fSOC

A small pine tree grown in a glass box shows the level of white, finely branched mycorrhizal threads or "mycelium" that attach to roots and feed the plant

Fungal Soil Organic Carbon (fSOC)

By R.J.B., Kangaroo Valley, Jan., 2024

Another simple question: What is global soil fungal carbon stock?

An official global fungal biomass range today is between 12 or 12.56–15 Gt Carbon.

My answer (as is fully justified below) is that soil fungi may store between **~340–3,760 Gt C**.

Blakemore (2018), several years ago, presented:

"*1.3.2. The Scale of Topsoil Biodiversity*

The majority of deep carbon in soils is stored as SOM-humus composed of earthworm casts, decaying plants and both living and dead (or dormant) animals, fungi, and microbes. One cubic metre of soil ideally supports ~200,000 arthropods, ~2,020 true megadrile earthworms (~305 gm^{-2}), countless other larger or lesser organisms, plus up to 112 km m^{-2} of fine-roots in just the top 30 cm (Lee 1985: tab. 7) [29,37]. A single gramme (~1 cm^{3}) of fertile topsoil may have three billion microbes (Bacteria, Actinomycetes, Archaea, Fungi, Protozoa, etc.), up to 60 km of fungal hyphae, with 10,000 to 50,000 microbial species having 1,598 km of DNA some dating to the beginning of life four billion years ago [3,5,38,39]. Soil biodiversity and food-web interdependence are layered and complex (Figure 5) [below]. *However, all biotic totals are underestimated without terrain at scale and depth*." Often these totals are doubled.

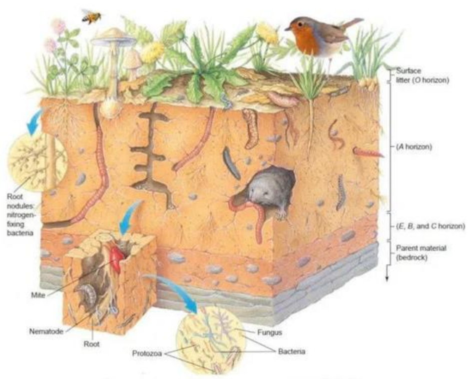


Image: http://geography.name/wp-content/uploads/2016/08/343477.jpg

Bar-On et al. (2018 : tab. S1) had soil microbes total ≈20 Gt C comprised of Bacteria & Achaea at ≈8 Gt C, and a soil fungi value of ≈12 Gt C, now doubled for terrain to 24 Gt. Their soil microbial error margin was 10-fold (i.e., possible fungal biomass range of 2.4–240 Gt C?).

Blakemore (2022) factored in terrain to properly and modestly double all soil (and land) biota. The “flat-Earth” model had 12 Gha soil-bearing land (excluding ice), now raised to >24 Gha.

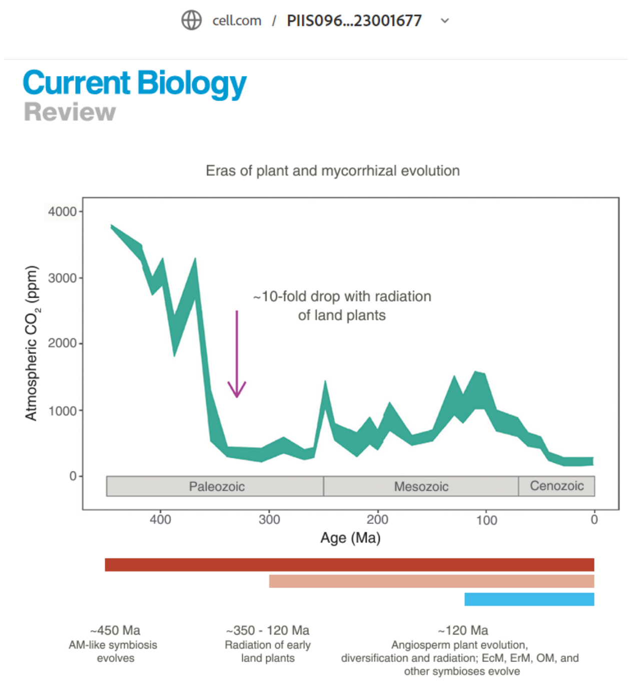
Blakemore (2023) later had:

