Ecosystem engineers can be seen as the crux of environmental change within our ecological systems. They create, break and shape their habitats around themselves to form a space suitable for them causing ripples throughout our inherently connected systems as organisms. (1) Currently, common thinking when such a biological buzzword comes to mind is organisms such as beavers, bees or even unexpected organisms such as certain species of tortoise. However, it could be argued that one of the most overlooked and crucial ecosystem engineers is the fundamental key to changing our ecosystem for the better; none other than the organism fungi.

Although the term "fungi" refers to a vast range of organisms all classed under a singular Linnean kingdom rather than specific species, some of the most vital and defining characteristics attributed to fungi places them firmly in the category of being classed as an ecosystem engineer. One such characteristic is their ecological role as a decomposer. Decomposers, as defined by National Geographic are organisms that "play a critical role in the flow of energy through an ecosystem. They break apart dead organisms into simpler inorganic materials, making nutrients available to primary producers". (2) What impact does this mean fungi have on the environment specifically? The answer comes in myriads. As a decomposer fungi become often the central stage of many natural nutrient cycles. A pivotal moment for many compounds before often being rebuilt for the fungi's own biological need to shape their ecosystem.

Moreover, another environmentally significant characteristics of fungi is their place within symbiotic mycorrhizal relationships with a variety of plant life, forming networks of hyphal connections that can fundamentally support life. These symbiotic networks, known colloquially as the "wood wide web" (3), have been demonstrated to form a connective medium between many different forms of plant. In many cases these networks have been shown to be able to support new life to grow via the translocation of nutrients and substances across plants. This has been demonstrated by studies indicating the movement of $C^{14}$ from a singular plant to its seedlings and plants connected to the same mycorrhizal network (4) and even movement of phosphorus, carbon and nitrogen between entirely different species only connected by a specific type of mycorrhizal network known as an ectomycorrhizal (EM) network. (5) This form of mycorrhizal relationship is formed not by fungal penetration of plant roots but by a forming of a kind of hyphal mesh, known as a Hartig net, around the cortical cells in the plant's roots. (6) These networks are also characterised and have much more soil contact and spreading over much vaster areas, forming more wide-reaching networks, although they are known to particularly form from association between fungi and species such as pine or oak.(7)

How then could a specific fungal species be used to have a vital impact on a part of the British Isles' diverse environment if so many of the stated characteristics often vary widely between species and even between individual genotypes? One of the most important aspects of introducing fungi as an ecosystem engineer, specifically for example through rewilding campaigns, is to reintroduce native fungi. Introducing non-native fungi can introduce potentially parasitic interactions between themselves and other species or may not help the rewilding effort at all due to a mismatch between local fauna and the given species. (8) One prime example of beneficial native fungi is found within the only indigenous British pine forest remaining, a once vast forest of Pinus sylvestris (Scot's pine) known as the Caledonian forest, with an endangered local fungus known colloquially as 'mealy tooth,' officially as Hydnellum ferrugineum (*H. ferrugineum*). Currently classified as an endangered species and protected under the Wildlife and Countryside Act 1981 (9), it is both a decomposer and an EM (ectomycorrhizal) forming fungi therefore meaning this fungus has the perfect mycological toolbox to become the exemplary ecosystem engineer for this niche yet vital environment. One of the less dramatic, but nevertheless crucial, examples of how specific fungi can shape an environment for the better as a rewilding tool using their many characteristics is their common role as "wood recyclers."

One of the shared characteristics of many fungal species is their status as saprotrophs-decomposers that specifically derives nourishment from non-living organic material also known as detritus. Saprotrophic fungal species are most-well known for their decomposition of wood, and so combined with the fungal ability to form vast mycelial networks across forest floors they have the potential to completely reshape seemingly lifeless habitats into the perfect environment for many organisms and therefore becoming an ideal textbook definition of an ecosystem engineer.

One example of this, although not of *H. ferrugineum*, was explored in a 2016 mycological study conducted by Michał Filipiak, Łukasz Sobczyk, and January Weiner. (10) This study was conducted to understand how many organisms which are elementally mismatched to the nutritionally scarce habitat of dead wood still manage to prosper and grow as populations. With the populations mentioned in question being certain species of xylophagous beetles, (beetles characterized by feeding in or on wood (11)) it was unclear how growth from the larvae to adulthood without nutrients simply not originally present in dead wood could occur. The answer that these researchers found? Mycelial networks.

