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How much does fungi contribute to weathering?
A Literature Review

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Abstract

Ectomycorrhizal fungi contribute to weathering and may be used as an alternative to fertilizers. Their usefulness is dependent on how much they can contribute to the weathering that takes place in the same area. This review discusses the current literature on how much ectomycorrhizal fungi contribute to the total chemical weathering rate. There are few studies that document said contribution, with most geomycological weathering studies only reporting weathering numbers for the fungi. The weathering contribution towards apatite and olivine appears to be higher (at 28% and 16% respectively) than the 0.2% and 0.5% attributed to feldspar and 2% attributed to biotite. More research is needed to understand how much fungi can contribute to weathering. It would be preferable to study multiple species of both minerals and fungi at once in the same drainage area.

Introduction

Anthropogenic eutrophication is a problem all around the world. To satiate our ever growing food demand, fertilizers are strewn over the farms in large doses at a time. Fertilizers generally bring bioavailable versions of the elements N, P, and K to combat the nutrient deficiencies that appear during farming and limit production (Matson et al. 1997). The large doses applied at once oversaturates the soil with respect to the plants' needs, which leads to some leaching out into the environment. These nutrients will then end up in water supplies and lead to eutrophication. Eutrophication of water supplies deteriorates the water quality for human consumption and causes more and more intense algal blooms which produce phycotoxins (Ho et al. 2019).

Eutrophication of the Baltic Sea has led to an increasing lack of oxygen due to the prevalence of algal blooms. This hypoxia strains the population of the overfished Baltic cod among other species (Hinrichsen et al. 2011).

In May 2020, the EU pledged to reduce nutrient losses in soil by 50% by 2030 and move towards the use of organic fertilizers instead of mineral fertilizers (Directorate-General Agricultural and Rural Development 2024 Mar 13). One way to do this is to take advantage of natural processes. Symbiotic fungi which sit at the roots of plants, mycorrhiza, are connected to one such process. They can weather nearby rocks to provide nutrients to their host in exchange for sugars (fig. 1). These mycorrhizal fungi could be a useful tool in our efforts for more sustainable farming (Rosenstock 2009).

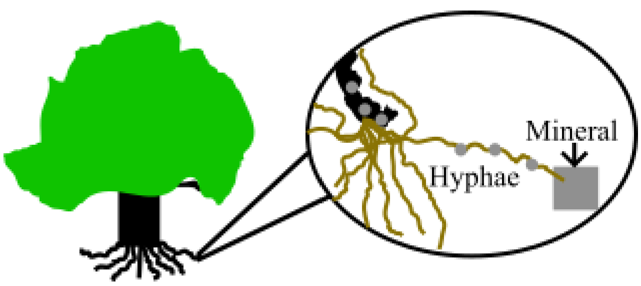

Fig. 1. Illustration of mycorrhizal fungi siphoning nutrients from a mineral into its host plant.

Mycorrhizal fungi could possibly replace the commercial mining for phosphates as fertilizers (Smits et al. 2012). Mining on its own has many environmental drawbacks. It is an inherently destructive process which creates pits and tunnels that cover a few thousand hectares (Florida Department of Environmental Protection 2023 Aug 16). Most mining equipment today runs on fossil fuels though that may be subject to change with more equipment becoming electric.

The first paper on fungus promoted weathering, *Rock-eating fungi* (Jongmans et al. 1997), studied ectomycorrhizae, a collection of mycorrhizal fungi species that are most commonly found with trees and bushes (Malloch et al. 1980). Most papers looking into the weathering rates of mycorrhizae have thus focused on ectomycorrhiza. Ectomycorrhizae weather rocks by excreting spores and a solution with acids, and siderophores called EPS (Li et al. 2016; Ke et al. 2023). These acids and siderophores weathers rocks chemically. Some physical erosion occurs when the hyphae dig into the rocks, in a process called tunneling (Gadd 2017).

Weathering rates are generally reported in 3 different ways in this field, either as weathering rates, dissolution rates, or weathering fluxes. Weathering rates is a catch all term. Dissolution rates refer to the rate at which the measured thing dissolves (LibreTexts Libraries 2016 Jun 27). In this field it would be minerals dissolving in an acidic solution. This measurement is common for laboratory studies. Weathering flux is used more in field studies and applies to the dissolved materials in runoff waters. It takes into account the water discharge, studied area, surface contact between water and rocks, the dissolution rate, and the concentration of the dissolved materials (Lerman 1994).

