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The University Of Sheffield.

WUN Weathering Science CONSORTIUM

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Using integrated experiments and mathematical modeling to upscale biotic weathering processes from pore to field and global scales

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Summary

Soil mycorrhizal fungi act through chemical interactions at nanometer scale to dissolve minerals, and transport weathering products to plant symbionts through metre scale mycelial networks at diurnal timescales [1]. Biologically-mediated soil development occurs at regional scale over millenia (ka) and coupling between ecological, geological and atmospheric systems is apparent over evolutionary (Ma) timescales [2]. Our hypothesis is that quantification of biologically-driven weathering reactions at molecular scale provides a basis for new conceptual approaches to processes such as soil formation and atmospheric CO_2 evolution that occur over much larger temporal and spatial scales.

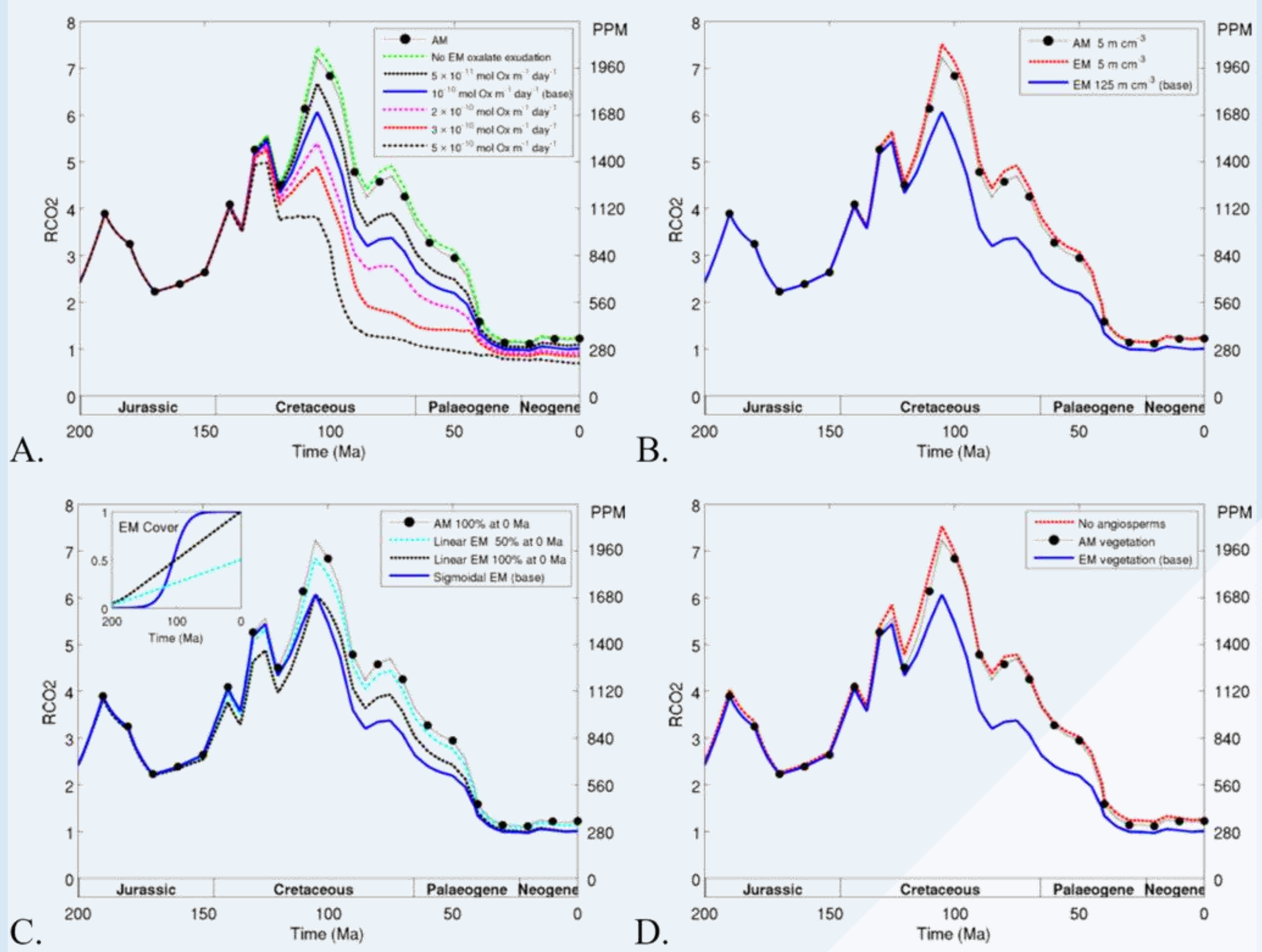
To test this we have applied an integrated suite of observations at scales from nanometre to decimetre using common minerals, fungi and physical and chemical conditions. Our experiment results demonstrate that fungal hyphae-grain contact leads directly to mass loss from mineral grains over time [3,4]. Cell exudates and nanoscale cell-mineral interaction forces progressively modify mineral surfaces and alter the pore microenvironment, conditioning subsequent biotic and abiotic weathering mechanisms. Crucially, these processes are directed by mycorrhiza towards minerals which yield the best nutrient supply for plants [1,4].