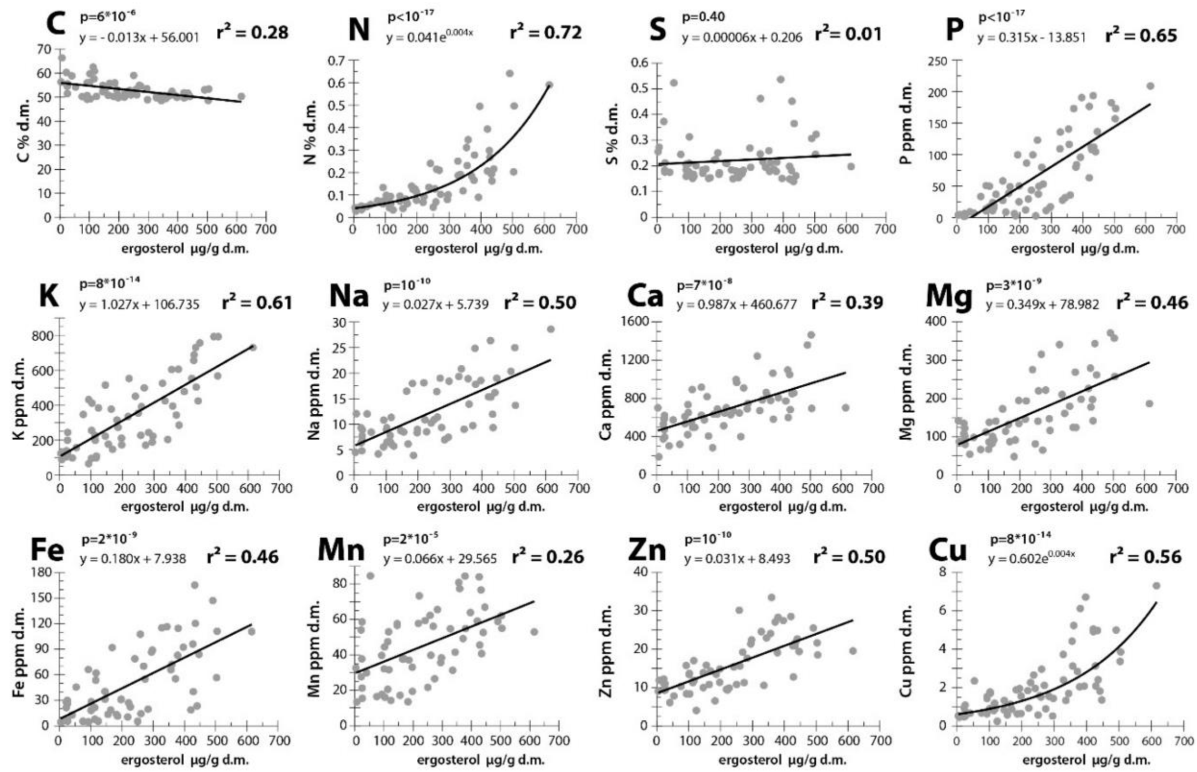


*Figure 1*

Mycelial networks throughout the forests, wherefrom samples of dead wood were collected at differing stages of decay, seemed to have had nutrients that were translocated from elsewhere into the stumps. Made possible by mycorrhizal relationships referenced earlier, these relationships resulted in networks that allow fungi to access extensive nutritionally diverse environments such as decomposing organic matter and deposit these resources in other environments. As shown in Figure 1, there is a direct correlation between a fungal membrane lipid, known as ergosterol, levels within decaying wood- ergosterol being a generally accepted biomarker substance for fungi (12)- and the increase in biologically significant elements. This clearly shows that the presence of fungi within these decaying woods create a pathway for the stoichiometric mismatch of new life and old to be bridged and for new life to therefore thrive and development.