To know the usefulness of fungi in sustainable farming, it is necessary to know how much they contribute to the weathering products in the soil. Literature quantifying the weathering impact of fungi are few and far between. This literary review aims to summarize the current literature on how much fungus promoted weathering contributes to the total chemical weathering.

Method

A systematic search was conducted over the databases GeoRef, Geobase, and Google Scholar. The searches were done in a period between 18 March 2024 and 26 March 2024, and on 19 April 2024. Each search query was used for each database.

20 search terms were used. These were selected from known papers prior to the systematic searches. 5 of them were related to fungi while the other 15 focused on the weathering process and weathering materials (Table 1). The fungi terms were used alone or combined with the other 15 terms to build the search queries.

Table. 1: Search terms used to create search queries.

Fungus related search terms				
Fungal-mineral Interaction	Fungus	Fungus-mineral interaction	Rock-eating Fungi	Fungal Bioweathering
Weathering related search terms				
mg/L	mol/m^2*s	Total chemical weathering	Anorthite	Orthoclase
Apatite	Phosphate	Rock Phosphate	Plagioclase	Feldspar
Phosphorus	Biotite	Weathering flux	K-Feldspar	Microcline

Combining search terms was done with an AND statement. In Google Scholar this was done by writing AND between the two search terms in a single search field. Geobase allows for combining two search fields with an AND statement in the quick search feature. Georef's advanced search feature was used by combining two search fields with an AND statement.

For Google Scholars the "include citations" option was selected. All fields were selected for both search fields in Geobase; in the drop down menus, all languages and all document types were selected and the autostemming feature was turned on. In GeoRef's Advanced Search all content was shown though journals and images were deselected, under "Build Query" All were selected in the Select a filter dropdown menus for both search fields.

To look through a manageable amount of literature an upper limit of 150 or less results that the Stockholm University Library has access to was selected. Results without the full text listed with them, and literature that were in languages other than English were not looked through. Van Schöll (2008) took up 2 papers of interest which were not found in any search queries but these were also assessed.

The numbers of results per search query and database were documented. Both the total amount of results and accessible literature were documented for searches where the number of accessible literature would reasonably fall below 150 result limit, 2 searches on Google Scholar with 169 and 172 total searches slipped in under the limit when it was applied to the amount of accessible literature instead of the total amount of results.

All the literature found in these searches were scoured for any sign of a comparison between a total weathering rate and the fungal bioweathering rate. The literature that was of interest there was then read through more rigorously, if it was a form of secondary or tertiary literature then the primary source was searched for. The queries and databases where each piece of literature of interest could be found was documented. Out of the number of promising literature, 6 were chosen to stay within the time allotted for this thesis. These 6 were chosen to cover multiple periodic elements and differing results in weathering rates.

The reported weathering rates were converted to $[\frac{g}{m^2 \times s}]$ if possible. Minerals were assumed to be the most common end member of 100% purity unless the composition had been documented.

Results

Searches

64 search queries were made by combining the search terms (table 2)

Table 2: A table showing the searches conducted for this literature review. Search queries were ordered alphabetically by fungus related search term, then by the category of other search terms and alphabetically within those categories. The numbers below each database shows the amount of accessible literature and the amount of literature per search respectively. If only 1 number is shown below a database then it is the amount of literature per search.

Nr	Search Query	Geobase	GeoRef	Google Scholar
1.	Fungal Bioweathering	16/17	5/23	2900
2.	Fungal Bioweathering AND mg/L	0	0	625
3.	Fungal Bioweathering AND mol/m^2*s	0	0	50/56
4.	Fungal Bioweathering AND Total chemical weathering	1/1	0	1730

