AN OVERVIEW OF THE ROLE OF FUNGI IN THE DYNAMICS OF SOIL FERTILITY AND STRUCTURE

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Abstract:

This paper presents and overview of the role of different types of fungi in soil formation and functions. Fungi species have been found to play a fundamental role in the formation, structure, and sustainability of agricultural (and terrestrial) soil. This role has been often overlooked due to the complexity of such contribution; bulked under the big banner of "organisms". Interestingly - as it may be, Fungi come in all shapes and sizes, and are not exclusively "micro".[1] I argue herein that fungi have not received their due attention - as a separate kingdom from plants and animals, and as more inclusive than what "microorgansims" term may stand for. I also argue that such attention is required for efficient soil sustainable-management, restoration and/or even "re-creation". I have used desert truffles in the Middle East as a case in point for the paucity in soil-fungal conservation awareness, and explored the possibilities of using commercial fungi to enhance soil fertility and structure, with some suggestions in relation to the UK soil.

Soil

Technically speaking, soil has been best defined as the **"**natural body, differentiated into horizons of mineral and organic constituents, usually unconsolidated, of variable depth, which differs from the parent material below in morphology, physical properties and constitution, chemical properties and composition, and biological"[2] (Joffe, 1936 cited in Jenny, 1994).

Jenny (1994) also defines soil independent forming factors as the following:

s = f (*cl, o, r, p, t …)* where f is function, (*cl*) is climate, (*r*) is topography or "relief", (*p*) is parent material and (*t*) is time.

On analysing each factor, all the rest of factors must be constant. That is:

s = f_{cl} (climate) *o, r, p, t,...*
(When analysing climate as an independent soil-forming factor)
s = f_{o} (organisms) *cl, r, p, t,...*

[1] Surprisingly - as it may be, the biggest living organism on earth is known to be a Fungi – *Armillaria solidipes* known colloquially as the "Humongous Fungus"! (Schmitt & Tatum, 2008)
[2] There are so many valid definition for soil aggregated in (Jenny, 1994). I have found the definition provided hitherto as the most comprehensive and dynamic, while not conflicting with other definitions.

(When analysing climate as an independent soil-forming factor)
s = f_r (topography) *cl, o, p, t...*
(When analysing climate as an independent soil-forming factor)
s = f_p (parent material) *cl, o, t...*
(When analysing climate as an independent soil-forming factor)
s = f_t (time) *cl, o, r, p...*
(When analysing climate as an independent soil-forming factor)

Blum (2005), on the other hand, articulate six basic soil functions - that need to be "harmonised", in case we are interested in functional sustainable societies.[3] The functions, as he lists them, are 1- biomass production, 2- protection of human activities and environment, 3- gene reservoir, 4- physical basis of human activities, 5- resource for raw minerals, 6- gelogenic and cultural heritage.

The role of fungi in soil formation, structure and sustainable management is best seen in light of the first three soil functions (ecological functions) and in relation to all soil forming factors. Evidence were found in fossils that fungi predated vegetation, and has emerged 460 million years ago (Redecker et al. 2000; Boddy & Coleman, 2010; CABI, 2013;). The main argument here is that (although) fungi might not qualify as an independent soil forming factor[4], it actually interrelate - indispensably, to each of the forming factors, that it would be erratic (as I propose) to consider any of such factors separate from its relationship to fungi. That is that fungi is a key co-agent in all forming functions and a key player in all soil ecological functions.

The role of fungi

> "Fungi provide so many important ecological services to soil and all her bearings; above, under and through. As Abigail Jenkins (2005) states; Fungi is a key player in "water dynamics, nutrient cycles and disease suppression". Along with bacteria, fungi are important as decomposers in the soil food web. They convert hard-to-digest organic material into forms that other organisms can use. Fungal hyphae

[3] Blum points out that working on harmonising soil function is a political rather than a scientific endeavour. Science is only capable of providing facts and showing options, but decisions are made by the people for their own interest as they (collectively) perceive it to be.

[4] More investigation into this matter could prove useful though.