“*3.2.3.5. Fungi*

Earthworms aside, Fungi are probably the next most important soil organisms. From Bar-On et al. (2018: fig. 5) Fungi were 12 Gt C and 10^{27} *cells, mainly in soils and herein at least doubled for terrain to 24 Gt C and 2 x* 10^{27} *cells. Contributions of Ectomycorrhizal fungi* [EM] *biomass they estimated as “roughly ≈0.2 Gt C” and for Arbuscular mycorrhiza (AM) “≈2 Gt C”. Rather than 12 Gt C as Bar-On et al. claim, Robinson (2004) found 15 Gt C in* [Ecto-]*mycorrhizal hyphae alone, doubled for terrain gives soil fungi >30 Gt C.*”

Bar-On et al.’s EM+AM fungi are about 0.2+2.0 Gt or 1.6+16.7% = 18.3% of the total 12 Gt C. Then, if Robinson is correct and EM alone is 15 Gt, as just 1.6% gives total fungi **1,880 Gt C**! When reasonably doubled for terrain, this would be **3,760 Gt C total** in global fungal biomass.

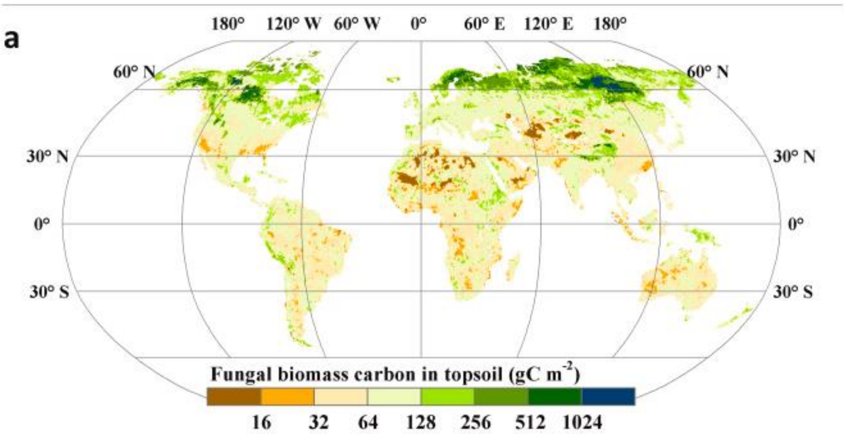
Hawkins et al. (2023 – their fig. 1 below), in an interesting review of fungi for global & historical carbon sequestration, quoted global SOC as ~1,500 Gt C, but did not give fungi carbon. So I emailed the authors enquiring whether they concurred with my initial fungal estimate of 30 Gt.



The kind reply from the primary author was:

“Dear Rob*… Upon having a closer look and looking at your questions: First, I don’t have an estimate of global fungal carbon. We made that estimate for mycorrhizal carbon as you know (3.6Gt C/yr) but of course this was preliminary with a number of uncertainties around fluxes, seasonality and permanence.*

But [this 2020 paper](#) made an estimation of fungal and bacterial carbon from PLFA measures between the 1960s and 2018. The come up with ***12.56 (6.64–16.42) Pg C (or Gt C) for fungal C and the C density map below:***



Second, about the underestimation of soil carbon because of flat-earth estimations, you are probably right! I am curious to know whether you have approached FAO or NOAA about your version of the carbon cycle and pools, and what has been the response? Perhaps you can look into using your 3-D estimations of soil carbon and re-analyze the data from the above study?

