above-mentioned levels.

Agrobiodiversity results from the continuous interactions of human societies and the land and living things for thousands of years (Snir et al., 2015). It is the basis for sustainable food security, and human survival, since human food, medicine, fibre, fuelwood and other resources are directly obtained from other species. There are many topics of research related to agrobiodiversity, and the most prevalent in literature, as found in Clarivate Web of Knowledge, are: pollution, conservation, climate change, biodiversity, genetic engineering and sustainable development (Figure 1).

Figure 1. Cloud word representation of the number of papers (ln) on topics related to the field of Agrobiodiversity after a search in Clarivate Web of Science (17/02/2023). Terms shown in the figure (number of papers): Pollution (1,408,655), Conservation (1,199,132), Climate change (429,996), Biodiversity (359,325), Genetic engineering (287,074), Sustainable development (169,923), Invasive species (66,830), Food security (62,255), Ecosystem services (50,924), Mutualism (41,895), Genetic resources (36,768), Abiotic stress (35,982), Deforestation (33,090), Landrace (32,315), Extinction (+biological species; 19,831), Habitat fragmentation (17,153), Habitat loss (16,707), Mycorrhiza (11,011), Endophyte (10,597), Agroecosystem (8,783)

BENEFITS OF BIODIVERSITY

Ecosystem services is a topic highly used in conservation biology and biodiversity management (Figure 1), and it is present in many national and international governmental agencies as a priority for investment (Bourguignon, 2015; Department of the Environment, Water, Heritage and the Arts, 2009; Seidl et al., 2021). The concept of "ecosystem services" arises when we think of diversity as a natural capital with the potential to produce human welfare. One way to value these services is by calculating how much it would cost humans to replicate them artificially with the technology available (Constanza et al., 1997). That is, the ecosystem processes that maintain human life.

Rawat & Agarwal (2015) identified four groups of distinctive benefits or ecosystem services: 1) utilitarian benefits or provisioning services: our health and wealth depends on the biological diversity because we obtain food, fresh water, fuel, a source for agriculture and medicine innovations, industrial raw materials, etc; 2) ecosystem benefits or regulating services: biodiversity has the potential to regulate climate and chemistry at both the local and planetary levels, by the sequestration of carbon, absorption of pollutants, buffering detrimental weather conditions, or the regulation of biochemical cycles, but also plays a vital role in pest regulation, thus maintaining the health of crops and forests; 3) ethical and moral benefits: we have the responsibility to conserve the biological diversity, because each species is unique, and the well-being of future generations depends on present generations; and 4) aesthetic value or cultural services: that is the enjoyment by stimulating our different senses when we practice activities in nature or surrounded by it, such as observing, listening, walking, photographing, etc.

THREATS TO BIODIVERSITY

The benefits that biodiversity provide have been studied for several decades and are well known (e.g., Constanza et al., 1997). There is an important international economic investment to boost conservation (Seidl et al., 2021). Nowadays, however, biodiversity is still seriously endangered, and in decline due to several stressors that do not affect all ecosystems equally, e.g., deforestation is a most severe threat to tropical ecosystems than to the European ecosystems (Marques et al., 2019). As the global population continues to grow, so does the demand for resources. This can lead to the degradation of natural habitats and the depletion of natural resources, further threatening biodiversity. In this context, the main threats are:

1) *Habitat transformation*, through degradation, fragmentation and loss, is the main threat to biodiversity (Figure 2). The three processes are causally connected. Degradation implies the reduction of habitat quality; fragmentation breaks the habitat into smaller patches, and habitat loss is the eradication of the habitat (Banks-Leite et al., 2020). The fragmentation of the habitat into small patches due to human activities such as deforestation, land-use change and urbanisation, has a direct effect on the ecological and physical properties of the remaining habitat (Fahrig, 2003). It has a negative impact on the population growth rate, reduces the trophic chain length, alters species interactions (e.g., predation rate), and affects foraging, breeding and dispersal success. In fact, human activities such as deforestation, land-use change, and urbanisation have destroyed or modified many natural habitats, making them unsuitable for many species (Figure 2). Furthermore, small patches suffer more impact, facilitated by the edge effects: the edges exhibit abiotic and biotic differences, and the smaller the patch, the bigger the edge relative to the inner area of the patch (Krishnadas et al., 2020; Warneke et al., 2022). The latter increases ecological connectivity loss by alteration, fragmentation, destruction, or reduction in quality (e.g., deforestation, drainage of wetlands, damming rivers, land-use change) of the ecosystem. Habitat degradation can be either permanent or temporal, whereas habitat loss implies irreversible damage. In fact, species in fragmented areas are more vulnerable to extinction. Furthermore, even protected areas are threatened by fragmentation if not protected from anthropogenic pressures in their surroundings (Lawrence et al., 2021).

