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Fungi the unknown Organisms – an underestimated Player in Global Change Ecology

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Introduction

Fungi are no plants and no animals, they form their own group of organisms – and they are to a large extent still an unknown factor in all terrestrial ecosystems. Of an estimated 1.5 million species only some 80.000 are described [1, 2].

There is no doubt about the ecological and economic importance of fungi. Pathogenic and parasite fungi play a critical role in agricultural as well as in human and animal health. Without saprotrophic fungi organic matter would not decay and the nutrients cycle would not be closed, and finally about 66% [3] - 80% [4] of higher plant species are in symbiosis with mycorrhiza fungi, which deliver nutrients, improve water availability, stabilize the soil and act as biological control against root pathogens [5, 6, 7, 8, 9]. In some case higher non-autotroph plants such as *Neottia nidus-avis* entirely depend on the nutrient delivery of certain fungi species [10]. Fungi play a particularly important role regarding the creation of lichens, as they are a symbiosis between fungi species¹ and algae species. In the Antarctica lichens dominate the vegetation in terms of biodiversity and biomass [11,12].

Regarding the global climate change there are many uncertainties about the response of fungi to increased temperature, elevated CO₂ levels and changes in precipitation. However, researchers believe that especially soil fungi may play an unknown, but important role in the carbon cycle [13, 14].

This chapter will give a short introduction to fungi and global change, continue on some aspects of climate change and fungi, but will focus further on mycorrhiza fungi and climate change.

This limitation has several reasons:

1. Global change comprises many processes and effects (see first subchapter) and fungi present a highly diverse

¹ A smaller number of lichens species are composed of a symbiosis between bacteria and algae.

group of organisms. The complexity is too great to be reviewed and analyzed within a few pages.

2. There is a large amount of scientific literature available on mycorrhiza. The online research in journals like “Global Change Biology” and “New Phytologist” for keyword such as “fungi and climate change” or similar queries resulted in almost all cases in a listing of articles about mycorrhiza fungi and non related to saprotrophic fungi.

3. Elevated atmospheric CO₂ concentrations as predicted will most likely not affect non-mycorrhizal soil fungi because CO₂ levels in soils are already high due to biotic respiration[15,16]. Elevated CO₂ may have an impact on carbon allocation via the fungi-plant symbiosis. It is estimated that mycorrhizal fungi receive up to 30% of the total carbon fixed by plants and therefore serve as a sink [17]. This sink might be affected; when elevated atmospheric CO₂ concentration alter the mycorrhiza plants carbon cycle.

Global Change and fungi

Human activities have altered the earth’s surface and its biodiversity. About one third of the terrestrial area has been converted into land for agricultural production [18] and this process still continues. Rainforests in the Amazonas Basin as well as in Southeast Asia are cut down to make place for the production of soy bean, sugarcane or other commodities. With a growing human population the demand for food, fiber and agricultural bio-energy crops will rise by an even higher percentage. Growing incomes in some countries such as China will regionally change diets towards more animal protein and processes of urbanization will accelerate, - both will increase pressure on land resources. Food is traded globally and the same seed brands and crop protection products are used by farmers all over the world. ‘Alien’ species, sometimes invasive species are brought to places far from their origin and establish in new habitats. Utilizing bio-technology humans have

altered genetically certain species, which are now used all over the world.

How will or does all this affect fungi?

There is little knowledge about fungi species [1, 2] but so far only one out of 16.000 described mushroom species and one lichen (out of 10.000 described) are listed as threatened on the IUCN Red list [19]. This small number of threatened fungi and lichens is due to the small number of evaluated fungi. IUCN lists only one mushroom and two lichens as evaluated with regard to the threat status [19]. On regional level, numbers are different. Looking at the Red Lists of the German Bundesländer reveals that many species of larger fruiting fungi species are regionally extinct or heavily jeopardized. In Mecklenburg-Vorpommern for example about 43% of the known large fungi species belong to the higher threat classes [20].

There are certain human activities which obviously affect fungi composition.

Converting a meadow or some other habitat into an asphalt road or into an urban settlement will extinct most existing species at that place. The expansion and intensification of agriculture might, besides climate change have the greatest impact on fungi species. Turning a rainforest into a soybean field will (locally) remove all fungi, which are specific to that habitat and the soybean as N-fixing leguminous plant will most likely change the soil's biota system including fungi composition. The soybean rust (*Phakopsora pachyrhizi*) and other pathogenic fungi might emerge on the field, which are then controlled by the farmer using chemical fungicides.

