



## Editorial: Anthropogenic impacts on symbiotic systems

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This special issue is part of the celebration by the International Symbiosis Society on World Symbiosis Day held the 30<sup>th</sup> July 2020 online. A short narrative of this event for those who could not attend is included in this issue (Dutta et al. 2021). A total of 11 articles are included in this special issue of Symbiosis, on ‘Anthropogenic impacts on symbiotic systems’. These articles are diverse and explore the impact of anthropogenic activities on various symbiotic organisms, especially those in the terrestrial environment. The articles explore the evolution of modern concepts, the methods for the study of symbiotic organisms, and the implications in dealing with negative changes. The anthropogenic impacts on various forms of symbioses such as algae-fungi (lichens), fungi-plant root (mycorrhiza), actinomycetes-roots (actinorhiza), and plant-microbes/fungi (endophytes) are discussed.

Human pressures on ecosystems and the earth, have already led to changes on the Earth’s surface, including global warming, mass extinction of species, environmental degradation, ocean acidification, increased frequency of floods, and droughts. These changes in natural ecosystems have resulted in earlier flowering, poleward shift in the distribution of animal and plant species and total ecological collapses (McMichael et al. 2003). The term anthropogenic was first used by the Russian geologist Alexey Pavlov with reference to human interferences on climax plant communities. Later, it was used by the British ecologist Sir Arthur Tansley (Bampton 1999). The Anthropocene is now recognized as the latest, and new, geological time period; the time during which humans have had a profound impact on geological and ecological systems (Waters et al. 2016). Hom and Penn (2021) have reviewed several aspects in relation to anthropogenic impacts on symbiosis as a unit of evolution. Symbioses are not merely collections of organisms but are co-evolved partners that arise from the synergistic combination of different genetic entities.

The present global COVID-19 pandemic has been identified as an outcome of the unbalanced influences of human impacts on ecosystems (Buck and Weinstein 2020). The growing awareness of negative impacts of mankind on the Earth has typically been limited to documenting changes in microbes, plant, and animal species. However, consideration

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of symbiotic interactions has generally been ignored. Given the central role of symbioses in ecosystem processes, functions, and services throughout the Earth's biosphere, the impacts of human-driven change on symbioses are critical to understanding how to deal with climate change and the growing human population. This is a significant oversight because symbiotic communities are generally the first responders to environmental perturbation and can either buffer environmental shifts, or exacerbate them by complex positive or negative feedback loops (Konopka et al. 2015; Trevelline et al. 2019). Symbiosis is a universal phenomenon on our planet and is of pivotal importance for allowing the Earth to function as a single, self-regulating system as defined by Margulis in 1998. Study of the interactions between flora and fauna in ecosystems including symbionts, and other known and unknown relationships, not only ensures balanced and harmonious coexistence of species, including humans, but also offers solutions to several biological problems on Earth (Kavousi et al. 2020). The discovery of the coherence and universality of symbiotic associations has brought new light to old debates in this field, including issues about the population or species concept (Hom and Penn 2021). An important aspect of these debates has been the formulation of the hologenome concept of evolution; the notion that holobionts are units of natural selection in evolution.

The impacts of anthropogenic activity on the ecology and function of microbial assemblages are multifarious and often largely undefined, but the advent of powerful new tools including next generation sequencing and novel modelling approaches has begun to shed light on this important question (Gupta and Gupta 2021). Another issue that is discussed is the surprising connection between symbioses and the Anthropocene, suggesting ways in which new symbioses could arise due to anthropogenic change (Hom and Penn, 2021). Symbioses could be agents of ecosystem change because, historically, symbioses, as broadly defined have helped humans and been "farmed". The organisms involved may have launched the Anthropocene. Indeed, Gupta and Gupta 2021 further discuss how there is a need for a multidisciplinary approach for the study of these organisms and how artificial intelligence has penetrated all areas of study related to anthropogenic impacts on symbiotic organisms. They suggest that there is a need for better communication among scientists in different disciplines in order to generate good quality data.

The article by Munzi and Giovanetti (2021) explores the impact of restrictions imposed by the COVID-19 pandemic on the study of lichens. Using the activities of the Italian Lichen Society (Società Lichenologica Italiana, SLI), Google Trends, and colleagues' contributions, the authors evaluated the performance and value of virtual tools on lichenological literacy. They compared the relative success of virtual and in-person events and the effort required. They also evaluated followers' appreciation of various categories of "posts" on the SLI

Facebook page; and they designed a questionnaire to collate information on individual experiences of in-person and virtual events linked to lichens. Without excluding the positive effects of in-person experiences, the authors believed that online events offer a powerful tool to help increase interest in, and knowledge about, lichens or any other symbionts. This on-line approach may help to mitigate the impact of anthropogenic activities on this sensitive component of our ecosystems.