Nr	Search Query	Geobase	GeoRef	Google Scholar
5.	Fungal Bioweathering AND Weathering flux	1/1	0	545
6.	Fungal Bioweathering AND Biotite	0	0/1	516
7.	Fungal Bioweathering AND Anorthite	0	0	59/81
8.	Fungal Bioweathering AND Feldspar	1/1	0	661
9.	Fungal Bioweathering AND K-Feldspar	0	0/1	141/169
10.	Fungal Bioweathering AND Microcline	0	0	98/120
11.	Fungal Bioweathering AND Orthoclase	0	0	381
12.	Fungal Bioweathering AND Plagioclase	0	0/1	339
13.	Fungal Bioweathering AND Apatite	3/3	0	452
14.	Fungal Bioweathering AND Phosphate	1/1	0/1	1740
15.	Fungal Bioweathering AND Phosphorus	1/1	0	1710
16.	Fungal Bioweathering AND Rock Phosphate	1/1	0/1	1580
17.	Fungal-mineral Interaction AND Total chemical weathering	2/2	0	114/147
18.	Fungus AND mg/L	1881	7/35	447000
19.	Fungus AND mol/m^2*s	1/1	1/2	14800
20.	Fungus AND Total chemical weathering	21/21	0	35800
21.	Fungus AND Weathering flux	17/17	2/3	19100
22.	Fungus AND Biotite	27/31	9/35	8000
23.	Fungus AND Anorthite	1/1	0	1390
24.	Fungus AND Feldspar	20/20	6/49	16500
25.	Fungus AND K-Feldspar	6/6	3/14	3440
26.	Fungus AND Microcline	3/3	1/7	2010
27.	Fungus AND Orthoclase	2/2	0	2700
28.	Fungus AND Plagioclase	1/1	0	5900
29.	Fungus AND Apatite	31/38	7/26	18400
30.	Fungus AND Rock Phosphate	94/110	0/4	47600
31.	Fungus AND Phosphate	1153	14/69	1250000
32.	Fungus AND Phosphorus	2171	7/28	576000
33.	Fungus-mineral interaction	412	28/146	65/83
34.	Fungus-mineral interaction AND mg/L	10/11	0	19/30
35.	Fungus-mineral interaction AND mol/m^2*s	0	0	3/3
36.	Fungus-mineral Interaction AND Total chemical weathering	3/3	0	37/54
37.	Fungus-mineral interaction AND Weathering flux	0	0	23/34

Nr	Search Query	Geobase	GeoRef	Google Scholar
38.	Fungus-mineral interaction AND Biotite	8/10	1/2	25/39
39.	Fungus-mineral interaction AND Anorthite	0	0	0/1
40.	Fungus-mineral interaction AND Feldspar	0	0	24/38
41.	Fungus-mineral interaction AND K-Feldspar	0	0	4/4
42.	Fungus-mineral interaction AND Microcline	1/1	0	12/12
43.	Fungus-mineral interaction AND Orthoclase	0	0/1	3/6
44.	Fungus-mineral interaction AND Plagioclase	0	0/1	8/10
45.	Fungus-mineral interaction AND Apatite	5/7	0/1	16/31
46.	Fungus-mineral interaction AND Phosphate	31/38	0/1	43/60
47.	Fungus-mineral interaction AND Phosphorus	65/76	0/1	42/60
48.	Fungus-mineral interaction AND Rock Phosphate	5/5	0	28/44
49.	Rock-Eating Fungi	4/4	8/63	877
50.	Rock-Eating Fungi AND mg/L	0	0/1	116/133
51.	Rock-Eating Fungi AND mol/m^2*s	0	0	28/33
52.	Rock-Eating Fungi AND Total chemical weathering	0	0	629
53.	Rock-Eating Fungi AND Weathering flux	0	0/2	361
54.	Rock-Eating Fungi AND Biotite	0	2/9	273
55.	Rock-Eating Fungi AND Anorthite	0	0/1	43/60
56.	Rock-Eating Fungi AND Feldspar	0	0	341
57.	Rock-Eating Fungi AND K-Feldspar	0	1/5	84/90
58.	Rock-Eating Fungi AND Microcline	0	1/2	106/115
59.	Rock-Eating Fungi AND Orthoclase	0	0/2	43/60
60.	Rock-Eating Fungi AND Plagioclase	0	1/7	137/172
61.	Rock-Eating Fungi AND Apatite	0	0/2	263
62.	Rock-Eating Fungi AND Phosphate	0	0/4	593
63.	Rock-Eating Fungi AND Phosphorus	0	0/2	585
64.	Rock-Eating Fungi AND Rock Phosphate	0	0/1	593

13 pieces of literature were found to be of interest and the 6 chosen became: Balogh-Brunstad et al. (2008); Breitenbach et al. (2022); Smits et al. (2005); Smits et al. (2012); Sverdrup et al.