The global 'harmonization' of agricultural practices and food trade results in a fast selection of certain pathogenic fungi. The usage of strobilurine fungicides all over Europe, for example lead within a very short period to a resistance of the fungi pest *Septoria tritici* in all European countries [21, 22].

In the US, increasing demand for bio-ethanol might increase the area of genetically modified corn even further. In 2007, about 50% of the corn planted was genetically modified (GM) to be resistant against insects. The GM plants contain genes from the bacterium *Bacillus thuringiensis* (Bt) [23]. Residues of this particular GM corn may lead to new ecological problems for mycorrhizal fungi [24].

Overall eutrophication and pollution coming from agricultural and industrial production affects nearby as well as remote habitats. Many lichens are especially sensitive to air pollution and therefore serve as bio-indicators [25, 12, 26].

This selective list of certain global changes or global trends, could possibly be continued, but the major point is to show that massive changes in land use, farming practices and pollution already have large impacts on fungi species, even if scale and quality remain unknown. The next chapter will take a closer look at climate change and fungi.

Pathogens and Climate Change - a deadly combination

Seventeen years ago, in the mountains of Costa Rica, the Monteverde harlequin frog (*Atelopus spec.* - see right foto) vanished along with the golden toad (*Bufo periglenes*). An estimated 67% of the 110 species of *Atelopus* have met the same fate. Accused of the extinction are the pathogenic fungus (*Batrachochytrium dendrobatidis*) along with global warming. It seems that exceptional warm years as occurred in the last decades make frogs more susceptible but favor the pathogenic fungi. Especially warmer nights support fungi growth. In addition, the fungi is usually killed at temperatures above 30°C, but increased cloudiness, which is caused by global warming, reduced direct radiant heating and lead to an increased exposure of the frog [44].



Climate Change and fungi

For most known fungi species the correlation between temperature and precipitation/moisture and growth is rather straight forward. They favor warm and moist climate, an exception of this rule are specific lichens, which are sensitive to higher temperatures [12]. For pathogenic fungi certain changes in climate change such as higher air humidity and higher or more moderate temperate are beneficial (see Box).

Global climate change due to increased CO₂ emissions will have different effects in different regions. Some regions will become warmer and wetter, while others become dryer and hotter [27]. On global scale, the mean temperature already rose between 1906 and 2005 by 0.74 degrees and a further increase is expected [ibid.].

Seasonal changes have already been observed with effects on the environment. A phenological meta-analysis of 125,000 observational series of 542 plant and 19 animal species in 21 European countries (1971–2000) showed that 78% of all leafing, flowering and fruiting records advanced by 30% significantly and only 3% were significantly delayed [28]. The authors conclude that since 1970 spring and summer in Europe advance on average about 2.5 day per decade.

Another phenological study looked at 50,000 fruiting pattern records of fungi (1950–2005) in Southern England [13]. The findings of the study confirm the observations of changed seasons. The first fruiting date has become significantly earlier, whereas the last fruiting date has become significantly later. Altogether the fruiting period doubled (33.2±1 day in 1950 to 74.8±7.6 days in 2005) with an especially sharp increase since 1975. The extended growth period suggests an increased decay of organic matter [13], which possibly affects the carbon-sink function of terrestrial habitats.

However, the response of carbon sequestration in terrestrial eco-systems to global climate change remains a major uncertainty. This uncertainty derives from of a particularly poor understanding of the origins and environmental responses of soil CO₂ efflux. For example, despite their large biomass, the contribution of mycorrhizal fungi to soil CO₂ efflux has not been quantified in the field [29, 7]. In order to give some ideas of the effect of climate change in mychorriza fungi the next chapter will look at mycorrhiza fungi and CO₂ increase, temperature and drought. The analysis will not look at effects of higher precipitation, which is (in general) in favor of fungi development and growth.

According to IPCC drought and heat waves will occur more frequently in the near future [27] and may cause major releases of soil carbon possibly also due to changed functioning of mycorrhiza symbiosis.

