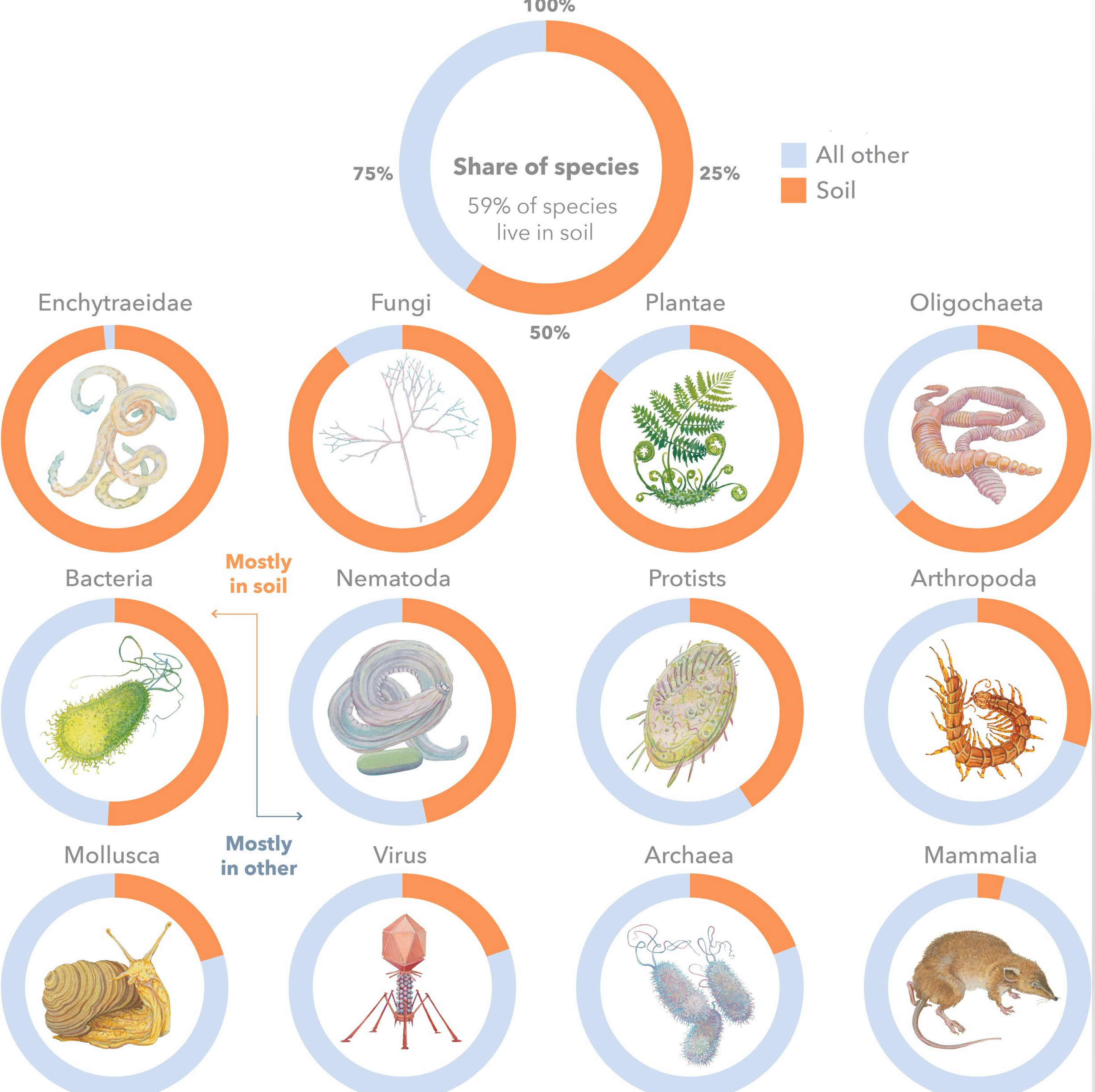
What if we managed forests to sustain soil life?