> physically bind soil particles together, creating stable aggregates that help increase water infiltration and soil water holding capacity" (Abigail, 2005)

However as Silvio Gianinazzi (2010) states, most people are "under the illusion that these ecosystem services are free" and thus take them for granted.

Plant Pathogen and healer!

The (wicked) role of fungi as a plant pathogen is probably the most perceived of all their roles - by the public. People tend to think of the "foes" of fungi as pathogen in their histories and gardens: Ergot (*Claviceps purpurea*) which inflicts the deadly syndrome of ***ergotism***[5] in humans and other animals - and has historically caused the infamous 1951's "The day of St Anthony's Fire". The fungus-like *Phytophthora infistans*, which arrived in Ireland 1844, coupled with the weather conditions, induced an unprecedented loss in potato crop which Ireland depended on, at that time, for feeding people and animals. 1000,000 people starved and another 1000,000 emigrated as a result (Boddy & Coleman, 2010). On the average, the global loss in crops mounts to $550 billion annually, with 40% caused by plant disease of which fungi is responsible for two thirds. Fungi, among some other microorganisms, however, is generally capable of supressing many soil pathogens; first by competing with them on nutrients (or by feeding on bacteria causing them), or through antagonistic biocontrol. A fungus such as the *Trichoderma* is capable of supressing several other species of fungi that induce root-rot infection. *Trichoderma* occurs naturally in many soils but may also be applied – as an intervention, by farmers (see The Living Soil, 2000).

Cordier et al. (1996) provides a list of soil pathogens and their antagonistic fungal species, based on his experiments. A comprehensive list of pathogenic fungi or antagonistic fungi is not available - nonetheless; as mycologist believe to have identified only 5% of fungal species out of an estimate 1.5 million species thought to exist (Hawksworth, 1997). The exploration of the role of fungi in soil dynamics, is actually

[5] Ergotism has caused the 1951 disaster called "The day of St Anthony's Fire" in a small town in France called Esprit (EOL).

interlinked to all and each of the soil forming factor and thus to soil health, fertility, structure, and productivity as well (Boddy & Coleman, 2010).

The objective of this argument is to provide evidence that the benefits of the dynamic interaction between fungi and other soil forming factors, as well as within the soil processes, outweigh the damage caused by the parasitic fungal species, especially if biocontrol tactics (Gomathi & Ambikapathy, 2011; Broadbent et al., 1971) were employed to limit/neutralise such damage, rather than synthetic arbitrary fungicides.

The greatest recycler – decomposition of "stuff"

The most abundant source of energy available for fungi is cellulose. Cellulose has the quantity of 10^{15} tons of world's reserve of carbon (McLaren and Skujins, 1971), and is regarded as the most abundant polysaccharide in nature. Cellulose forms about 40-60% of wood and mature plants, and is commonly present in the walls of plant cells, as well as in some microorganisms. Not all fungi possess the same capacity of dilapidating this material due to the absence of the cellulose enzyme in some fungi. Studies by Domsch and Gams (1970) and Schubert and Nord (1950; cited in Johnston, 1962) show that certain species of fungi are selective to which form of cellulose to use, for instance by "attacking" wood logs rather than linen or vice versa. In spite of the fact that not all fungi can utilise cellulose, once such "complex molecule" is dilapidated down to simpler forms, cellulose becomes available to a wider range of organisms. Species of *Aspergillus, Chaetomium globosum, Penicillium* – among others, have been found (variably) capable of rapid decomposition of cellulose even in linen which is resistant of bacteria decomposition. Many scholars as well as Permaculture practitioners have confirmed the role of fungi as 'biological fertilisers' (see Jakobsen, et al., 1992) due to the capacity of fungi culture to accelerate the breakdown of nutrient in the compost on one hand, and the vital role of mycorrhizae in transferring hard-to-reach and insoluble nutrients to the plant root, on the other hand; enhancing soil fertility and structure at the same time. However, more specific studies are required in this respect.