(2002); Wild et al. (2021). Out of these Sverdrup et al. (2002) was not found from any search query but it was cited in other literature (Table. 3).

Table 3: Where the literature used for this review was found in each database. The numbers refers to the number of the search queries in table 2.

	Balogh-Brunstad et al. 2008	Smits et al. 2005	Smits et al. 2012	Sverdrup et al. 2002	Wild et al. 2021
Geobase	52		37, 39, 40, 41		55, 64
GeoRef					1, 2, 3, 6, 52, 55, 56
Google Scholar	5, 6, 24, 58, 59	23, 24, 26, 27	5		

Sverdrup et al. (2002) was chosen as a dissenting opinion on the field as a whole, Balogh-Brunstad et al. (2008) tested on biotite, Wild et al. (2021) and Breitenbach et al. (2022) both looked at olivine, Smits et al. (2005) looked at feldspar, and Smits et al. (2012) looked at apatite.

Documented Weathering Rates

Sverdrup et al. (2002) mentions that the total weathering rate should be between 5 to 50 $[\frac{kg}{ha \times yr}]$ $(1.59 \times 10^{-8}$ to 1.59×10^{-7} $[\frac{g}{m^2 \times s}])$ and found a total weathering rate for potassium of 7.280 $[\frac{kg}{ha \times yr}]$ $(2.31 \times 10^{-8}$ $[\frac{g}{m^2 \times s}])$. Historical weathering estimations explain 98% of all weathering through abiotic causes while tunneling by fungi may contribute at most $0.2[\frac{kg}{ha \times yr}]$ 6.34×10^{-10} $[\frac{g}{m^2 \times s}]$ or 0.15 $[\frac{keq}{ha \times yr}](4.77 \times 10^{-10}$ $[\frac{eq}{m^2 \times s}])$ in 2 other estimations.

Fungal induced apatite weathering rates were determined to be 3.7×10^{-11} $[\frac{mol}{m^2 \times s}](4.0 \times 10^{-8}$ $[\frac{g}{m^2 \times s}])$ while it is stated that the weathering rates of P increased by $7.5 \pm 1.1 \times 10^{-10}$ $[\frac{mol}{m^2 \times s}](2.3 \pm 0.34 \times 10^{-8}$ $[\frac{g}{m^2 \times s}])$ to $2.2 \pm 0.52 \times 10^{-9}$ $[\frac{mol}{m^2 \times s}](6.8 \pm 1.5 \times 10^{-8}$ $[\frac{g}{m^2 \times s}])$ (Smits et al. 2012).

Balogh-Brunstad et al. (2008) measured that fungi accounted for 2% or 3.7×10^{-12} $[\frac{mol}{m^2 \times s}]$ ($1.7 \times 10^{-9}[\frac{g}{m^2 \times s}]$) of the total dissolution rate of biotite $2.1 \times 10^{-10}[\frac{mol}{m^2 \times s}]$ ($9.6 \times 10^{-8}[\frac{g}{m^2 \times s}]$). In the abstract the total dissolution rate of biotite is $2.7 \times 10^{-10}[\frac{mol}{m^2 \times s}]$, since this number does not show up in the body of the paper, it is omitted.

Fungi tunneling was determined to weather 6.34×10^{-13} $[\frac{g}{m^2 \times s}]$ Ca and 1.27×10^{-12} $[\frac{g}{m^2 \times s}]$ K corresponding to 0.2% and 0.5% for Na/Ca-feldspar and K-feldspar respectively (Smits et al. 2005).