Here, we describe the development of mathematical models for key nano-scale weathering processes coupled to stochastic, agent-based simulations of hyphal growth at the nm to cm scales which permit quantitative analysis of the dynamic interactions between plant carbon energy supply and soil mineral weathering rates, mediated by mycorrhizal fungi. This conceptualisation of soil profile weathering is transferred to global scale models by aggregating soil profile descriptions at continental scale [2,5]. The resulting global models thus reflect processes that are transferred from both the nanometer and soil profile scale as constraints on global weathering and its mathematical description.

Influence of EM fungi on the geochemical carbon cycle

Identification of fungi growth and mineral weathering rates at nano- to plant scale provides input to a process-based soil chemistry module integrated within the GEOCARBSULF carbon cycle model (Taylor *et al.*, in review).

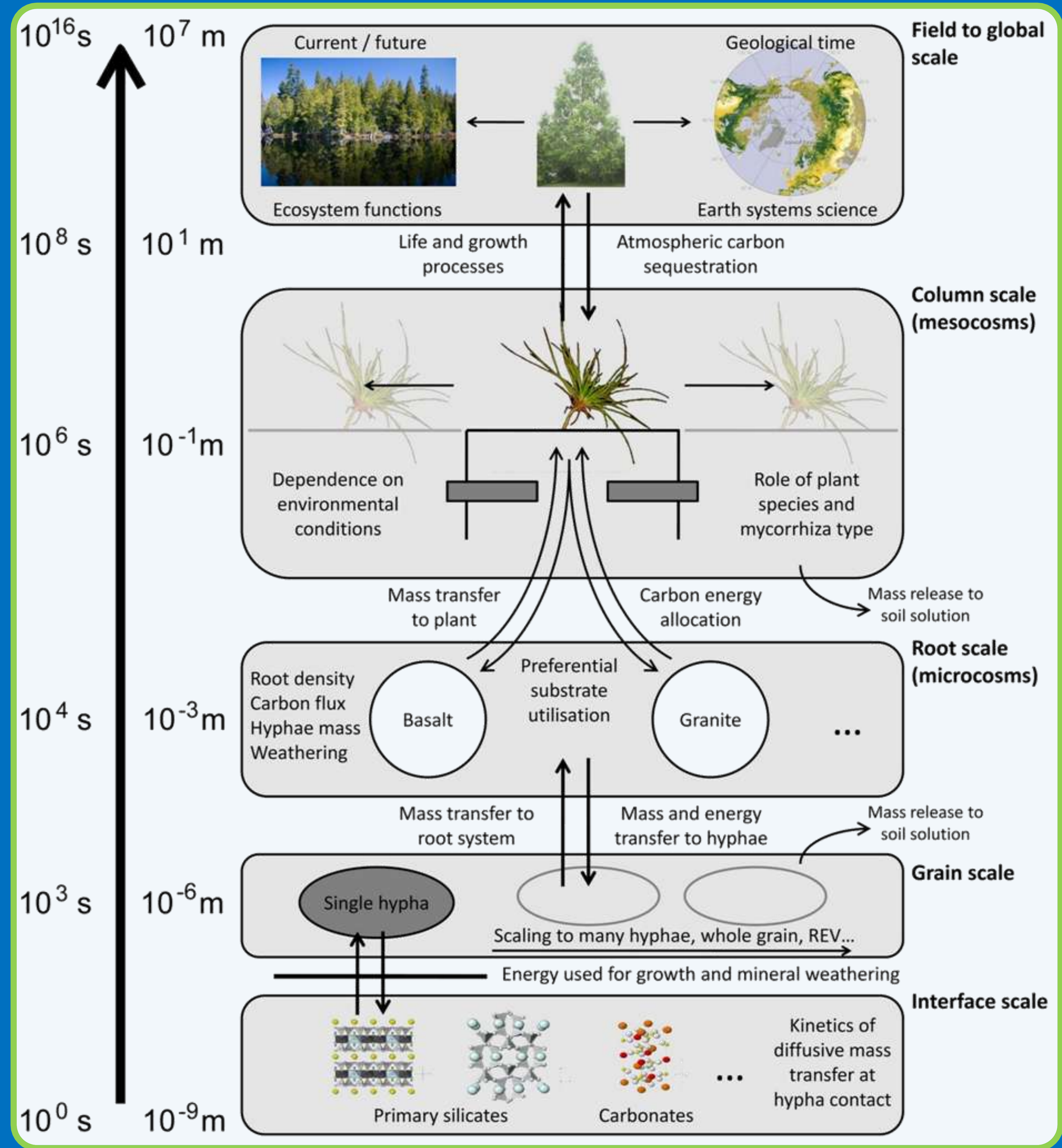
Work to date suggests that the evolution of ectomycorrhizal fungi and tree symbionts accounts for the CO_2 reduction in the last 120 Ma that was previously attributed to angiosperm expansion.