Abigail Jenkins (2005) confirms three types of fungi groups - as far as soil is concerned:

Decomposers – Mutualists, including Mycorrhiza – pathogen, splitting into two main kinds; Endomycorrhizae, forming a symbiosis by penetrating the (host) plant root; comprising three major classes; 1- Vesicular Arbuscular Mycorrhiza (VAM/AM), 2- Orchid, 3- Ericoid and the more advanced but less common Endomycorrhizae, forming the symbiosis by surrounding the plant root.

Vesicular Arbuscular mycorrhiza (VAM/AM) is the most popular form of mycorrhiza. An estimated 90% of all plants enter some form of my mycorrhizal association with fungi. The benefits for both symbionts are immense as will be further explored.

Multi-functional mycorrhizae

As Sullia (1990) explains, over 90% of plants participate in mycorrhizal associations with fungi. Mycorrhizal fungi form a symbiotic relationship with plant roots so as to provide the plant with hard-to-reach nutrient from the soil while the plant provide them with photosynthetic nutrients such as starch. Mmycorrhizal fungi grow inside plant roots and outward.

Up to 5m of hyphae may be extracted from 1g of soil (McLaren and Skujins, 1971). This amazing volume and mass of fungal enhance the plant’s resistance to pests, draught, salinity stress and draughts. They act as a filter against many pollutants and assist the plant to access hard-to-reach nutrients.

Symbiotic association involves a partnership between two agents: a mycobiont and a photobiont, the mycobiont agent (fungi) will capture up to 20% of the fixed carbon from the host plant, but the plant benefits – in return, from the minerals and nutrient uptake, and root protection from pests and pathogens. Up to 80% P and 25% N is obtained through fungi. Absorbing such nutrient from the deep soil cause cation change and a change in the parent material and thus accelerate more chemical weathering to happen.

The P and K being added to soil to boost the growth of plants, disrupt the symbiotic relationship as the plants get their easy uptake of nutrient and is no longer interested to make themselves available for inoculation of fungi through ion exchange and Rhizosphere’s excretion, and thus not only the plant loses the benefits of partnership but the soil formation process due to the dynamics of mineral uptake and replacement, would be impeded. Another aspect of the symbiotic relationship between fungi and plant rood motivated by the scarcity of P and |K in soil, is the formation of hyphae itself as it enhances soil structure and protect it from degradation. Excessive N, P and K were generally found to harm soil microorganisms (Sullia, 1990). Closer observation, and holistic soil profile and analysis is required to address such threats.

It has been found that some species of Vesicular - Arbuscular Mycorrhiza may be commercially used as 'biofertilisers' and/or to adjust irrigation-water salinity (Sullia, 1990; Ebrahim, 2014). Lichens, which result from a symbiotic relationship between algae (or cyanobacteria) and fungi, play a crucial role in soil formation and the introduction of “biological succession”.

Lichens

Lichens are very important in soil formation. Lichens are fungi living in partnership with species of algae and cyanobacteria. They will prosper in favourable conditions but can stay dormant in adverse ones to resume growth later.[6].

In terms of soil formation, Lichens are the first colonisers of bare rocks and bare soil and thus they initiate the first step in soil formation. In Polar Regions, lichens’ carbon fixation is a key contributor to soil structure in the absence of other forms of vegetation.

Lichens were found to act on bare rocks in a way that accelerate the weathering of minerals both mechanically and chemically. The expanding hyphae penetrate the rock substance and the expanding/contracting *thalluses* - together with other biological processes, cause the rock to break. The chemical substances excreted by the lichens dissolve the minerals and chelate metallic cations. However, much investigation is still required to analyse – comprehensively, the role of Lichens in soil formation and their effect on the weathering and formation of soil processes (Chen, et al., 2000).

Desert truffles in the Middle East, a case in point

[6] Lichens have been “exposed to the vacuum and solar radiation of outer space on orbiting space satellites”, and they were surprisingly able to recover after coming back to earth and resume growth. Some go as far as to suggest that it is a form of life transmitted to our planet from another planet.