In the future, climate change might be the main driver towards a fast reduction of global biodiversity [2] and with each plant species associated fungi might be lost. However, very little is known about the specificity of fungi to the host, it seems that most plant species are able to go into symbiosis with several different fungi species [30, 31, 32], while some fungi species such as *Suillus luteus*, *Leccinum spec.* depend on a specific host. This may lead to an extinction of specialised fungi species along with the respective host.

However, regarding extinction risk from climate change Thomas et al. did not include fungi species in their projections [33].

Elevated atmospheric CO₂ and mycorrhiza fungis

Biotic communities in general are expected to respond to elevation of atmospheric carbon dioxide (CO₂), but complex interactions among ecosystem components generate uncertainty about the nature of these responses [8, 16]. There is a large number of studies on the response of fungal and plant growth to elevated CO₂, but until today a generalized causal relationship cannot be established. Apparently, different plant species as well as different types of mycorrhiza (e.g. arbuscular mycorrhiza and ectomycorrhiza¹) react differently to elevated atmospheric CO₂ levels [ibid.].

The most prevalent research assumption is the question of a positive feedback loop, in which plants respond to elevated CO₂ by increased carbon fixation followed by the transfer of more carbon to their root systems; consequently, mycorrhizal fungi might experience growth increase.

A review of research studies on arbuscular mycorrhiza and elevated atmospheric CO₂ levels conducted in 2000 showed that although decreases in root colonization are rarely seen, increases and null responses are about

1 The reader may apologize that explanations of the different mycorrhiza types are not give in this limited place. The Internet provides a vast variety of information. A simple summary in German is for example available at the Biology Department of the University of Ulm: <http://www.biologie.uni-ulm.de/lehre/allgbot/ernspez.html>

equally frequent. Investigations of the morphological structures of the fungi (hyphae, arbuscules, vesicles) also reported almost all possible combinations of increase, decrease and no response [16]. A research paper about a comparative experimental series with 14 different plants species, both mycorrhiza and non-mycorrhiza plants and 5 different fungi species (CO₂ levels up to 720 ppm) published in 2005 confirms the findings of the review on arbuscular mycorrhiza. The authors conclude that affects of CO₂ enrichment on arbuscular mycorrhiza function varies with plant and fungal taxa and both decrease as well as increase of arbuscular root colonization was determined [34].

Regarding ectomycorrhiza some research findings present a different view. A meta-analysis of about 35 studies on elevated CO₂ and ectomycorrhiza fungi conducted in 2007 showed significant positive effects of elevated CO₂ on parameters such as fractional root colonization with ectomycorrhiza and the number of ectomycorrhiza per root tips [35].

However, two earlier reviews e.g. meta-analyses about elevated CO₂ and mycorrhiza revealed no clear tendency. The review of 2000 concludes that hyphal biomass or growth on both ectomycorrhiza and arbuscular mycorrhiza tend either to increase or produce no change [36], whereas the 2005 meta-analysis reports significantly positive responses for both mycorrhizal fungi and mycorrhizal plants to elevated CO₂, with a much higher positive response in ectomycorrhiza than in arbuscular mycorrhiza fungi [37].

Looking at mycorrhiza literature it seems that in most cases elevated CO₂ either increases fungi growth or fungi growth does not response. Ectomycorrhiza fungi tend to response stronger in a positive way. Decreased growth is much less reported. However, most experiments are done with potted plants under exclusion of other soil biota and with abrupt CO₂ increase. Both scenarios do not present the reality and especially experiments with abrupt CO₂ increase have been criticized [38].

Increased fungi growth could mean that elevated CO₂ leads to more carbon storage, but possibly other soil organisms such as earthworms, which feed on fungi, might neutralize increased carbon storage, due to a positively related population response and a faster turnover. Higher temperature might also increase soil carbon turnover [29].

Increased temperature and impacts on mycorrhiza fungis

Temperature affects the growth of all organisms because it controls the rates of metabolic reactions. Regarding general soil respiration there are large uncertainties concerning the relative responses of different respiration components (microbes, fungi, animals) to changes in soil temperature [3].

Temperature responses of arbuscular mycorrhiza fungi have not been investigated intensively if compared to studies on elevated CO₂ [39] and up to 2003 no study has combined plant root and plant shoot warming in the field to simulate properly the impacts of a warmer climate [39].