Sensitivity of atmospheric CO_2 to **(A)** rate of EM hyphae oxalate exudation; **(B)** EM length density in soil; **(C)** percentage of EM vegetation in weathering hotspots. **(D)** Comparison of model results (blue) with a 'vegetation-free' GEOCARBSULF output (red)

GLOBAL

Conceptual model: from nanoscale weathering to global scale systems



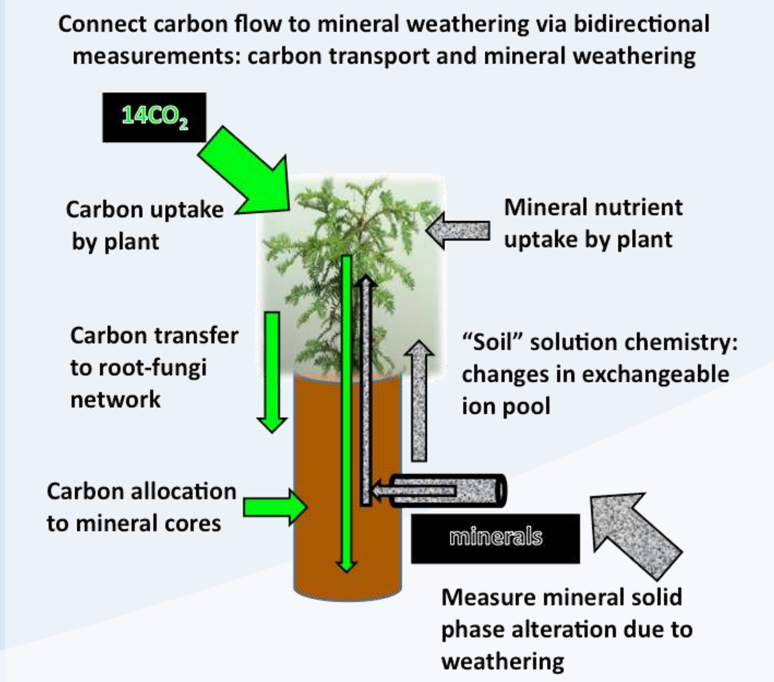
Millimetre → metre scale

Figures courtesy of Megan Andrews