Desert truffles is an amazing fungus! It has enormous socio-economic, industrial and medicinal value (Gajos et al., 2014), and countless applications. To the sandy soil – when available, it can be a lifeline. Desert truffles are naturally occurring organisms, which form a mysterious symbiotic relationship with desert host plants. They are known in the Middle East as the *Manna* which God, according to the biblical account, gave to the Israelites[7] for food and has, thus, a cultural value to Jews, Christians and Muslims (Soliman, 2013) in the region.

The fungi as it forms mycorrhizal symbiosis with several specific desert shrubs, protects the soil from degradation and assist plant growth in the aridness[8]. However, humans don't seem to appreciate the importance of desert-soil to our ecosystems: In Egypt, as Mubasher (2010 cited in CABI 2013) reported; some of the areas known for the occurrence of desert truffles were (ecologically) destroyed by the establishment of houses, roads, touristic resorts, and other developmental activities, while some others in Sinai, were disrupted by military activities. Alsheikh (1995 cited in CABI 2013) aggregate reviews on the appalling impact of the Iraqi invasion of Kuwait 1990s stating that in many areas where the fungi occurs, social and political upheaval have devastating impact on the soil. He paradoxically hoped that the existence of some landmines in war zones might deter collectors from accessing fungi that it might be reserved.

Touristic activities and safari dwellers using 4-wheel cars disrupt the desert ecosystems, and fungi are not immune to damage by pollutants. Plans to exploit desert soils for generating solar energy without considering the ecological impact on their soil biota, is one thing rarely pondered. Desert truffles (world-wide) are currently - using Red List IUCN criteria, assessed as Vulnerable. (CABI, 2013)

Alleviation of salinity stress

Several studies has been conducted to examine the effect of Vesicular arbuscular mycorrhizal on plants growing under salinity stress. I have not found one study – so far,

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[7] According to the common belief in the region, because of the similarity in the biblical description and that it requires no work to be produced.

[8] Desert truffles are also known to be the most expensive food in the world.

that dismisses the benefit of the fungal "roots" (hyphae) in such case. In an experiment to examine the impact of the fungus *Glomus macrocarpum* and salinity on growth of *Sesbania aegyptiaca* and *S. grandiflora*, the leaves of the mycorrhiza-inoculated plant exhibited higher chlorophyll content than the control specimen's. The reduction in Na uptake together with an associated increase in P, N and Mg uptake were observed.

A British scientist called Geoffe (2009) has initiated a successful permaculture project in the Middle East - Jordan which he named Jordan Valley Project. Greening the Desert: Greening the Middle East. Geoffe found that the growth of a certain type of mushroom (which he didn't name) decreased soil salinity and allowed amazing plant growth in the arid land (also see Tarafdar, 1996). The mushroom "appeared" naturally though - perhaps due to the utilisation of organic matter as backbone of 're-creating' the soil in the region. I have not found recent update on the project but found several commercial e-flyers promoting commercial mycorrhiza for 'healthy gardens'.

I have also designed a circular economy project to be implemented on a global scale - that I called IPNAMME (2012-2015), registered as a United Nations Rio+20 higher education initiatives for the *Future We Want*. The project comprises three models where the deployment of fungi is central to the dynamic design. The project was partially hindered by the political upheaval in the Middle East.

In the UK, where the excessive amount of rain induces intensive leaching and loss of nutrients, it might be useful to consider aiding the soil by commercial mycorrhizae to make up for the lost nutrients and help protect the soil from erosion. A better understanding and conservation of the UK's mycoflora, can be of a great impact on soil management. Employing fungi for biocontrol and bio fertilisation may also eliminate a great deal of ground-water pollution and nitrous oxide emission problems (see British Geological Survey © NERC).

To wrap up, this paper explores the need for a closer examination to the role of fungi in the dynamic soil ecosystem. I have showed how fungi are imprecisely (and indeed erratically) lumped up under the "microorganisms"' umbrella, while they are a whole kingdom that come in all shapes and sizes. The role of fungi is so complex that it interrelate indispensably to all and each of the soil forming factors. Creating a holistic profile of soil would assist in better management of soil.

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