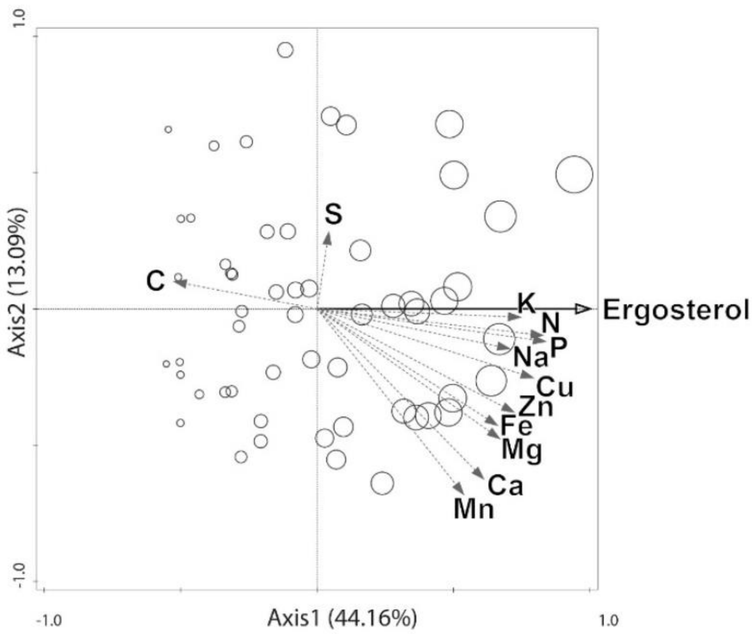


*Figure 2 Multivariate analysis of the relationships between ergosterol and studied elements. The RDA plot and the first two axes (circle size indicates ergosterol content).*

Furthermore, the much slower decrease in the stoichiometric levels of carbon distinctly showed that this was not natural decomposition of carbon but rather a complete substitution of elements undertaken by the fungi present. (10) This is further explored by the researcher's use of a redundancy analysis (RDA), shown within figure 2, as a triplot to analyse the strength of correlation between the two variables of ergosterol and the amount of the selected elements. A redundancy analysis, which is a relatively new form of data analysis, allows these researchers to compare both an exploratory matrix (in this case variables relating to the levels of ergosterol) and a response matrix (variables relating to the moles of elements) in the context of the different cites (the selected tree stumps). (13) This graph comprehensively shows that extremely biologically significant elements such as nitrogen- used in the synthesis of integral proteins (14) - or phosphorus- essential to cell membrane structure, DNA, and much more (15)- showed a strong correlation (indicated by a gradient close to that of ergosterol) with increased ergosterol levels.

What does this mean for *H. ferrugineum* and the Caledonian forest? This research, and many other studies, clearly show the immense impact fungi have on shaping any environment. Although the above study appears to demonstrate only a positive correlation between creating a good nutritional environment for primary consumers, in this case xylophagous beetles, and increasing levels of mycorrhizal fungi that is in fact not the case. All ecosystems are inherently connected in the form of trophic levels and so creating a better environment for organisms occupying the second trophic level creates a better environment for organisms occupying the higher trophic levels (creatures that consume those in lower trophic levels) therefore benefitting the whole ecosystem, not just one species or trophic level. Reintroducing *H. ferrugineum* into the Caledonian could provide a pathway for the regeneration of this major British forest. A British forest that has seen substantial change because of another major ecosystem engineer in our world- humans. Due to the industrial revolution and it's consequences the forest now stands at only 1% of its colossal prehistoric size of around 15,000km$^2$ once covering a vast majority of Scotland, existing now only as 35 meagre remnants according to the Scottish conservation group Trees for Life. (16) Not only have these human actions influenced the plant life of this great habitat but also the fungal, with *H. ferrugineum* especially being negatively correlated to excess nitrogen deposition that resulted from increased agriculture. (17)

*H. ferrugineum* could be one of the many ecosystem engineers reintroduced by such conservation groups as Trees for Life to restore this crucial habitat that for many creatures such as Western capercaillie, Scottish crossbill (endemic to the Caledonian) (18) and even large predators such as European wildcat. (19) Letting this ecosystem collapse would be a detriment to British biodiversity. *H. ferrugineum* has been shown to thrive in sandy soils and poor-quality soil- a major soil present in the Caledonian- and even create further podzolized soil, the ideal environment for Pinus sylvestris according to a research report published by the forestry commission. (20) *H. ferrugineum* does this by making the soil more acidic, decreasing the humus layer (the first layer of soil) as well as decreasing groundwater penetration. (21) As well as creating the geological conditions for podzol *H. ferrugineum* also does this by demonstrating some saprotrophic behaviours at the fringes of their ectomycorrhizal mats specifically with Sylvius Pinus (17), this creates the necessary layer of decomposing organic material podzol is found under. This becomes a specific example of *H. ferrugineum* demonstrating the exact capability of an ecosystem engineer and as a perfect candidate for use in the British isle.