With kind regards
Heidi Hawkins"

This indeed I did: I re-analyzed data from He et al. (2020) of "*Global stocks of living microbial biomass*" with fungi estimated as 12.56 Gt C. However, this is only "*in 0–30 cm topsoil*", and they gave a global estimate of SOC (684–724 Gt C in 0–30 cm), thus they said approximately 1.8% of SOC is stored in soil fungi. They also compared their result saying: "*It is likely that the differences in the soil depths between this study (0–30 cm) and Bar-On et al. (2018) (entire soil profile) might underpin the discrepancy in estimated global budgets*..". Really? Bar-On et al. have 12 Gt C fungi in the whole soil profile, so extrapolating He et al. would be much higher.

Actually, Bar-On et al. (2018: supplement) average their soil depths between 0–1 m and 0–8 m saying that microbial biomass below 1 m depth averages between ≈2–30% of the total microbial biomass as found in the top 1 metre of soil. Then they took a geometric mean of the fraction of fungal biomass out of the total biomass of soil microbes they estimated as ≈60%.

This contrasts to Hu et al. (2024) who say: "*AMF biomass accounts for 20–30 % of the total soil microbial biomass, and roughly 15 % of the SOC pool in diverse terrestrial ecosystems (Miller et al., 2012, Deng et al., 2023)*". But perhaps Arbuscular Mycorrhizal Fungi (AMF) are only about half of the total fungi in which case this ≈60% of total biomass may well be correct? But it is difficult to reconcile the Hu et al.'s 15% of SOC with He et al.'s (2020) mere 1.8% of SOC!?

Other major problems of soil biota estimates are omission of full soil depth, and of terrain. Moreover, of the five major global C stores: Continental Lithosphere, Ocean (mainly inorganic C!), Soils (mainly organic carbon), Land Plants and Atmosphere; all are measured to full depth or height, except for some reason soil that is ridiculously measured to just 0.3-1.0 depth...

How deep is soil?
Shangguan et al. (2017) found "*The mean absolute DTB* [Depth to Bedrock] *predicted was 33.6 m*" but their table 1 Maximum Absolute DTB was up to 312,54 m or 3.1 km soil depth!

For mainland China alone, Yan et al. (2020) found "*predicted mean DTB was 42.20 m*" and maximum depth was 1,106.91 m (1.1 km) which are roughly similar values adding credibility.

Mineral soils are reported up to 100 m deep. For example, Richter & Markewitz (1995) said: "*soil is much more voluminous than it is often conceived. For example, in the southern Piedmont and Ridge and Valley Provinces of the eastern United States, the A plus B horizons may be only 0.5 to 2.5 m in depth, whereas the A through C horizons range up to 50 m in depth. In the humid tropics, 20 m of weathered and highly acidic saprolites are found on the Malaysian peninsula (Eswaran and Bin 1978). Similar profiles up to 100 m deep are found on the island of Hong Kong (Carroll 1970, Ruxton and Berry 1957). These enormous soil volumes and their occupation by plant roots and microbes need more detailed exploration by biologists, ecologists, and soil scientists. These volumes of weathered crustal material must be better integrated into concepts of soil and the biosphere*".

In SW Western Australia, Harper & Tibbett (2013) sampled SOC down to 38 m (mean 21 m) and found that 50–75 % of the SOC occurred within the top 5 m of soil profiles, with mean SOC mass densities at least 2–5 times greater than would be reported with standard IPCC sampling depth of just 0.3 m. This shows just how ignorant we are of deep soil, deep soil carbon and, presumably, the deep soil microbes and fungi at full soil depths.

According to Yu et al. (2022): "*Global SOC stocks ranged from 577-1171 Pg C and 1086-2678 Pg C at 0-30 cm and 0-100 cm depth.*" In other words, to 1 m the 0–30 cm values about double.

In addition to mineral soils up to 100 m, Peats are up to 200 m deep, and Permafrosts up to 1.5 km (or perhaps the 3.1 km as reported for global soils above?), from Blakemore (2023).