2) *Changes in ecosystem composition*: the relationship between biodiversity and ecosystem performance has long been recognised. Thus, species' types and abundance affect the ecosystem functions (e.g., Carrick & Forsythe, 2020; Wagg et al., 2014). The loss of species might decrease ecosystem processes and ecosystem resilience against climate change effects, invasive species and pests.

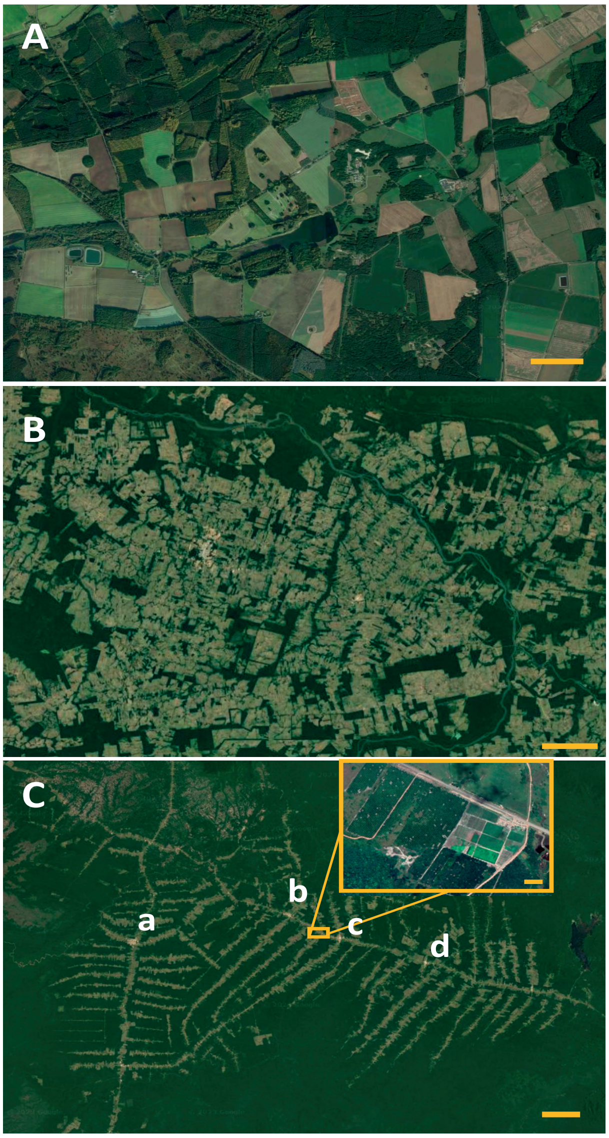

Figure 2. Land use and habitat patchiness. A - boundaries of Sherwood Forest, Nottinghamshire, UK; bar denotes 500 m. B - remnants of Amazonian rain forest close to Teles Pires river, municipality of Alta Floresta, Mato Grosso state, Brazil; bar denotes 10 km. C - farmland areas gained to the rainforest are disposed around roads at Roraima state, Brazil; a, b, c, and d - designate four settlements (Rorainópolis, São Luiz, São João de Baliza, and Caroebe, respectively) with populations between 25000 and 6750 people). The ampliation shows the diversity of crops (achiote, banana, cassava, cocoa, coconut, coffee, corn, orange, peach palm, and rice); small bar denote 100 m. Maps were acquired from Google Maps (https://www.google.com/maps/@53.2339092,-1.0656144, 5046m/data=!3m1!1e3, https://www.google.com/maps/@-9.8947945,-55.8896434,93607m/data=!3m1!1e3, and https://www.google.com/maps/@0.886638,-60.0164303,123829m/data=!3m1!1e3, respectively; accessed: 21st February, 2023)

3) *Introduction of invasive species*: the introduction of invasive alien species in an ecosystem can affect the ecosystem's biodiversity, e.g., by outcompeting native species, disrupting the food web and nutrient cycling and, thus, accelerating the loss of biodiversity (Vilà et al., 2011). For example, the introduction of mangrove propagules from the Philippines, Florida and the Bahamas in the Hawaiian archipelago led to habitat loss for several species of birds (that is, had a negative impact on local fauna), produced a new habitat for non-native species, and altered the coastline hydrodynamics (Allen, 1998; Nakahara et al., 2021).