Cindy Prescott
University of British Columbia

cindy.prescott@ubc.ca



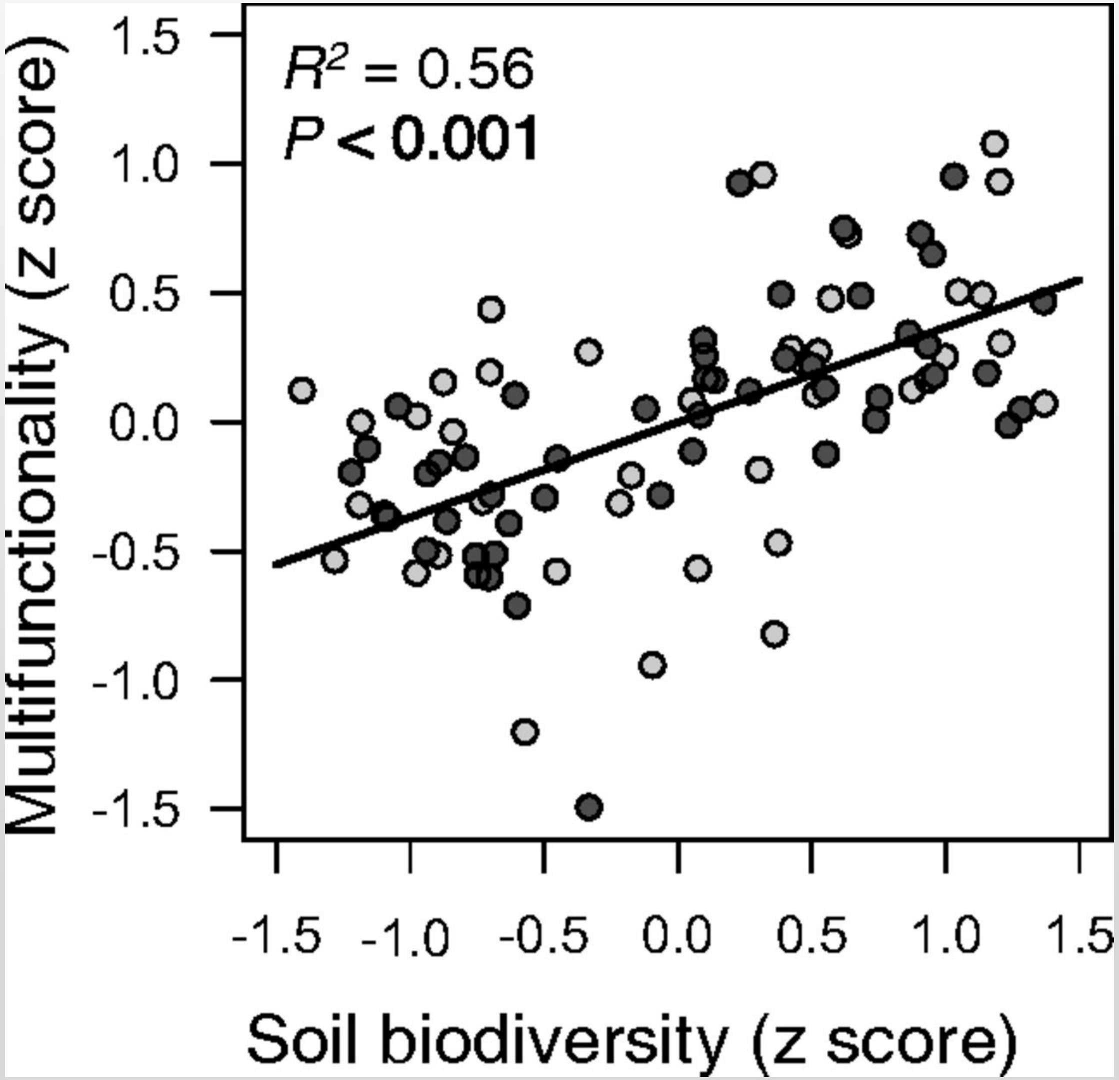
Soil is home to more than half of all life:

About 59% of all species on Earth live in soil.

Soil is the planet’s single most biodiverse habitat.
Soil is home to:

- 99% of enchytraeidae worms,
- 90% of fungi,
- 86% of plants and
- >50% of bacteria

Anthony et al. 2023
www.pnas.org/doi/10.1073/pnas.2304663120



Soil biodiversity drives ecosystem function

Soil biodiversity is responsible for multiple ecosystem functions, including plant diversity, decomposition, nutrient retention, and nutrient cycling.

All measured ecosystem functions exhibited a strong positive linear relationship to indicators of soil biodiversity, suggesting that soil community composition is a key factor in regulating ecosystem functioning.

Wagg et al 2014 Soil biodiversity and soil community composition determine ecosystem multifunctionality PNAS https://doi.org/10.1073/pnas.1320054111

How would we manage forests if our primary goal was to promote soil life?