Why Permafrost and Peat are so important is these both may have up to 50% SOC and, furthermore, as reported in the latter science-blog report, an additional ~50% glomalin derived from AMF. Clearly shown in the image above from He et al. (2020: fig. 3a), it seems fungi are most abundant in the boreal regions where these two soil eco-categories are most prevalent.

Moreover, VAM, EM or AM fungi are intimately associated with plant roots and, as explained by Blakemore (2023), roots have been reported as deep as 68–70 m (Ref.) or up to 120 m (Ref.) although an average global figure may be around 4.6 ± 0.5 m (Ref.). Roots can penetrate into saprock/bedrock thus may be deeper than officially classified soil depths (Ref.).

Saprock carbon, that may add 26–30% to soil carbon tally and extend the soil profile +8 m deeper, if only in part of fungal origin, may be of great relevance for fungal SOC stocks; see - https://vermecology.wordpress.com/2023/11/06/up-2-c/.

A further consideration, if partly of fungal origin, may be Lignite (global total ~3,000 Gt C) under Peat (also ~3,000 Gt C); see - https://vermecology.wordpress.com/2023/06/14/missed-peat/.

Terrain Recalibration

As Blakemore (2018, 2023) explained, topographical terrain is ignored in all calculations but, when properly considered, at least doubles, or possibly quadruples, all terrestrial soil metrics.

'Circling back' (as they say) to Hawkins et al. (2023)'s finding that fungi process ~36% of annual global fossil fuel emissions. With terrain this is at least doubled, possibly quadrupled, so is hereby raised to about the same as global FF emissions (~6–12 Gt C/yr). But we already know this as FF emissions are about 10 Gt C/yr and Soil Respiration is about 220 Gt C/yr (Blakemore 2018, 2023). They have AM fungi: "*drawing an average of 3–13% but up to 50% of a plant partner's NPP*" and, as NPP is also now up to 220 Gt C/yr, this is quite substantial.

So…
So finally getting back to the re-analysis question of He et al. (2020) fungi of 12.56 Gt C…

An initial problem with He et al. (2020) value is that it is only for "*living microbial biomass*" and, for example, Burkert et al. (2019) have "*In temperate soils, up to 40% of DNA is from dead or compromised cells (3). In permafrost, the amount of relic DNA may be even higher because frozen conditions preserve DNA from dead cells*." They cited just 25–26% viable cells in some Permafrosts suggesting about 75% were dead or dormant. Other authors have similar or higher estimates, e.g., Sorensen & Shade (2020) say: "*Furthermore, a majority of the microbial cells or richness in soil is dormant [**13**,**19**], reportedly as high as 80%, representing a considerable pool of microbial functional potential. Finally, across heterogeneous soils, an average of 40% of the microbiome DNA was necromass that existed extracellularly [**15**]. This suggests that DNA-based methods of determining microbiome dynamics include both inactive and necromass reservoirs…*". Thus, it is not unreasonable to at least double He et al.'s value.

12.56 Gt C x ~2 for dormant/dead microbial cells = 25.12 Gt C.

Also, He et al. only measure microbes in the top 30 cm while SOC averages are of around 828 Gt and 1873 Gt, for 0-30 cm 0-100 cm soil depths, respectively, or about double. And, as Harper & Tibbett (2013) found: 50–75 % of the SOC occurred within the top 5 m of soil profiles, with mean SOC mass densities at least 2–5 times greater at depth, this may be doubled again.

25.12 x ~4 for soil to full depths >30 cm = 100.48 Gt C or about 8x their value (which may partly account for their 1.8% discrepancy vs. fungi being "*roughly 15 % of the SOC pool*"?).

Then there is GRSP glomalin of AMF origin that may increase all SOC values by 30–50%.

100.48 x ~40% median for GRSP glomalin = 140.7 Gt C.

Deep saprock/bedrock carbon may also increase SOC by 30%, or add ~30 Gt C in fungi?