Furthermore, invasive species can harm human health and economics. For example, the establishment in the USA of the Asian tiger mosquito, *Aedes albopictus*, a vector of chikungunya, dengue, and West Nile arboviruses, in combination with high temperatures in summer, which poses a health risk issue (Taber et al., 2017). Roads boost habitat fragmentation and development, but they are also a factor that increases invasiveness (Laurance et al., 2014; Quintana et al., 2022). In addition, the spread of diseases can have a significant impact on species and ecosystem health, particularly when combined with other threats.

Overall, invasive species have an impact on ecosystem services, which translates into economical annual costs of millions of US$ (Charles & Dukes, 2016).

4) *Over-exploitation of biological resources*: overhunting, overfishing, and the over-collection of plant species, can have a significant impact on the survival of species and the overall health of ecosystems, causing ecosystem perturbations, irreversible loss of species, the spread of pathogens, and lead to food shortages and economic losses (Koh et al., 2013).

5) *Pollution*: this anthropogenic stressor comes from toxic chemicals, smog, waste, and other sources that can contaminate ecosystems and harm or kill species, in addition to the serious human health issues they pose. Pollution can act at the local, regional and global scales. It has an impact on biodiversity when altering the biological fitness of the organisms, e.g., by altering the genetic diversity within populations and their reproductive potential, shrinking crop or wild species production, and changing the structure and function of an ecosystem (Barker

& Tingey, 1992). Air pollution can produce acid rain, with high concentrations of nitric and sulphuric acids, damaging trees and soils, and acidifying water sources, thus affecting terrestrial and aquatic life. Eutrophication of water bodies due to accumulation of nutrients (e.g., nitrogen), promotes the growth of algal and plant populations that can kill aquatic species.

6) *Climate change*: changes in local climatic patterns (temperature and precipitation) due to climate change have profound implications for biodiversity. Many species at the edge of extinction might be unable to survive the extraordinary abiotic stressors. Thus, climate change can cause shifts in species distribution and the extinction of certain species.

In addition, climate change effects drastically affect the ecological relationships between species, e.g., the flowering and the pollinators must happen simultaneously to be successful. Climate changes affect the phenology of plants and hibernating species. This has a direct negative impact on crops and agrobiodiversity.

Many of these threats to biodiversity act simultaneously and are often interconnected, making it challenging to address them individually.

RESILIENCE AGAINST CLIMATE CHANGE AND STRATEGIES TO IMPROVE THE MANAGEMENT OF AGROBIODIVERSITY

Climate change is one of the major challenges of the 21st century, and its impacts on biodiversity are widely recognised. Amongst the main effects of this global change, we can easily identify the increased frequency and intensity of extreme weather events, such as droughts, floods, and storms, which directly impact agroecosystems and biodiversity. Therefore, we need to devise approaches to generate resilience against the adverse effects of climate change and boost agrobiodiversity conservation. One approach is to increase the diversity of crops and their varieties, as this can provide a buffer against the effects of climate change. For example, incorporating traditional and neglected crops can diversify the genetic resources available for adaptation. This could increase crop yields and economic incomes, improving food security and reducing poverty, facilitating the societal transition towards more sustainable ways of life (Birthal & Hazrana, 2019; Vernooy, 2022).

Agrobiodiversity, and thus biodiversity, is considered part of our natural capital from an economist point of view. Therefore, conserving our natural resources has become mandatory to face present and future challenges, such as the adverse effects of climate change. Several effective strategies can be implemented to improve the management of agrobiodiversity. A classical approach is *ex-situ conservation*, which involves conserving and managing agrobiodiversity outside its natural environment, in gene and seed banks, arboreta, or other repositories. There are more than 1500 seed banks around the world safeguarding more than 200,000 edible species of plants. The biggest of them is the Svalvard Global Seed Vault in the Arctic Circle; and the oldest, with more than 100 years, is the Vavilov Research Institute of Plant Industry in St. Petersburg. This strategy aims to ensure the long-term survival of crop diversity, especially in the face of environmental and social changes.