major life forms found in soil
https://www.pnas.org/doi/10.1073/pnas.2304663120

Manage the flux of labile C from leaves to roots and soil

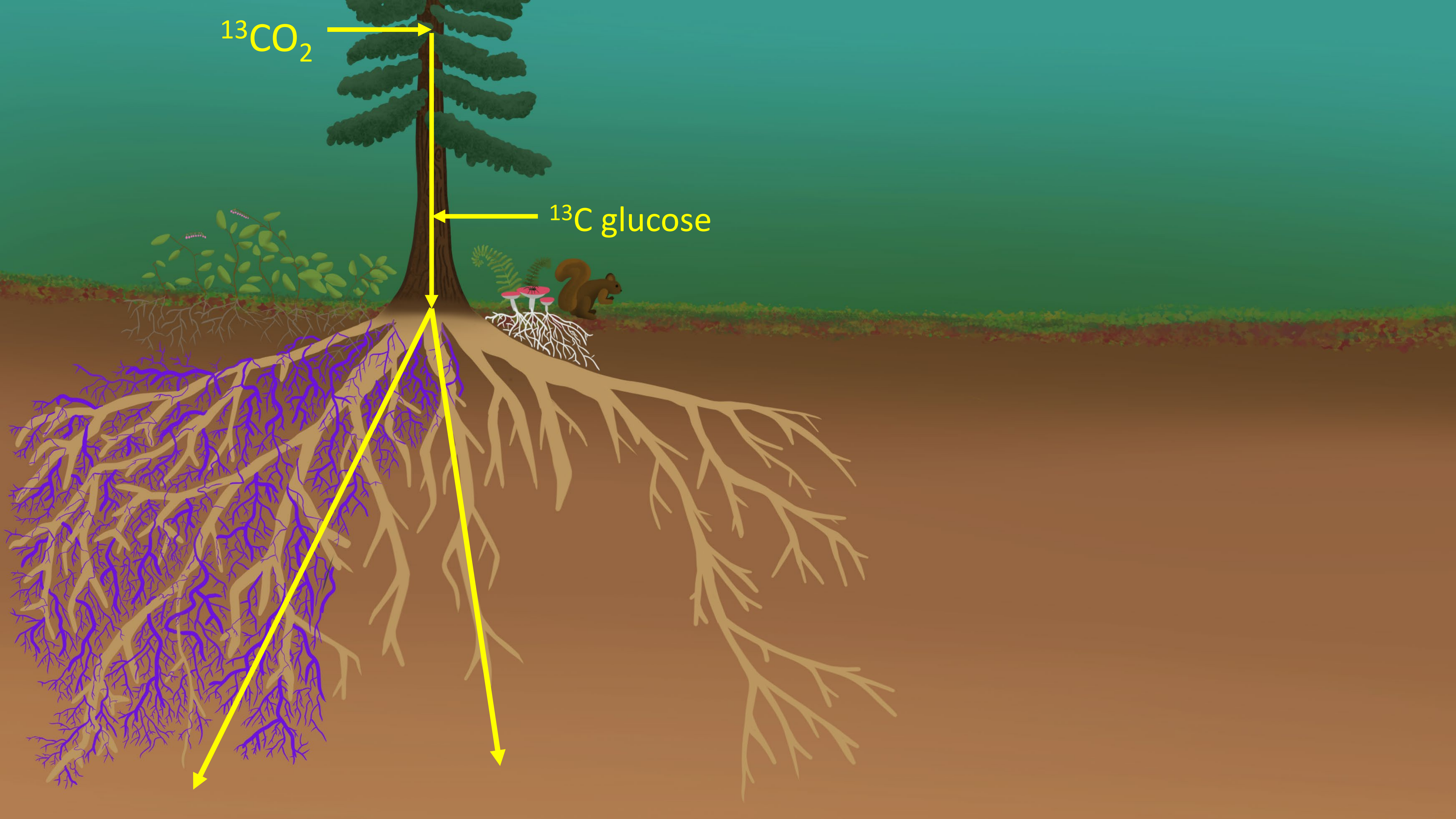
Stripped the stem bark to terminate the supply of current photosynthates to roots and their mycorrhizal fungi.

Soil respiration decreased by up to 37% **within 5 days**.

Girdling reduced soil respiration by about **54%** relative to respiration on ungirdled control plots within 1-2 months.

Half of the biological activity in a boreal forest soil is fueled by C that was fixed through photosynthesis a few days earlier.

Högberg et al 2001. Large-scale forest girdling shows that current photosynthesis drives soil respiration. Nature 411:789-92.


$^{13}CO_2$
^{13}C glucose

Carbon-labeling experiments

Labelled photosynthate with the stable isotope ^{13}C

Tracer levels peaked after 24 hours in soluble carbohydrates in the phloem in the stem,
and after 2–4 days in soil respiration and **soil microbial cytoplasm**.

Högberg et al 2008. High temporal resolution tracing of photosynthate carbon from the tree canopy to forest soil microorganisms. New Phytologist, 177: 220-228.

^{13}C tracer pulse-chase experiment in a boreal 14-yr-old Scots pine forest

Labelled C from canopies transferred to soil within 2–4 days following photosynthetic C fixation.

Labelled C was primarily found in **ectomycorrhizal fungi**.

Collembola became labelled within days.

Collembola selectively graze highly active mycorrhizal mycelium – sink for recent photosynthate.

Högberg M et al 2010. Quantification of effects of season and nitrogen supply on tree below-ground carbon transfer to ectomycorrhizal fungi and other soil organisms in a boreal pine forest. New Phytologist 187: 485-493.

^{13}C tracer pulse-chase experiment in a boreal 14-yr-old Scots pine forest

Flux was 500% higher in August than in June

Addition of N caused a 60% reduction of below-ground C allocation to soil biota after 1 year

Högberg M et al 2010. Quantification of effects of season and nitrogen supply on tree below-ground carbon transfer to ectomycorrhizal fungi and other soil organisms in a boreal pine forest. New Phytologist 187: 485-493.