140 + ~30 for saprock/bedrock fungal carbon = 170 Gt C.

Finally, terrain (Blakemore 2018, 2023) likely at least doubles all soil values, including fungi.

170 x ~2 for terrain = **~340 Gt C** which is about 27 times He et al.'s initial **12.6 Gt C** value.

Furthermore, from Blakemore (2018, 2023, and https://vermecology.wordpress.com/2023/11/06/up-2-c/) in all its forms, SOC totals 15,000–25,000 Gt, mean ~20,000 Gt C thus, if fungi truly are "*15 % of the SOC pool*", = **~3,000 Gt C**. This may be compared to the total of **3,760 Gt C** noted above as calculated earlier. *Q.E.D*.

This 10-fold margin of error (range **~340–3,760 Gt C**) is the same as Bar-On et al. (2018)'s.

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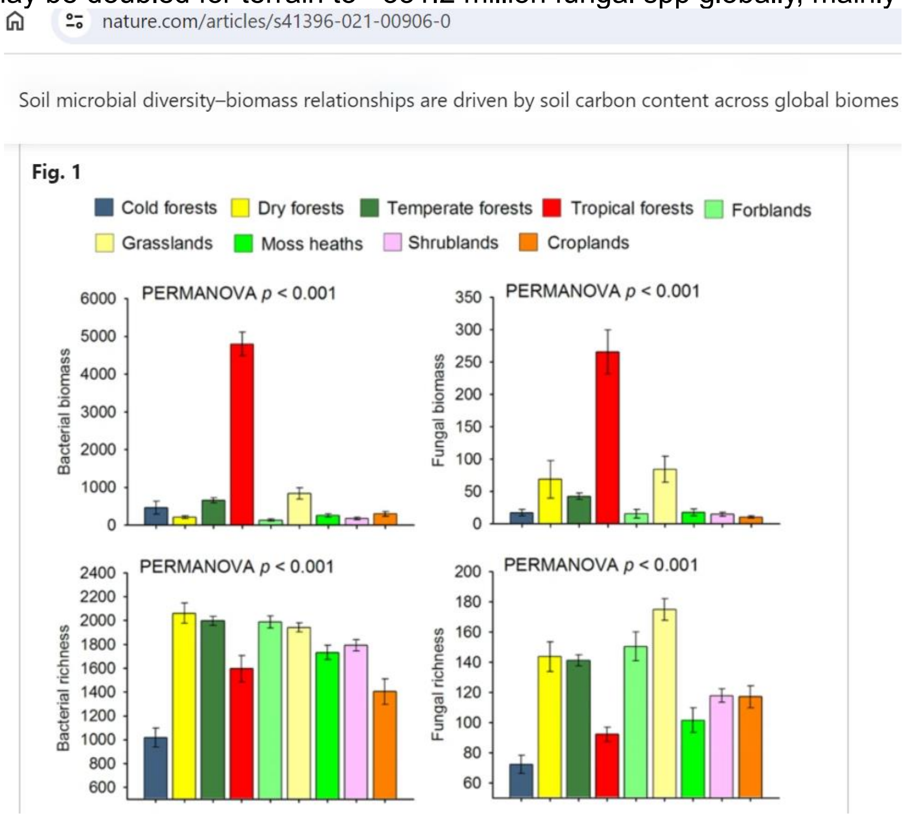
AFTERNOTE
Increase in soil fungal biomass, to at least 340 Gt C, puts it higher than Bacteria/Archaea at around ~200 Gt C (Blakemore 2018, 2022, 2023: tab. 2) and further increases species totals.

Two recent papers are relevant. One claimed a potential market value of Global Fungi at US$54.57 trillion/yr (Niego et al. 2023), offset by an economic burden of >$48 billion in USA alone (Ref.) that if extended worldwide may be 100x or more to >$4.8 trillion losses. Please note, terrain or topography do not factor into such economic or external accounting methods.