After the 1980s, the scientific community realised that farmers and gardeners, mainly women, were managing and caring for many species and varieties that were not present in collections (Brush, 2000). That is, the *in-situ conservation*, of agrobiodiversity on-farm, in the original environment where it evolved and continues to evolve. It includes practices such as seed saving, crop rotation, and mixed cropping. An example of successful in situ conservation can be found in the traditional farming system in the Andean regions of Bolivia, Ecuador and Peru, where peasant associations are strongly involved in conservation activities, such as seed fairs, and seed banks at local and regional levels (Jarvis et al., 2011)

The *participatory plant breeding* (PPB) strategy involves the collaboration of researchers and scientists with farmers to improve crop varieties adapted to their local conditions and needs. In this way, resilient and productive plant varieties can be developed, while maintaining and enhancing crop diversity, and improving the productivity of farming systems (Altieri, 2002; Ceccarelli & Grando, 2019). Overall, PPB programmes involving farmers can increase the resilience of crops to climate change selecting traits such as drought tolerance or heat resistance.

A different strategy is *sustainable use*, which involves using agrobiodiversity to maintain crop productivity and health minimising the use of agrochemicals (Figure 3). Some sustainable practices are soil conservation, water management, and integrated pest management.

Improving soil health and fertility can enhance the ability of plants to cope with abiotic stressors and increase CO_2 sequestration (Ray et al., 2020). Other practices that can contribute to soil health and fertility are agroforestry systems, conservation tillage, and cover cropping, which can also help conserve beneficial soil microorganisms essential for plant growth and health. Another important aspect is to promote the use of integrated pest management (IPM) practices, such as biological control, to reduce the use of synthetic pesticides. This can help maintain beneficial insects, such as pollinators, which are vital for the reproduction of many plant species.

One additional strategy aimed at enhancing the efforts focused on agrobiodiversity conservation is based on *capacity building*, *capacity development* and *knowledge sharing*. The first concept was adopted in the 1990s and evolved to the second, defined as "the process whereby people, organisations and society as a whole unleash, strengthen, create, adapt and maintain capacity over time" (Bester, 2015). The former term implies starting to build capacities from zero, whereas the latter means building capacities on existing skills and knowledge. Then, once the capacity is developed, the horizontal and vertical sharing of the experience and knowledge maximises the success of the initiative. That is, building the skills and knowledge of farmers, researchers, and other stakeholders to better manage and conserve agrobiodiversity. This strategy includes diverse activities such as farmer-to-farmer exchange, training programmes, and information sharing through fairs, networks and online platforms (Kremen & Miles, 2012; Wezel et al., 2020).

Figure 3. Agroecological and traditional practices: sustainable farming systems in three different communities from Ecuador. A - Criollo farm at Ñañal, Chilla (3°27'48.0"S, 79°34'16.1"W); B - Saraguro farm at Saraguro (3º37'21"S, 79º14'18"W); maize, beans, and figleaf gourd association; C - Shuar Farm at San Juan, Nangaritza (4°19'11.7"S 78°39'45.9"W); ayahuasca, cassava and maize growing in scarcely cleared small areas of the Amazonian rainforest. Pictures by M. X. Ruiz-González

Overall, approaches to generate resilience against climate change and boost agrobiodiversity conservation require a multidisciplinary effort involving different stakeholders, including researchers, farmers, policymakers, and civil society.