For the olivine related experiments, Wild et al. (2021) found that fungal weathering accounted for $3.5 \pm 0.3 \times 10^{-12}$ $[\frac{mol}{m^2 \times s}]$($5.1 \pm 0.5 \times 10^{-10}$ $[\frac{g}{m^2 \times s}]$) or 16% of the total weathering flux $2.2 \pm 0.2 \times 10^{-11}$ $[\frac{mol}{m^2 \times s}]$($3.2 \pm 0.3 \times 10^{-9}$ $[\frac{g}{m^2 \times s}]$) and a local dissolution rate of $2.2 \pm 1.2 \times 10^{-10}$ $[\frac{mol}{m^2 \times s}]$($3.2 \pm 1.8 \times 10^{-8}$ $[\frac{g}{m^2 \times s}]$). Lastly, Breitenbach et al. (2022) found a dissolution rate of $38 \pm 13 \times 10^{-16}$ $[\frac{mol}{cm^2 \times s}]$ ($5.6 \pm 1.9 \times 10^{-9}$ $[\frac{g}{m^2 \times s}]$) for forsteritic olivine (fig. 2).

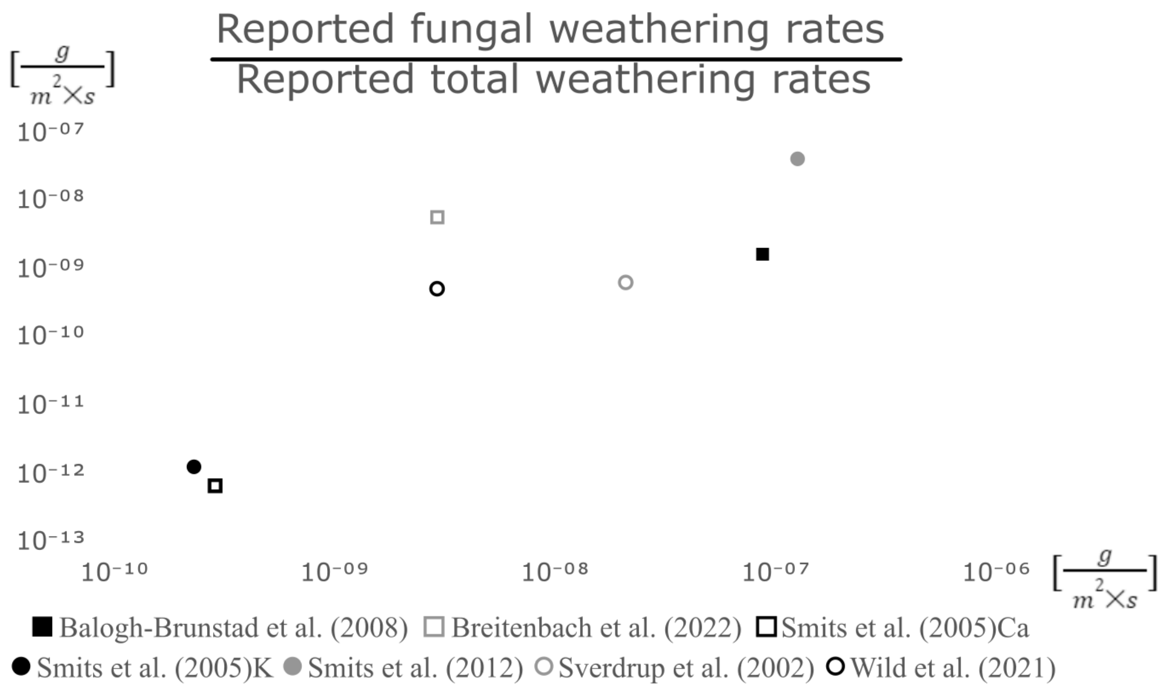

Fig. 2. A logarithmic graph showing the weathering rates found in the reviewed studies. The total weathering rates for apatite were taken from Newman (1995).

As Wild et al. (2021) did not provide a chemical composition for their olivine, the assumed composition became that of Breitenbach et al. (2022). Breitenbach et al. (2022) did not provide a total dissolution rate. Comparing their results to the total weathering rate found in Wild et al. (2021), makes it so that it would account for 175% of the total weathering (fig. 3).