In contrast, a second paper confidently estimated Fungal biodiversity – or species richness – total of ~2.5 million taxa (Niskanen et al. 2023). As this presumably assumes an unrealistic planimetrically-flat landscape, so it may be doubled for terrain, topography & soil micro-relief to ~5 million fungal spp. However, these authors ignore Larsen et al. (**2017**: fig. 1, tab. 1) that already proposed 165.6 million fungal spp – a difference of two orders of magnitude! This latter figure too may be doubled for terrain to >331.2 million fungal spp globally, mainly in the soil.



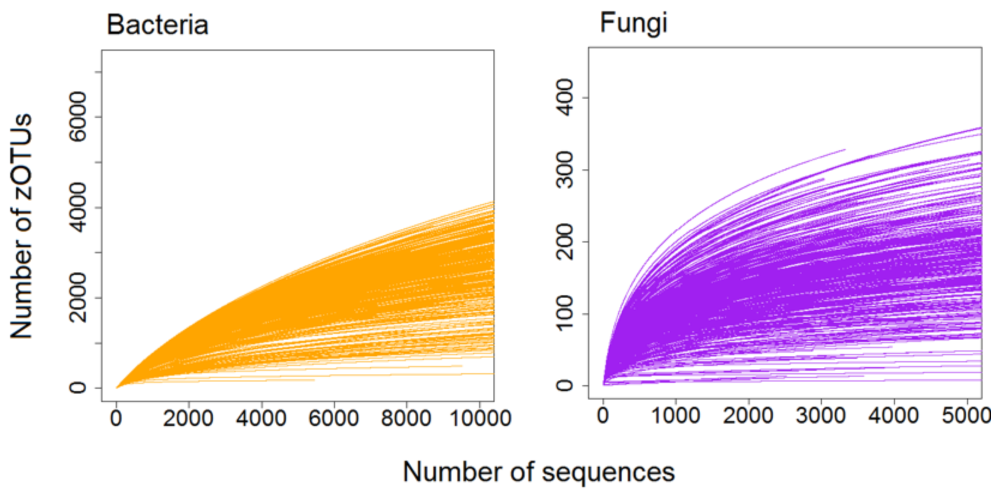
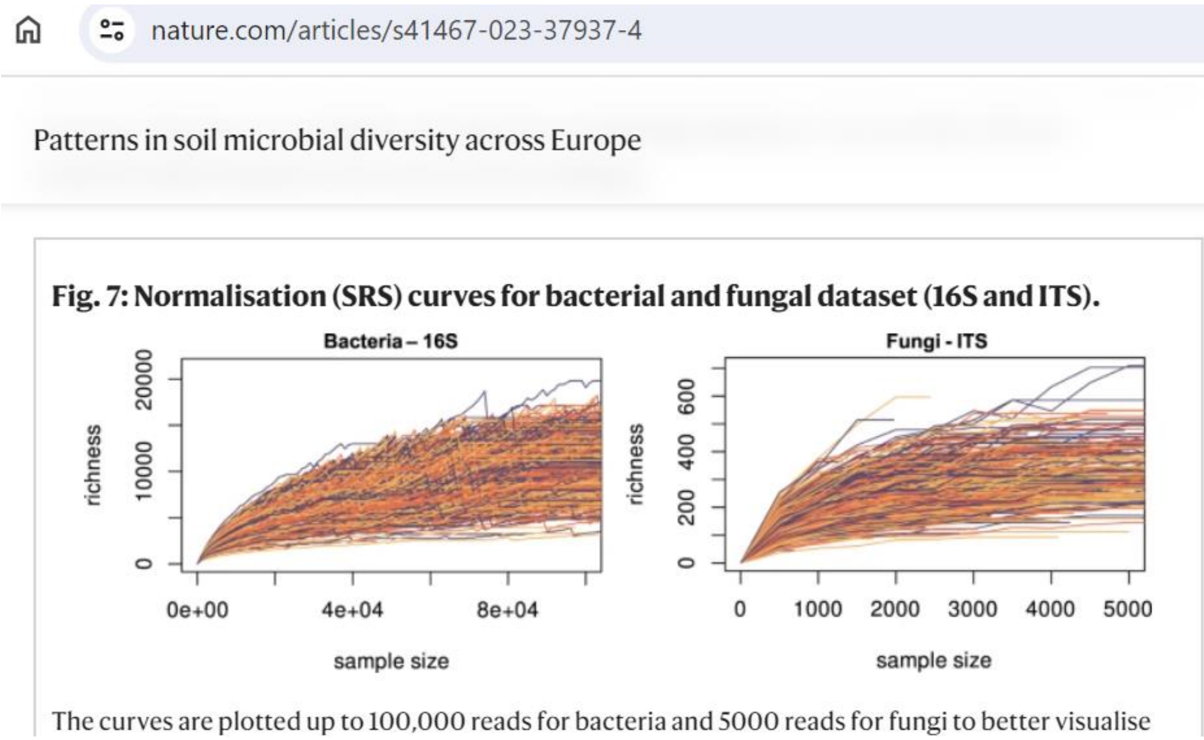