Tracing carbon from trees into soil organisms

Stem-injected Sitka spruce trees with ^{13}C-labelled glucose

Soil DOC peaked days 2-6

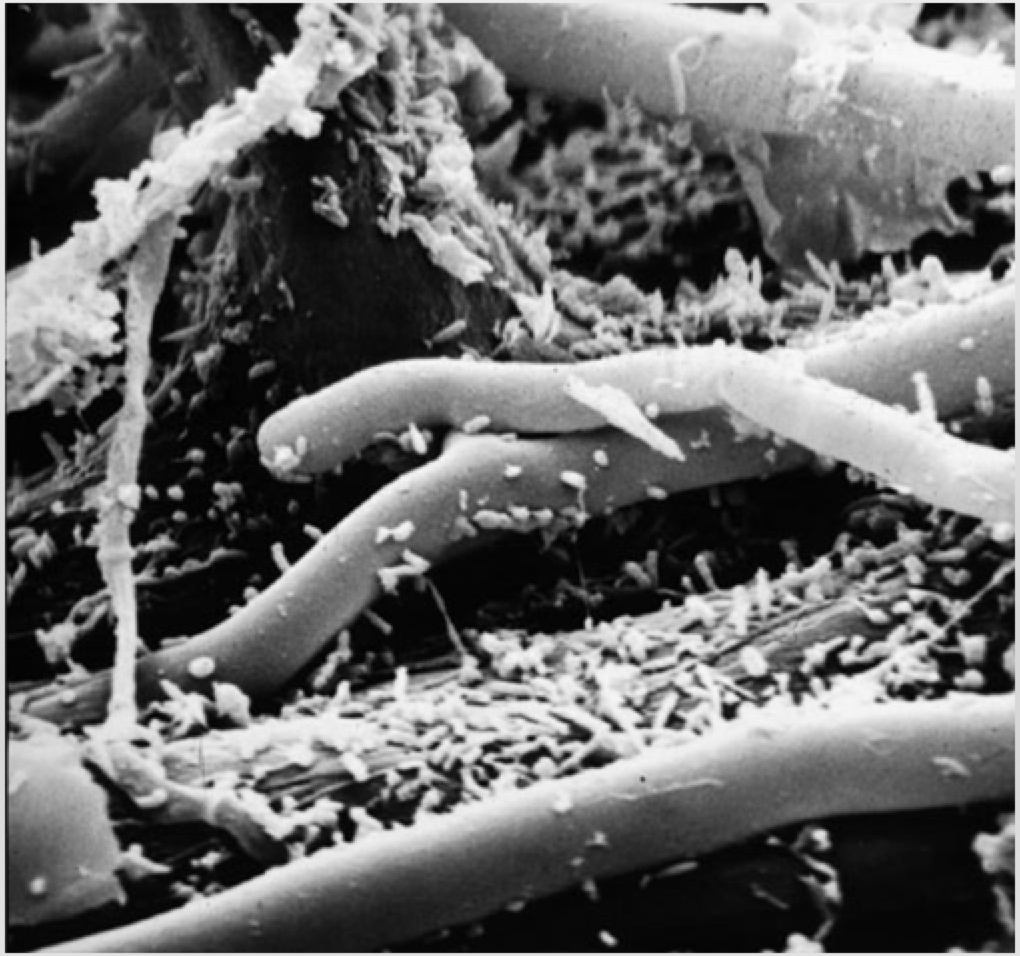
Soil microbes peaked days 2-4

Mites, enchytraeids peaked days 4-6

Churchland et al 2012. Rapid Comm in Mass Spec 26: 2493-2501.

Rapid transfer of plant photosynthates to soil bacteria via ectomycorrhizal hyphae

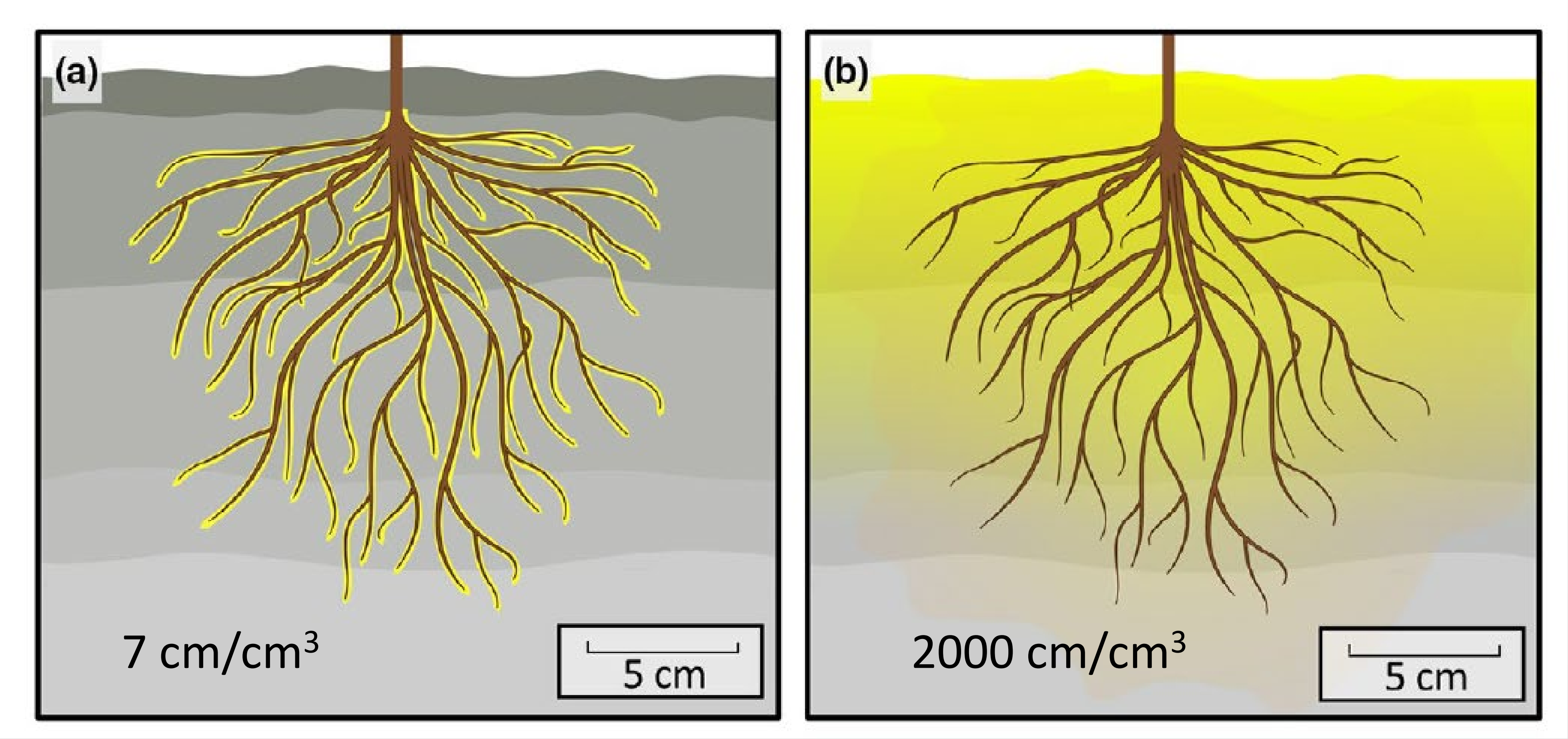
Gorka et al 2019.
Rapid transfer of plant photosynthates to soil bacteria via ectomycorrhizal hyphae and its interaction with nitrogen availability.
Frontiers in Microbiology
https://doi.org/10.3389/fmicb.2019.00168