So why is this conservation using such an ecologically important tool as fungi not already taking place? Bias. A historical, aesthetic and even scientific bias is waging a war against fungal conservation and usage. Within the British isle there is strong evidence of a mycophobic culture:  A culture with a deep-rooted fear of all things fungi. (22) Even within Europe there is a clear divide between the west and east even mycologically. A war between eastern mycophillia and western mycophobia. (22)  It has been shown that most Germanic originating cultures hold a closely regarded fear that even today still heavily effects any fungal legislation and cultural views. (23) Even over a century ago mycophobia was identifiable within Britain as seen by author William Delisle Hay in 1887 who noted that for many 'Englishmen' 'No eye can see their [fungi's] beauties… but are considered something abnormal, worthless, and inexplicable.' (p.6). (24) This powerful and emotive language clearly represents the depth in which British mycophobia has long existed. Some of this fear is correctly rooted in the existence of pathogenic fungi but this fear can also lead to ignorance of non-pathogenic fungi such as mycorrhizal fungi which has instead been shown to overall benefit plant health. (25) Much like a fungi's much misunderstood mycelium this irrational fear has dug itself deep into much of the common conception of fungi and their place among us.  Even medically it has been shown that "less than 3% of infectious disease budgets are spent on medical mycology". (26) We should not be letting this fear stop the future of innovation in halting our ongoing international ecological crisis.

Considering this only one conclusion can be made. Not only should *H. ferrugineum* be considered with great weight towards the conservation of the crucial Caledonian overall but Fungi as an organism kingdom should be considered with the greatest weight. As Sylvia Plath's 1960 poem "mushrooms" notes, we should no longer allow fungi to remain "perfectly voiceless" (27) but instead be held in the forefront of our modern efforts facing this unprecedented challenge of conservation.

**Bibliography**

1: Wright, J.P., Jones, C.G. & Flecker, A.S. An ecosystem engineer, the beaver, increases species richness at the landscape scale. (2002). Oecologia 132, 96–101 https://doi.org/10.1007/s00442-002-0929-1

2: National Geographic. (2023). Decomposers. [Online]. NationalGeographic.org. Available at: https://education.nationalgeographic.org/resource/decomposers/ [Accessed 15 March 2024].

3: Giovannetti, M., Avio, L., Fortuna, P., Pellegrino, E., Sbrana, C., & Strani, P. At the Root of the Wood Wide Web: Self Recognition and Nonself Incompatibility in Mycorrhizal Networks. (2006). Plant Signaling & Behavior, 1(1), 1–5. https://doi.org/10.4161/psb.1.1.2277

4: Amaranthus, M. P.; Perry, D. A. "The functioning of ectomycorrhizal fungi in the field: linkages in space and time". (1994). Plant and Soil. 159 (1): 133–140.

5: Simard, Suzanne W.; et al. "Net transfer of carbon between ectomycorrhizal tree species in the field". (1997). Nature. 388 (6642): 579–582.

6: Sally E Smith, David J Read. Mycorrhizal Symbiosis. (2002). 2nd ed. Academic Press. pp.163-232.

7: Ann L. Rasmussen, Ryan R. Busby, and Jason D. Hoeksema Host preference of ectomycorrhizal fungi in mixed pine–oak woodlands. (2017). Canadian Journal of Forest Research. 48(2), pp.153-159. [Online]. Available at: https://cdnsciencepub.com/doi/abs/10.1139/cjfr-2017-0227 [Accessed 29 March 2024].