Plant-free control

Sequoia

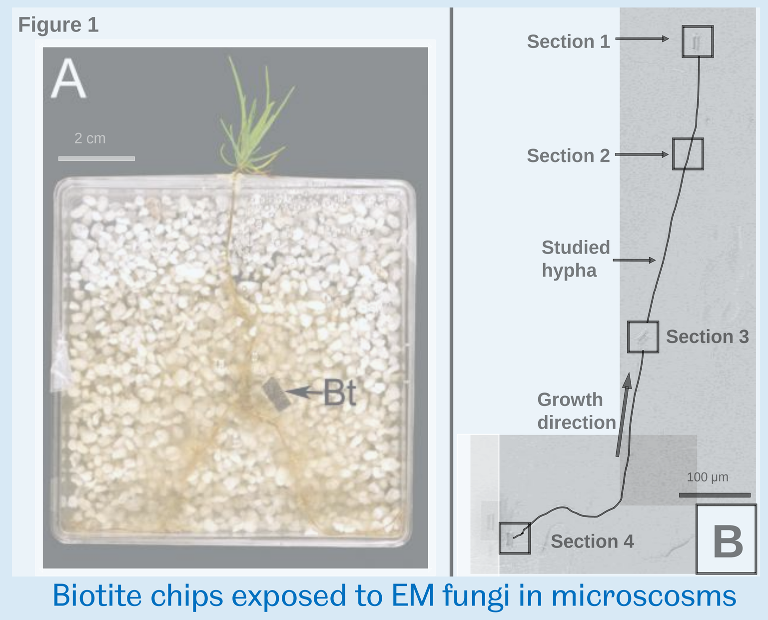
Pine



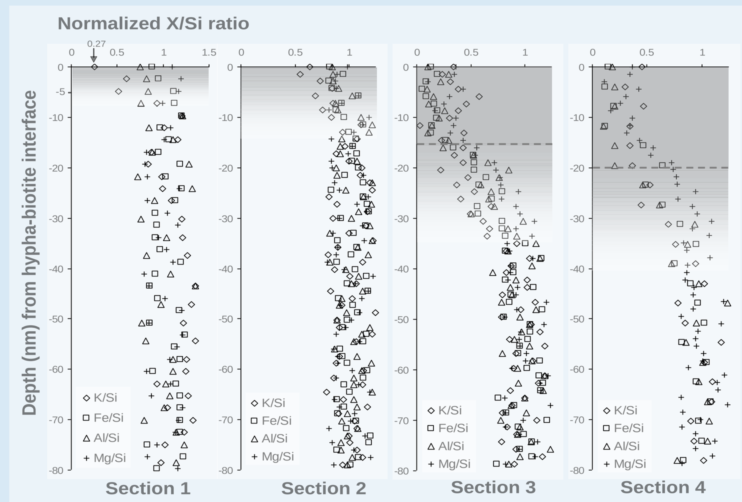
Model predictions compared with mineral weathering data coupled to plant-scale carbon drawdown in mesocosm expts.

Mineral weathering at hyphae interfaces

NANO



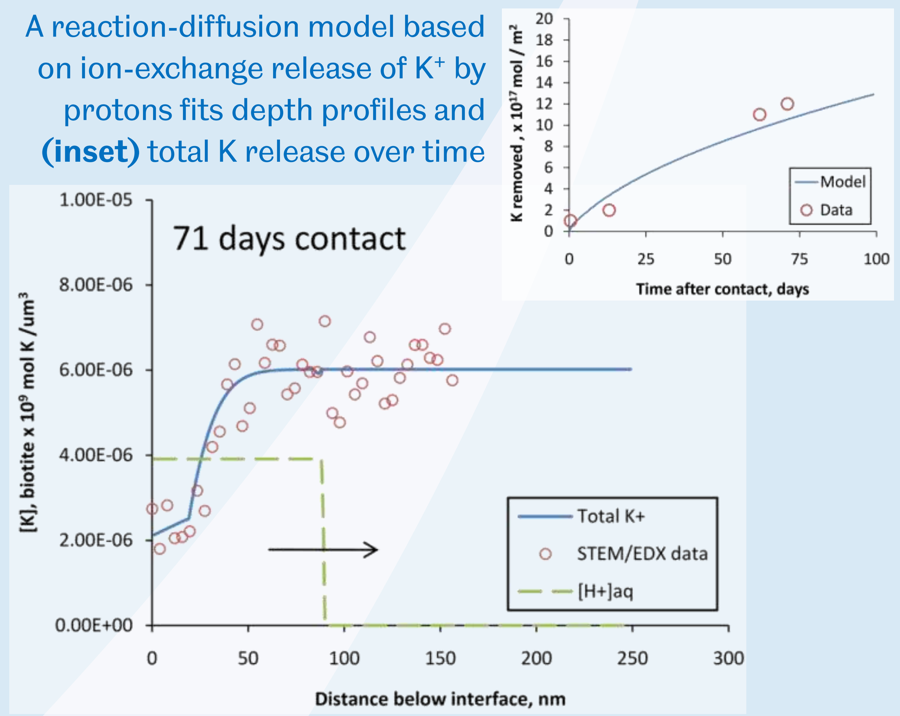
Biotite chips exposed to EM fungi in microscosms **(A)** sectioned by FIB **(B)**. STEM/EDX depth profiles