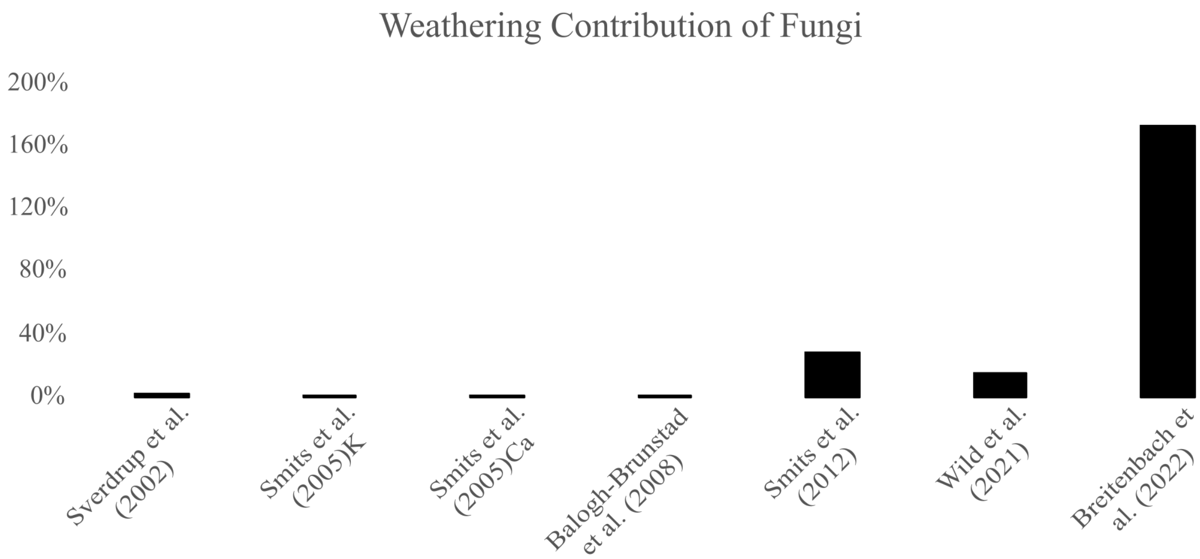

Fig. 3. The weathering contribution of fungi reported in the reviewed literature. The total weathering rates for apatite were taken from Newman (1995).

Discussion

The found weathering rates for olivine differ from each other. The weathering rate found in Breitenbach et al. (2022) is almost twice that of the total weathering rate in Wild et al. (2021). Wild et al. (2022) does also report a number higher than their total weathering rate in the form of a local dissolution rate. Though they vary in magnitude, this local dissolution rate could be similar in concept to what Breitenbach et al. (2022) found.

Feldspar weathering rates seem noticeably lower than the other measurements. Feldspar is weathering resistant. Smits et al. (2005) believes their measurements to be underestimated due to it only reflecting measurements of the tunneling that is left after other weathering forces have acted upon them. The weathering rates of albite could increase to somewhere between the magnitudes of 10^{-10} and 10^{-8} $[\frac{mol}{m^2 \times s}]$(~$2.8 \times 10^{-8}$ and

$\sim 2.8 \times 10^{-6}[\frac{g}{m^2 \times s}]$)(van Breemen et al. 2000). Either way, the nutrient contribution of fungi into the soil is much lower compared to atmospheric deposition (Smits et al. 2005).

Comparing olivine and feldspar introduces the acidity of minerals into the equation. Feldspars are felsic, reacting with H^+ions at a ratio proportional to $H^{\sim 0.5}$ (Blum 1994). Olivine, on the other hand, is ultramafic and much more reactive with H^+ it being proportional to $H^{\sim 3.26 \pm 0.65}$ (Oelkers et al. 2018). With most of the weathering contributions of fungi occurring through acids, it is understandable that fungi may contribute less to feldspar weathering.

The iron inside the fungal biomass increased during the biotite weathering experiment (Balogh-Brunstad et al. 2008). Free iron particles and secondary minerals inhibit further abiotic weathering (Santelli et al. 2001). Fungi take up iron by excreting siderophores and thus fungi can also contribute to the occurring abiotic weathering (Breitenbach et al. 2022).

Balogh-Brunstad et al. (2008) did not have a plant host for their fungi. Ectomycorrhiza may function better with a host but it lacks research (Rosenstock 2009). No correlation between the mycelium coverage on biotite and the nutrient needs of their plant host has been found (Hagerberg et al. 2003).