THE CONSERVATION OF AGRO-BIODIVERSITY

Abiotic factors and phenology

All living organisms interact with their environment. The physical and chemical non-living parts of the environment are the abiotic factors, which affect the biological fitness of the organisms, and the range of environmental conditions that allow the survival of a species and its distribution. The species and their populations are adapted through natural selection to this range of abiotic conditions, such as temperature, water, sunlight, oxygen and CO_2 concentrations in the atmosphere, or salt, heavy metals or nutrients in the soil. Due to the fast changes in abiotic conditions due to climate change, many species are endangered. The latter is even more critical for sessile organisms that cannot escape the substrate where they have grown (e.g., plants and coral reefs). Furthermore, the effects of abiotic factors on wild plants and crops can be evidenced in changes in their phenology (Parmesan & Yohe, 2003; Ruiz-González & Vicente, 2022); that is, the timing when developmental events critical for the success of the organism occur. The timing of plant phenology is influenced by abiotic factors such as temperature, precipitation, nutritional resources, and day length. Changes in these variables can significantly impact the survival and reproduction of plant species and the animals that depend on them. Furthermore, the effects of changes in the timing of flowering and fruiting can affect the availability of food for pollinators, seed dispersers, and herbivores (Donoso et al., 2015). Thus, phenology could also lead to the desynchronisation of seasonal interactions amongst species with cascading effects on the entire food web, with implications for population dynamics and ecosystem function, and severe economic consequences (Kharouba et al., 2018; Menzel et al., 2006; Piao et al., 2019). Rainfall and temperature are the main drivers affecting plant phenology, with some responses more disproportionate in Mediterranean ecosystems and other warmer regions (Gordo & Sanz, 2020).

In terms of conservation, understanding the relationship between abiotic factors and plant phenology can help inform management strategies. For instance, conservation managers may need to consider changes in the timing of plant phenology when planning habitat restoration or invasive species management. Moreover, monitoring the timing of plant phenology can provide valuable information about the health and functioning of ecosystems over time. Furthermore, the analysis of the effects of abiotic changes on phenological and morphometric characters also represents an important tool to identify species and varieties more tolerant to new conditions or at higher risk of being lost, as well as for more efficient crop management (Figure 4; Acosta-Quezada et al., 2022; Tandazo-Yunga et al., 2017).

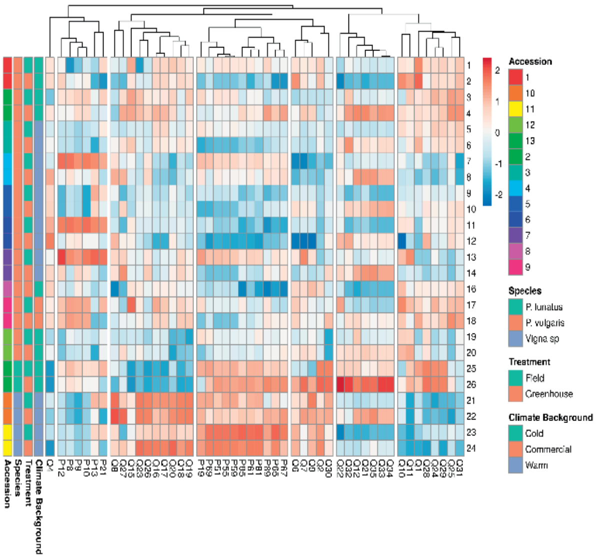

Figure 4. Effects of two climatic conditions on 48 morphological and phenological characters in 13 accessions of *Phaseolus* and *Vigna* from Andean agroecosystems. Bean varieties more susceptible to the effects of climate were identified (Acosta-Quezada et al., 2022)

Characterising plant phenology, therefore, is essential for enhancing resilience against climate change because it improves our understanding of how plant species respond to changing climatic conditions and predicts their economic impact on crops (Brown et al., 2012). By studying the timing of plant life cycle events such as flowering, fruiting, and leaf senescence, we can gain insights into how plants might be impacted by changes in temperature, precipitation, and other environmental factors. This knowledge can then be used to develop effective conservation strategies for protecting agrobiodiversity and boosting food security in the affected regions.

Abiotic factors and the hidden world

Microorganisms are a fundamental component of agrobiodiversity, playing key roles in soil and plant health, degradation of organic matter and nutrient cycling, and improving plant disease resistance. Therefore, the identification and conservation of microorganisms can help improve agricultural productivity and sustainability by promoting more efficient nutrient cycling, reducing dependence on synthetic fertilisers and pesticides, and enhancing plant resilience to environmental stresses. Thus, the characterisation of microbial functions in agroecosystems is important for understanding microbial ecology and soil health. Thus, several studies have shown the importance of microbial functions in agroecosystems. For example, Mäder et al. (2002) found that organic farming systems, which have higher microbial activity, have improved soil fertility, crop yields and soil health compared to conventional farming. Moreover, there is a relationship between microbial diversity and decomposition, which reduces up to 40% of CO_2 emissions, and microbial diversity is also related to nutrient availability (Maron et al., 2018).