Bonneville *et al.*, submitted to Geochim. et Cosmochim. Acta

- Minerals incubated in controlled microcosms with *Pinus sylvestris – Paxillus involutus* (3-6 months)
- Single hypha on biotite identified and sectioned to analyse sub-interface mineral composition profiles
- Removal of K, Al, Mg, Fe over 72 day contact time
- Model fits data by diffusion-controlled hydrated layer formation and release of ions from lattice
- **Significant new dry soil weathering process**

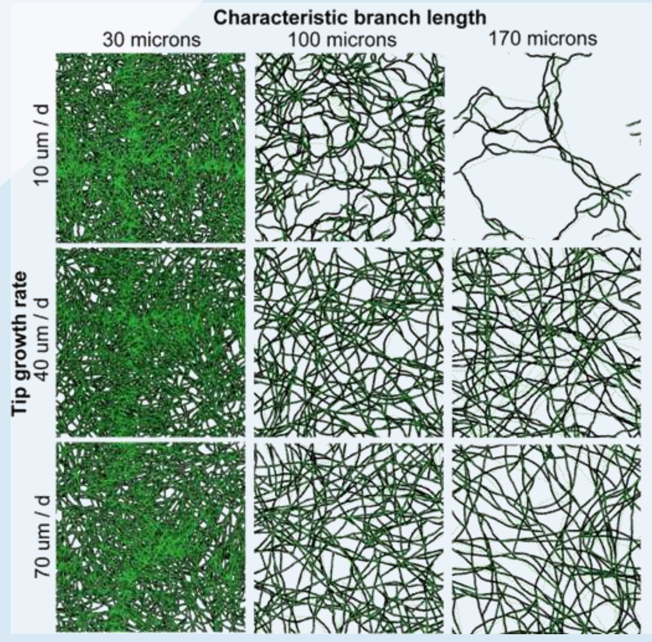
A reaction-diffusion model based on ion-exchange release of K⁺ by protons fits depth profiles and **(inset)** total K release over time



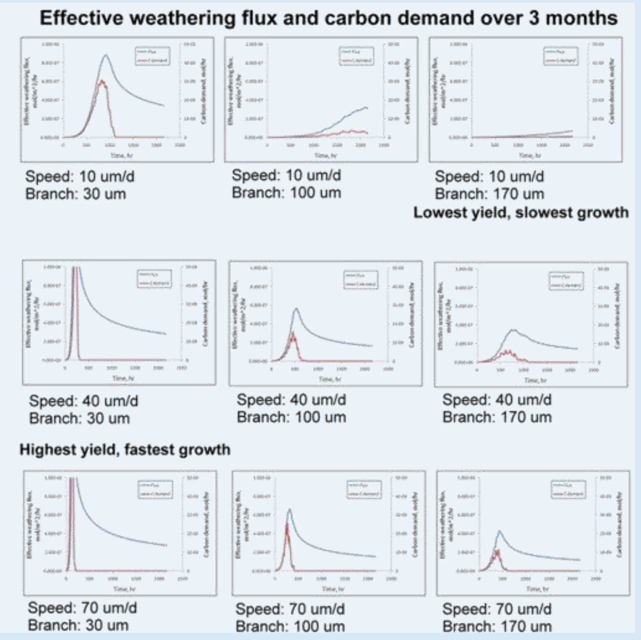
Stochastic modelling of hyphae growth: sub-mm scale

- Weathering rates measured at single hyphae are summed together to predict rates for whole mycelium growing across a mineral
- An agent-based model is used to translate hypha-scale data to weathering and carbon demand as a function of time at 'grain' scale
- Rules for how hyphae move, weather, branch
- Growth and branching rates control coverage
- Weathering flux and carbon demand strongly nonlinear in time as colonized area increases
- Total weathering flux ∝ total carbon demand
- **Efficiency of weathering not constant – maximum at high growth, low branching**
- Possible mechanism for growth regulation

Simulated hyphal coverage after 2160 timesteps (simulating 3 months' growth) as a function of tip growth rate and branching frequency with unlimited carbon supply. Domain is 0.5 x 0.5 mm.



Resulting predicted variations in model weathering flux (blue) and carbon demand (red) over 3 months simulated growth.



References and Acknowledgements

[1] Leake et al. (2008) Mineral. Mag. 72, 85–89. **[2]** Taylor et al. (2009) Geobiology 7, 171–191. **[3]** Bonneville (2009) Geology 37, 615–618. **[4]** Schmalenberger et al. (2009). Geochim. Cosmochim. Acta, 73(13), A1177. **[5]** Banwart et al. (2009). Geochim. Cosmochim. Acta, 73(13), A84.

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