## 1 Arbuscular mycorrhiza

The first example of symbiotic association, where anthropogenic influences were explored in the webinar, was the arbuscular mycorrhizal (AM) symbiosis between plant roots and fungi (subphylum Glomeromycotina of Phylum Mucoromycota). This was because of the hope that AM could be a saviour in the present situation of food scarcity and may help to achieve the world's sustainable development goals (Gupta and Abbott 2021). These fungi facilitate a plant's mineral acquisition, improve growth and protect them from biotic and abiotic stresses. The elevated carbon dioxide (eCO<sub>2</sub>) level, elevated temperature, increased nitrogen, and phosphorus deposition, all influence plant phenology and functioning through changes in the diversity and community composition of AM fungi. Study of the AM fungal community may help in predicting the mycorrhizal responses to chemical fertilizers, eCO<sub>2</sub>, temperature, and drought. Chourasiya et al. (2021) concluded that AM symbiosis can be effectively integrated into global climate change models which could eventually lead to a better understanding of ecosystem resilience. This could enable mankind to further exploit the resident AM fungal communities to offset some of the detrimental effects of anthropogenic environmental change. The role of AM symbiosis in phytoextraction and the process of phytostabilization is reviewed by Solís-Ramos et al. (2021). The authors discuss the role of this symbiosis in altered uptake and distribution of heavy metals, improvement in mineral nutrition and water availability, protection against oxidative stress, and increments in the physical stability of soil. This results from the production of glomalin in response to heavy metals and persistent oxidative pollutants. In a wetland environment, AM fungi expand the aeration system of wetland plants, store oxygen through their own vesicles, or change plant's the structure to help it survive (Huang et al. 2021). Even under waterlogged conditions, certain AM fungi species have been reported to improve the survival and development of wetland plants by regulating different physiological activities, the including enhancement of antioxidant defensive systems. Human activities can negatively affect these fungi in the wetland environment, by reducing their diversity and abundance.

## 2 Ectomycorrhiza

Vincent and Declerck (2021) studied the anthropogenic impacts on ectomycorrhizal symbiosis (the interaction between plant roots and fungi belonging to phyla Basidiomycota and Ascomycota) at various scales - from species to populations and ecosystems. The authors concluded that common anthropogenic activities, like enrichment of atmospheric carbon dioxide, have resulted in an increase of global temperature, as well as atmospheric pollution, nitrogen deposition, use of pesticides, land use management, the introduction of invasive species and biodiversity loss, etc. These features are likely to affect ectomycorrhizal symbiosis through alteration of plant metabolism and spatial distribution of trees. Although effects of industrial pollutants and pesticides remain less clear at large scales, N-deposition and/or fertilization could induce ectomycorrhizal shifts and alter nutrient cycling. Regarding other anthropogenic parameters (e.g., land use, invasive species), they point out that it may affect ectomycorrhizal fungal communities by having an impact on fungal diversity, abundance, and richness.

## 3 Actinorhiza

Actinorhiza, the symbiosis between nitrogen-fixing actinobacteria *Frankia* and non-leguminous angiosperm roots, render them to be highly tolerant to salinity, drought, flooding, and heavy metal pollution. These associations are extensively used for the rehabilitation of degraded sites. Maity and Pawlowski (2021), reviewed how the xeromorphic adaptation and wide climatic and edaphic range make *Casuarina* species well suited for carbon sequestration under increased temperatures. The authors point out that *Casuarina* species have been used to combat climate change hazards in the Pacific Islands. However, as a result of multipurpose application of actinorhizal associations in agriculture and forestry, they have been widely introduced outside their native habitat especially in tropical, arid, and semiarid countries across the globe. This anthropogenic influence in some areas has resulted in the actinorhizal *Casuarina* spp. becoming well-integrated into the regional farming systems but in other places they have become invasive.

## 4 Endophytes

Endophytes are another group of symbionts that live asymptotically and sometimes symptomatically within plant tissues. Unlike mycorrhizae, they intrude not only into roots but also into the above ground plant tissues such as leaves stems, bark, petioles, and reproductive structures. Agricultural intensification to meet human food demand generates pressure on

the whole soil environment, and especially on the associated endophytes. Understanding the effects of various methods for increasing yields like hybridization (Sahu and Mishra 2021), chemical fertilization (Beltran-Garcia et al. 2021), and organic fertilizers (Khatri and Sharma 2021) using endophytes, could lead to improved soil health and make progress towards sustainable agriculture more possible. With the advent of the holobiome concept, the importance of the microbiome in plant performance health and productivity is being increasingly realized. Decoding the transmission/colonization of endophytes upon hybridization (i.e. from parents to progeny) is a pre-requisite for laying the foundation for plant holobiont breeding (Sahu and Mishra 2021). Similarly, Beltran-Garcia et al. (2021) show how inorganic N-fertilization induces a shift in bacterial communities by increasing as copiotrophic. These belong to the phyla Proteobacteria, Actinobacteria, Firmicutes which can and reduce the abundance of phylum Acidobacteria. The former are classified as slow-growing oligotrophs and considered as keystone taxa in soil ecosystems. The authors also discuss how the shifting of microbial diversity, induced by a fungal disease of banana, is related to the phenomenon called “cry for help”. This further raised a question about the wisdom of indiscriminate application of commercial microbial inoculant formulations, such as those involving the genus *Bacillus*. The authors suggest that biofertilizers and biopesticides should be carefully evaluated on target crops to ascertain that they do not have negative effects on crop development or microbial diversity in the plants or soils. Such an understanding is important for the maintenance of soil health and for safely achieving better farming efficiency. Khatri and Sharma (2021) critically re-evaluate the decade-old question as to how organic farming shapes the microbial diversity of arable land, as well as the importance of diversity in plant-associated microbial communities. They consider the value of the popular next-generation sequencing that aims to pave the way for future studies and they also attempt to identify research gaps.

Lastly, we wish to extend our sincere thanks to all participating authors for their contributions to this issue, which we believe will be a valuable resource as terrestrial ecosystems continue to experience increasing anthropogenic impacts.

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