Therefore, gaining knowledge on microbial diversity and function can lead to the development of microbial-based biofertilisers and biocontrol agents for sustainable agriculture. However, the identification and conservation of microorganisms can also present challenges. Many microbial species are difficult to identify and culture, and their functions in agroecosystems still need to be better understood. One useful strategy for identifying and conserving microorganisms is establishing microbial gene banks. These repositories collect and preserve a wide range of microorganisms (bacteria, fungi, and viruses) for use in agricultural research and development (Ryan et al., 2019). By providing a source of genetic diversity, these gene banks can be further used to develop new microbial strains that can improve crop productivity and resilience against abiotic stresses.

To characterise microbial functions in agroecosystems, we can apply diverse ‘omics’ techniques, such as metagenomics, metatranscriptomics and metaproteomics. These methods can provide insights into the structure and function of microbial communities and help identify the species and their functional genes and pathways involved in nutrient cycling, plant-microbe interactions, and other vital processes. The functional characterisation and identification of microbial diversity are pivotal for biodiversity and ecosystems conservation because microbial communities are also prone to suffer drastic consequences in response to climate change events such as increased temperatures, permafrost thaw, drought, increased precipitation, seawater intrusion, fire, and elevated CO_2, thus affecting carbon sinks and cycling (Jansson & Hofmockel, 2019).

Microorganisms are found almost everywhere, adapted to diverse and extreme environments, including eukaryotic organisms. The interactions that microorganisms establish with eukaryotes can be positive (symbiotic mutualists and commensals), negative (pathogens), or neutral (no effects between host and microorganism). Plants produce exudates that can be used by microorganisms, which, in return, improve the host's nutrition, development, growth, health and tolerance to abiotic stresses (Moënne-Loccoz et al., 2015). Thus, microorganisms are becoming an important tool to boost sustainable agriculture by using microbial inoculants, which are formulations of beneficial microorganisms that can be applied to crops to enhance nutrient uptake, disease resistance, and stress tolerance. Moreover, beneficial microorganisms can be found in the phyllosphere and the rhizosphere. In both the aerial and the underground worlds, microbial species can interact non-parasitically with plant organs as epiphytes or endophytes. Epiphytes are as diverse as bacteria, fungi, yeast, algae, and nematodes. In the phyllosphere, epiphytes are adapted to the harsh conditions of the leaf surface (limited resources, heterogeneous temperature and moisture, UV); they can modify the chemical properties of the leaves (e.g., by producing biosurfactants or the plant growth regulator indole-3-acetic acid, which promotes cell wall loosening), and are usually pathogenic (Lindow & Brandl, 2003). These communities can be sorted by factors other than the plant species, such as geography or other biotic interactions (Ruiz-González et al., 2019). Endophytic microorganisms are obligately heterotrophic endophytes and can act as mutualists, saprophytes or pathogens, but all have an essential role in nutrient cycling and plant health, e.g., by increasing tolerance to abiotic or biotic stresses (Arnold & Lutzoni, 2007; Khare et al., 2018; Saikkonen et al., 2015).