8: Loo, J.A. Ecological impacts of non-indigenous invasive fungi as forest pathogens. In: Langor, D.W., Sweeney, J. (eds) Ecological Impacts of Non-Native Invertebrates and Fungi on Terrestrial Ecosystems. (2008). Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-9680-8_6

9: Dr A. Martyn Ainsworth. BAP fungi handbook (ENRR600). (2004). [Online]. English Nature. Available at: https://publications.naturalengland.org.uk/publication/113017 [Accessed 29 March 2024].

10: Filipiak M, Sobczyk Ł, Weiner J. Fungal Transformation of Tree Stumps into a Suitable Resource for Xylophagous Beetles via Changes in Elemental Ratios. (2016) Insects. 9;7(2):13. doi: 10.3390/insects7020013. PMCID: PMC4931425.

11: “Xylophagous.” Merriam-Webster.com Dictionary, Merriam-Webster, https://www.merriam-webster.com/dictionary/xylophagous. Accessed 30 Mar. 2024.

12: Mille-Lindblom C, von Wachenfeldt E, Tranvik LJ. Ergosterol as a measure of living fungal biomass: persistence in environmental samples after fungal death. (2004) J Microbiol Methods.;59(2):253-62. doi: 10.1016/j.mimet.2004.07.010. PMID: 15369861.

13: Daniel Borcard, François Gillet, Pierre Legendre. Numerical Ecology with R. (2018). Springer,. pp.204-210.

14: Bernhard, A. The Nitrogen Cycle: Processes, Players, and Human Impact. (2010) Nature Education Knowledge 3(10):25

15: Royal Society of Chemistry. Phosphorus - Element information, properties and uses. (2012). [Online]. rsc.org. Available at: https://www.rsc.org/periodic-table/element/15/phosphorus [Accessed 16 April 2024].

16: Tree's for Life. Caledonian Forest Story. (2019). [Online]. treesforlife.org.uk. Available at: https://treesforlife.org.uk/about-us/narrative/ [Accessed 30 March 2024].

17: Trappe MJ, Cromack Jr K, Caldwell BA, Griffiths RP, Trappe JM Diversity of mat-forming fungi in relation to soil properties, disturbance, and forest ecotype at Crater Lake National Park, Oregon, USA. (2012). Diversity. 4 (2): 196–223.

18: W.M Adams. Future Nature A Vision for Conservation. (2003). London: British Association of Nature Conservationists. p.30.

19: The Wildlife Trusts. Caledonian. [Online]. (2020). wildlifetrusts.org. Available at: https://www.wildlifetrusts.org/habitats/woodland/caledonian-forest [Accessed 16 April 2024].

20: Paul McLean. Research Report- Wood properties and uses of Scots pine in Britain. (2019). Edinburgh: Forestry Commission.

21: Veikko Hintikka, Ossi Näykki. Notes on the Effects of the Fungus Hydnellum Ferrugineum (Fr.) (1967). Karst. on Forest Soil and Vegetation. Metsäntutkimuslaitoksen julkaisuja. 62

22: Hawksworth, D. Mycophobia and mycophilia. (1996). Nature 379, 503–504 https://doi.org/10.1038/379503a0

23: Ursula Peintner ,Stefanie Schwarz,Armin Mešić,Pierre-Arthur Moreau,Gabriel Moren. Mycophilic or Mycophobic? Legislation and Guidelines on Wild Mushroom Commerce Reveal Different Consumption Behaviour in. (2013). [Online]. PLOS ONE. Last Updated: May 21, 2013. Available at: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0063926# [Accessed 2 April 2024].

24: William Delisle Hay. An Elementary Text-book of British Fungi. (1887). Lowrey: S. Sonnenschein. P.6.

25: Bonfante-Fasolo, P., Perotto, S. Mycorrhizal and Pathogenic Fungi: Do They Share Any Features?. (1991). In: Mendgen, K., Lesemann, DE. (eds) Electron Microscopy of Plant Pathogens. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-75818-8_20

26: UK Research and Innovation. Why we need an international effort to study fungal infections. (2021). [Online]. ukri.org. Last Updated: 20 Oct 2021. Available at: https://www.ukri.org/blog/why-we-need-an-international-effort-to-study-fungal-infections/#:~:text=Th [Accessed 2 April 2024].

27: Sylvia Plath. The Colossus and Other Poems:(1960) Heinemann.