Bacteria on the surface of strands of fungal hyphae.

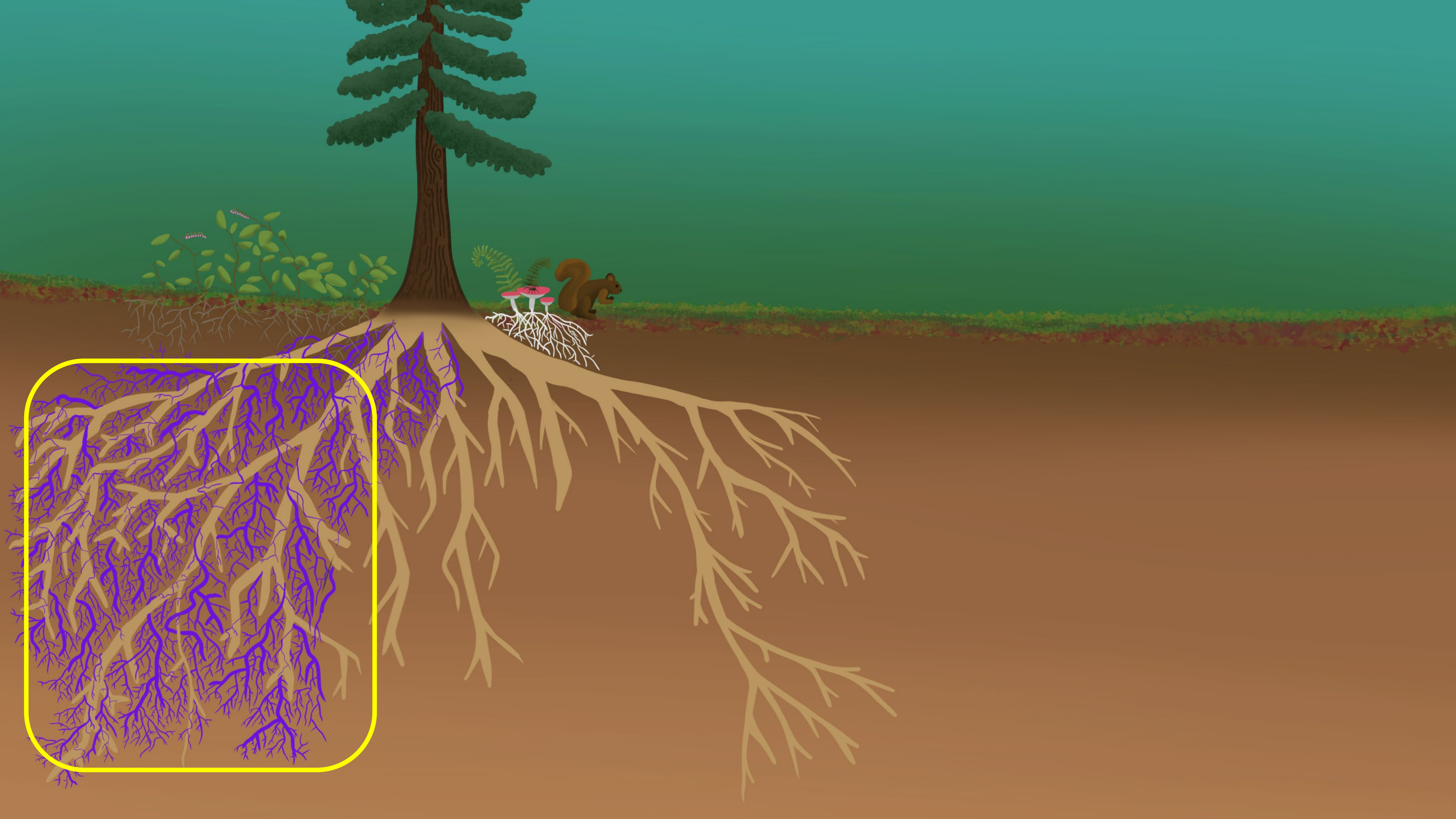
https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/health/biology/?cid=nrcs142p2_053862