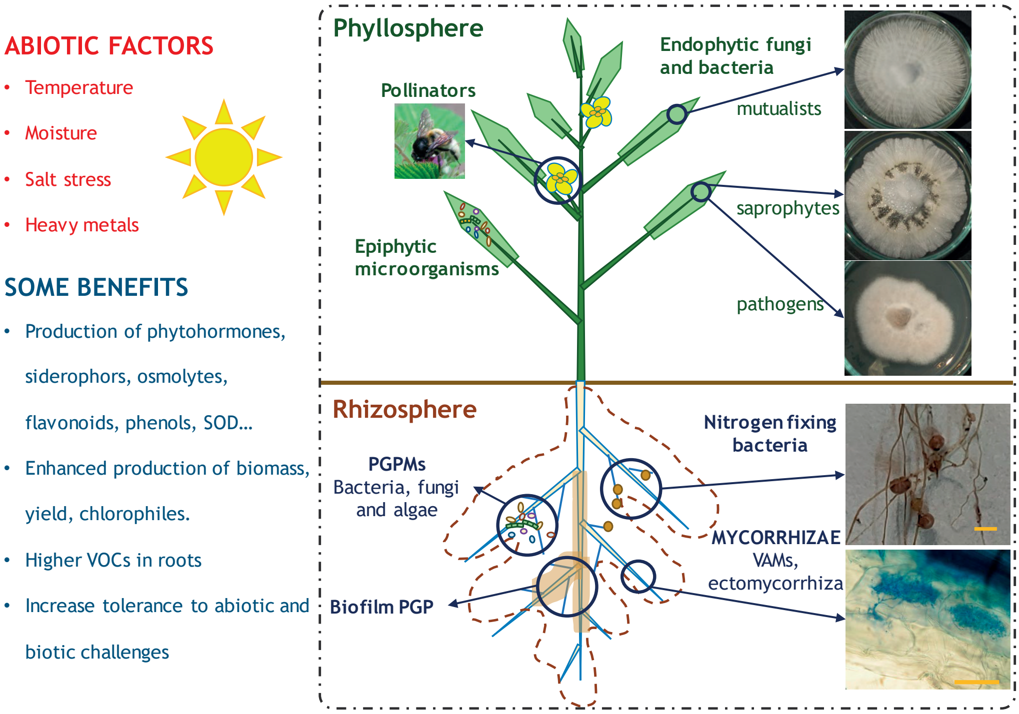

Figure 5. Biotic interactions in the plant at the rhizosphere and phyllosphere. Endophytes isolated from *Coffea* arabica: unknown species of mutualist fungus; the saprophyte fungus *Xylaria adscendens*, and the pathogen fungus *Colletotrichum* sp. Scale bars: in bacteria nodules, 2 mm; in arbuscular mycorrhizae, 20 µm. (Pictures by M. X. Ruiz-González)

Our knowledge of the diversity, the ecological roles and the biological interactions of microorganisms in the phyllosphere is yet insufficient. Exploratory works unveil extremely complex multipartite interactions between eukaryotes and microbes, finding unexpected roles, like the Chaetothyriales fungus *Trimmatostroma* sp. that acts as an aerial mycorrhiza by transferring nitrogen to the plant through the leaves (Ruiz-González et al., 2011; Leroy et al., 2011).

The microbial ecology of the rhizosphere also displays a very rich diversity of interactions. Plants release nutrients, exudates, and other low-molecular-mass compounds such as sugars and amino acids that represent carbon sources to attract microbial communities, thus, facilitating the plant-microbe interactions (Philippot et al., 2013). Common plant growth-promoting beneficial microorganisms (PGPMs) can interact with the roots at different degrees of intimacy, e.g., free-living, forming biofilms on the root surface or living endophytically within the root tissues (Figure 5). Mycorrhizal fungi can be present within the root cortex, on the root surface or around the root epidermis: arbuscular mycorrhiza, ectomycorrhiza, orchid mycorrhiza and ericoid mycorrhiza (van der Heijden et al., 2015). Bacteria, fungi and some algae can exert diverse functions to enhance plant fitness through the production of biomass and seeds, or boosting its health: synthesis of phytohormones, production of siderophores, alleviation of heavy metal stress, upregulation of genes involved in nutrient acquisition, metal homeostasis or plant defence, N_2 assimilation, production of enzymes, higher pigments content, enhanced contents of compounds involved in the antioxidant response system or the osmotic balance, and the induction of plant defence-related genes (Antoszewski et al., 2022).

The characterisation of wild microorganisms with beneficial roles for plants is a fundamental step to support biodiversity conservation and will help design and generate appropriate microbial inoculants at the local and regional scales. In this way, the introduction of microbial species that might become invasive or whose impact on new ecosystems is yet unknown, would be avoided.

CONCLUSIONS

Diversity is challenged by many different non-exclusive threats, with direct consequences for human health and the economy. The conservation of agrobiodiversity is a priority if we want to ensure resilience against the effects of climate change and food security. There exist different strategies involving different actors and stakeholders contributing to agrobiodiversity conservation. However, due to the impact of the unpredictable effects of abiotic factors and the fast pace of climate change, it is a priority to investigate how the species and varieties of agronomic importance face these changes by analysing the heterogeneity in their phenological and morphological characteristics. Finally, robust works from the last decades on the long-time neglected world of microbial ecology highlight the necessity to investigate and characterise the diversity and roles of mutualistic microbial species interacting with plants to develop sustainable agriculture, thus contributing to buffer global change.

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