Figure S2. Raferaction curves for bacterial and fungal communities in this study.

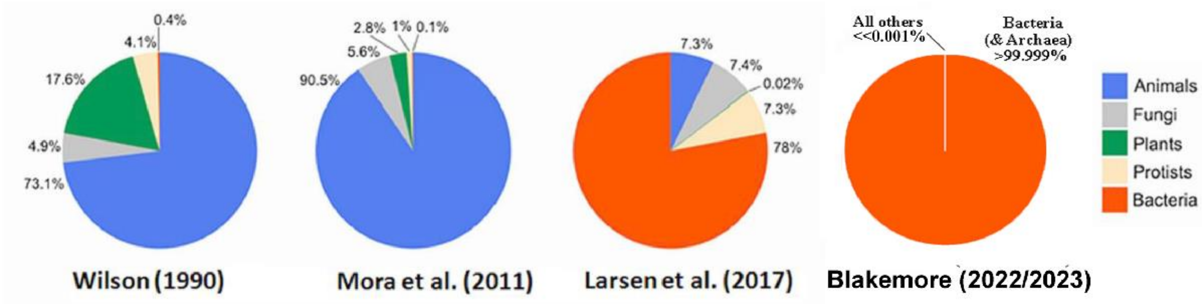
This invites the logical question: What is the average ratio of Bacteria:Fungi in soils? Previous estimates were of $10^{8\text{-}9}$ Bacteria and $10^{5\text{-}6}$ Fungi per g of soil (Ref.), or about 1000:1 abundance. Soil microbial species (OTUs) number about $10^{2\text{-}6}$ per g (Ref.), and Bastida et al. (2021: figs. 1, S2 above) have biomass & diversity ratios both roughly 10:1 for Bacteria vs.

Fungi across the globe (up to about 3,000 vs. 300 zOTUs for 5,000 PCR sequences). Similar ratios of biomass & species richness were confirmed in Europe (Labourie et al. 2023: fig. 7):



This is relevant as Blakemore (2022, 2023: fig. 4, tab. 2) had total soil microbial biodiversity of median ~2.1 x 10^{24} taxa. If these wide ratios stand, this is approximately ~$10^{21\text{-}23}$ global fungal species biodiversity, median 10^{22}, far above all earlier estimates but still highly uncertain.

This again shows how ignorant we are of soil/soil biota as how our perceptions are steadily rising, combined with a much greater depth of understanding of what lies beneath our feet:



Micro Monde: New data (Blakemore **2022**, **2023**: tab. 1) after Larsen et al. (**2017**: fig. 1, tab. 1) now mostly doubled for terrain; see - https://vermecology.wordpress.com/2023/08/31/not-unreasonable-new-global-biotic-total/. Data increases rapidly, yet we still have much to learn.