Total weathering rates for P ranges between 5×10 $[\frac{g}{ha \times yr}](1.6 \times 10^{-10}[\frac{g}{m^2 \times s}])$ and 5×10^3 $[\frac{g}{ha \times yr}](1.6 \times 10^{-8}[\frac{g}{m^2 \times s}])$ (Newman 1995). Assuming that all P from weathering comes from apatite with the composition stated in Smits et al. (2012) $[Ca_{11.5}(PO_4)_6(F_{1.3}Cl_{0.02}\,OH_{3.7})]$ would mean a maximal total weathering rate of $1.4 \times 10^{-7}[\frac{g}{m^2 \times s}]$. Thus the reported weathering rates for fungi would account for at least 29% the total weathering rate.

Fungi weather apatite by using oxalic acid which creates whewellite ($CaC_2O_4 \bullet\ H_2O$) (Mendes et al. 2021). Whewellite is harmful to humans (Calcium Oxalate Monohydrate SDS (Safety Data Sheet) | Flinn Scientific 2017 Aug 15). This may not be appreciated in the food industry, but would not pose any health concerns through the forestry industry. Calcium oxalates are naturally found in crops like rhubarb and taro corms (Kumoro 2012; Khan et al. 2024). In taro corms it can be removed through multiple methods (Kumoro 2012).

Sverdrup et al. (2002) uses different units for similar equations with a lack of available information to convert them to the same unit within the timeframe of this study. The units used are $[\frac{kg}{ha \times yr}]$, and $[\frac{keq}{ha \times yr}]$, both referring to weathering rates. The equivalent (eq) describes how much of an molecule that can react with another molecule and equates to nV where n is the amount of moles and V is the valency (The International Union of Pure and Applied Chemistry (IUPAC) 2006). This can be changed into mol if you know the valency of every reactive compound used. Sverdrup et al. (2002) does not provide a reference to the data used to estimate 4.77×10^{-10} $[\frac{eq}{m^2 \times s}]$, thus this can not be fully compared with the other measurements though the magnitude may not change much by dividing with the valency.

There are 4 hypotheses in the field of geomycology that Sverdrup et al. (2002) aims to disprove, though number 1 and 4 are the exact same. This lends less credence to the points. The hypotheses regard the contribution to weathering from organic acids by mycorrhiza and whether weathering rates are independent of mineral surface areas, though where these hypotheses are taken from is not addressed.

Weathering rates being independent of mineral surface area would mean that the phenomena occurs uniformly over any given area. This is not the case, as we can see with the reported dissolution rates in Wild et al. (2021). Though there are no references to papers that have claimed otherwise.

Sverdrup et al. (2002) uses the temperature dependency factor found in fields and laboratory experiments as an angle to dispute the weathering contribution of mycorrhiza. Temperature dependency factor refers to how fast a reaction may take place depending on the temperature (Laidler 1984). The temperature dependency factor for organic acids found in, non cited, laboratory studies were lower than the two examples from field studies which means that is dominated by other reactions according to Sverdrup et al. (2002). With the rates shown, organic acids account for 5% to 15% of the total weathering rate (Sverdrup et al. 2002), though all the organic acids found in soil are not attributed to fungi.

Looking at the current literature in geomycology, the weathering contributions of fungi seems to be poorly understood. The contribution to the total weathering rate of fungi seems to fluctuate depending on the mineral in question. Older studies have focused largely on the physical weathering aspect of fungi (Smits et al. 2005), which overlooks other contributing factors of fungal weathering. Newer weathering models have also made it easier to look into the weathering contributions of ectomycorrhiza (Wild et al. 2021). Lab experiments are hard to relate back to weathering rates found in the field. Thus more research is needed on the weathering contributions of fungi, preferably with multiple species of both minerals and fungi in the same drainage area. Rosenstock (2009) provides multiple recommendations on how to improve experiments in this field, such as having test groups with both a surplus and deficiency of the tested nutrient.

Conclusion

This literary review demonstrates the differences in reported numbers on the contribution to the total weathering rates for ectomycorrhizal fungi. The current literature shows higher weathering contributions for apatite(29%) and olivine(16%) compared to biotite(2%) and feldspar($0.2\%\ to\ 0.5\%$). The latter two fit within the proposed maximum for the contribution of fungi as laid out in a dissenting opinion. But due to a lack of information and apparent flaws, numbers in the dissenting opinions can not be fully compared with other studies. It is possible that ectomycorrhiza contribute different amounts to the total weathering depending on the mineral but more research is needed.

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