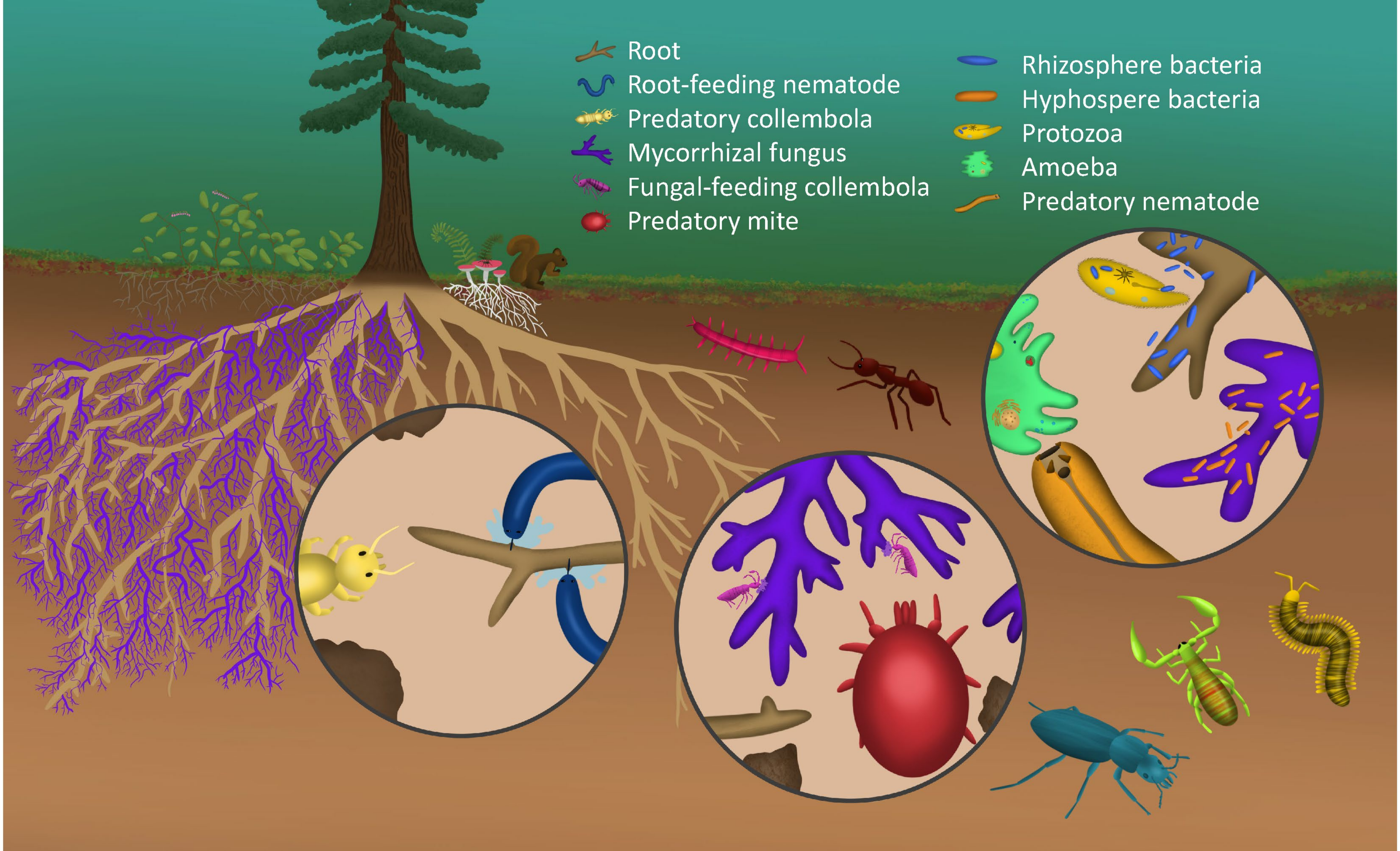
Rhizosphere Hyphosphere



Spatial extent of the rhizosphere (in yellow, panel a), and the hyphosphere (in yellow, panel b).