Results from the few studies on temperature effects on arbuscular mycorrhiza showed that mycorrhizal root colonization increased when temperature increased between 5 and 37°C [40]. Other studies suggest that arbuscular mycorrhiza have a narrower range (> 18°C and < 30°C) of temperature for good development [41]. In an experimental trial temperature increase was correlated with increased growth of extraradical mycelium (ERM) and the authors suggest that increased biomass will become a greater carbon sink than soil respiration, which seems to acclimate. However, the result of this study should be interpreted with caution, the experiment was done with only one plant species (*Plantago lanceolata*) in a growth chamber and below-ground soil heating [14] and a similar experiment using *Holcus lanatus* did not show the same effect [39].

Field studies on effects of temperature on mycorrhiza fungi are scarce and in general it seems that soils are too complex systems with too many unknown properties. A long term field trial over 7 years on warming and drought presented two interpretations of the observed effect: 1. climate-induced changes in the vegetation, especially plant species relative abundance and/or 2. direct mycorrhizal response to the climatic manipulations [42]. Experimental designs and indicators are not yet elaborated. Therefore solid knowledge does not exist and casual relationships cannot be drawn. However, looking only at mycorrhiza fungi, when assessing possible consequences of global warming on soil carbon storage, is too short sighted. Overall soil respiration must be the indicator to measure.

Drought and mycorrhiza fungi

The IPCC Fourth Assessment Report and recent temperature history show that summer heat waves and drought will occur more frequently [27]. Both have had and will have large impact on soil respiration. Researchers estimated that the hot summer of 2003 in Europe resulted in an emission of 0.5 Giga Tonnes CO₂ and reversed the sink effect of four normal years. Increased microbe soil respiration was partly responsible [43]. The question to be answered is to what extent mycorrhiza fungi contribute to the carbon balance under drought conditions.

In general, the symbiosis of a plant with a fungi improves water availability, but it seems there are certain thresholds [9, 26]. An older research review on water, drought and arbuscular mycorrhiza published in 2001 showed that in comparison to non-mycorrhiza plants mycorrhiza plants can resist adverse drought effects longer and recover better [9]. However, when drought continues the fine root system and the connected fungi are severely affected. A meta-analysis about 10 drought studies published in November 2007 revealed that drought had a significant negative effect on ectomycorrhiza roots. The effect was attributed to the highly negative effect of drought on fine root biomass, whereas fractional colonization of roots showed small, insignificant increases [26].

Longer droughts have severe effects on the soil environment. Along with fine roots the associated mycorrhiza disappears. The authors of the 2007 meta-analysis observed that on remaining roots mycorrhiza colonization increased insignificantly. This means that the plants maintain carbon delivery to the fungi. However, the authors conclude that ectomycorrhizal colonization is an unsuitable indicator for environmental change, while fine root length and biomass could be useful.

Conclusion

Human activities have had a large impact on earths' ecosystems. Land use change, industrial and agricultural pollution and climate change touches even the remotest and most natural habitats. The realm of fungi is unknown to a large extent, but obviously massive changes in land use such as conversion of forest into agricultural land affects fungi species as much as all other species.

Fungi play a crucial role in the earths' terrestrial ecosystems and they are especially important in the carbon cycle. Focus of this review is laid upon mycorrhiza fungi and possible effects on elevated atmospheric CO₂, increased temperature and drought. Much research has been conducted on elevated CO₂ and its impacts on mycorrhiza fungi. About the relationship between temperature, drought and mycorrhiza fungi literature resources are rather scarce. However, it seems that elevated CO₂ has more positive effects on fungi growth or at least no effect, decreased growth is reported less frequently. Regarding carbon storage these are positive news, but study designs and experiments have to this point not been elaborated deeply enough. In addition, the mycogenic research approach may lead to misinterpretations. When researchers conclude that - based on experiments under very controlled conditions - elevated CO₂ is taken up by the soil via mycorrhiza, they may oversee other counteracting processes. Eventually, the scientific community still knows very little about the processes within soils and if fungi would indeed provide more carbon to the soil – other organisms feeding on this carbon may respire as much carbon as gained additionally. This would go along with the common ecological understanding that increased food supply results in faster population dynamics.

Overall global warming, heat waves and higher precipitation in boreal and temperate eco-systems apparently lead to higher soil respiration and losses on soil carbon – this may accelerate global warming. The detailed processes are unknown, but from the perspective of Global Change Management, human society must mitigate climate change and stop continuing the 'Global Warming Experiment' with unknown consequences.

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