See et al 2022. Hyphae move matter and microbes to mineral microsites: Integrating the hyphosphere into conceptual models of soil organic matter stabilization. Global Change Biology [*https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.16073*](https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.16073)

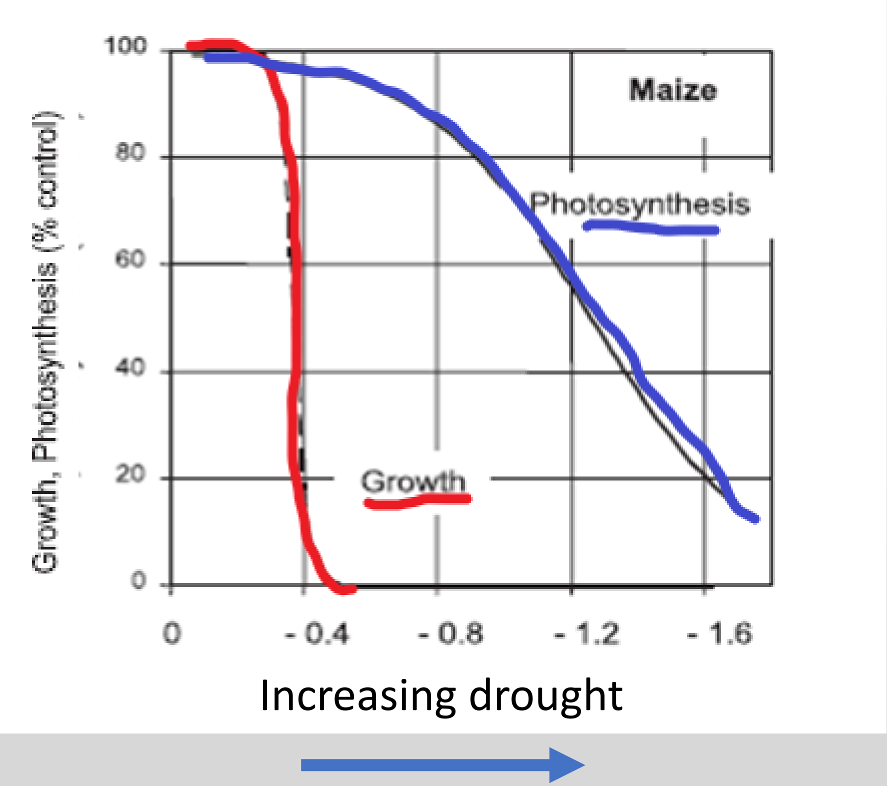




Root
Root-feeding nematode
Predatory collembola
Mycorrhizal fungus
Fungal-feeding collembola
Predatory mite
Rhizosphere bacteria
Hyphospere bacteria
Protozoa
Amoeba
Predatory nematode

Why?

As nutrients or water become deficient, leaf growth declines before photosynthesis declines



Muller et al 2011 Water deficits uncouple growth from photosynthesis, increase C content, and modify the relationships between C and growth in sink organs. Journal of Experimental Botany 62, 1715–1729 doi:10.1093/jxb/erq438

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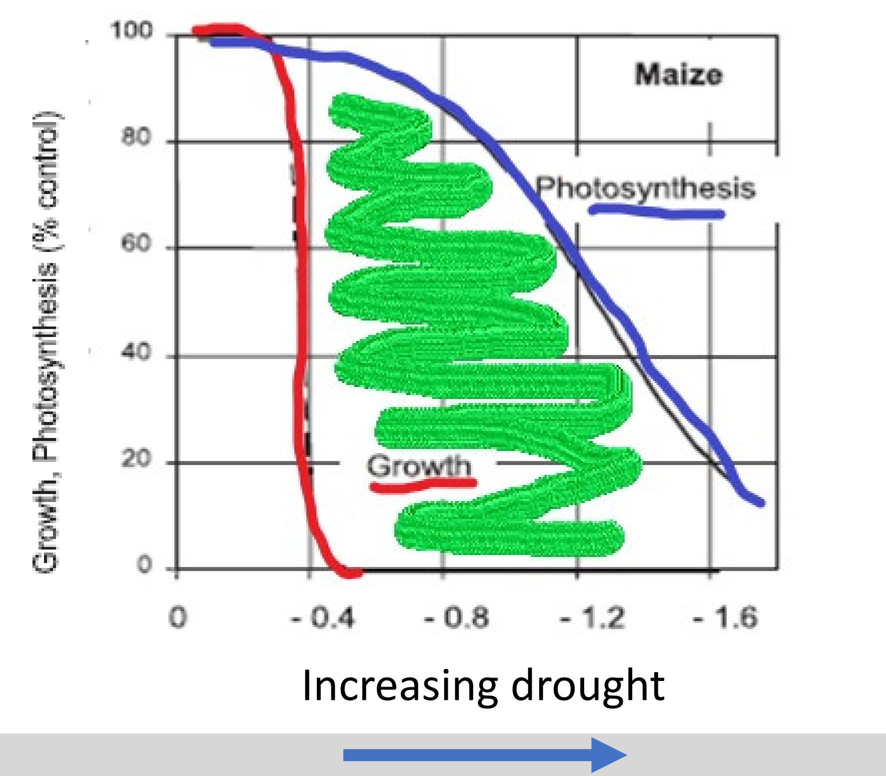
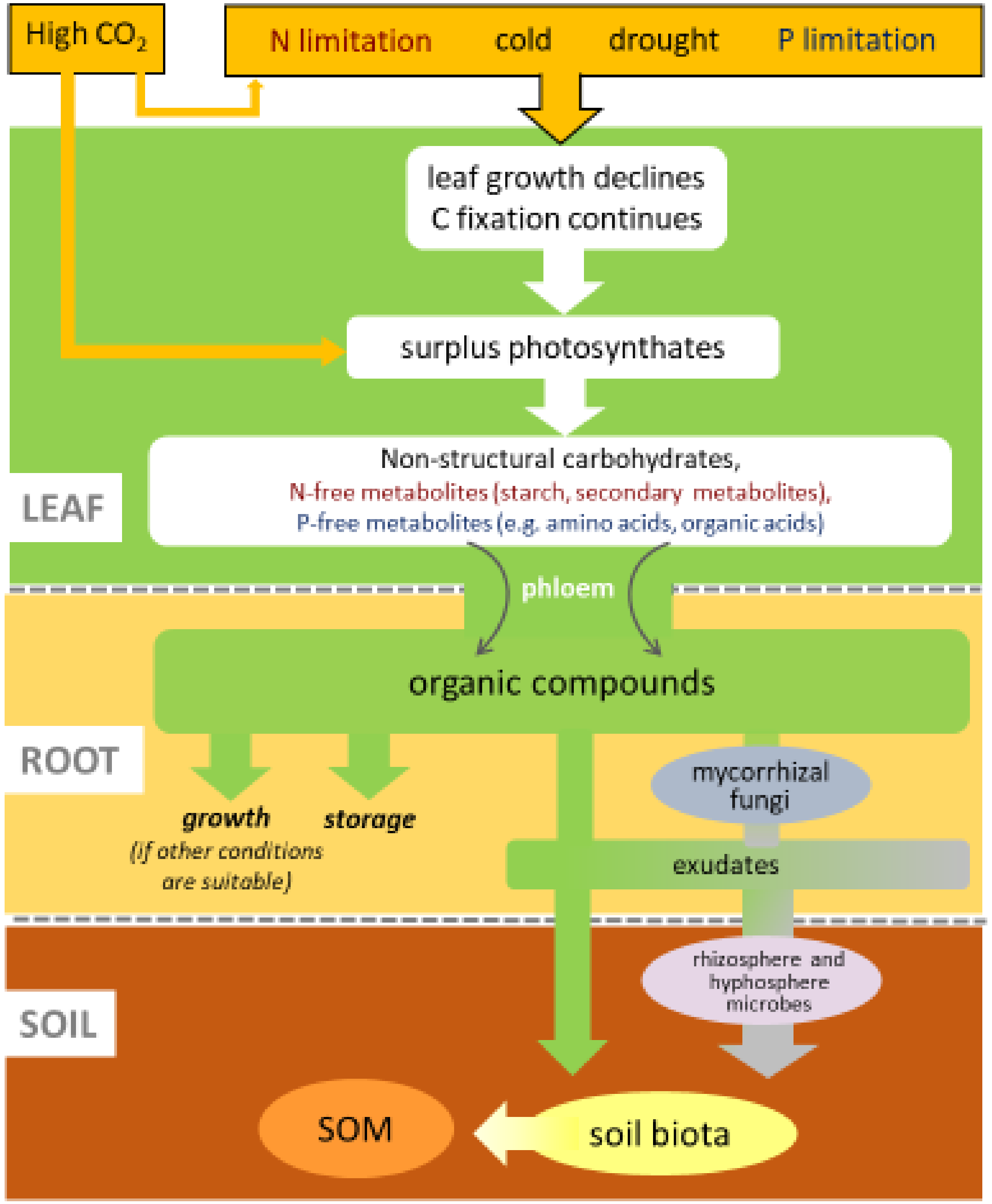


During this stage of deficiency, surplus photosynthate is transported from leaves to active sinks elsewhere in the plant

The Surplus Carbon Hypothesis

Under common environmental conditions plant leaf cells produce more photo-assimilates than they are able to use for primary metabolism and growth, and so have ‘surplus carbon’

Such conditions include: moderate deficiencies of water, nitrogen or phosphorus, high light, low temperatures, or elevated atmospheric carbon dioxide concentrations



The Surplus Carbon Hypothesis

Prescott et al. 2020. Surplus carbon drives allocation and plant–soil interactions.
Trends in Ecology and Evolution
https://doi.org/10.1016/j.tree.2020.08.007

More photosynthate is sent belowground when leaf growth is constrained by deficiency of water or nutrients

- also following full leaf expansion

Prescott et al (2020). Surplus carbon drives allocation and plant–soil interactions.

Trends in Ecology and Evolution 35, 1110-1118

How can we manage forests to maintain the flux of labile C from trees to the belowground ecosystem?

Continuous Root Forestry

Influence of living roots extends < 10 m from stem

Minimize the area of a cutover that is more than 10 m from a living tree stem

Aggregated Retention

“clearcut with reserves”

Prescott & Grayston 2023. Continuous root forestry—Living roots sustain the belowground ecosystem and soil carbon in managed forests. Forest Ecology & Management 532: 120848

Dispersed retention
40 trees /ha
15 m between stems

Principle 2. Reduce inputs

Principle 2. Reduce inputs

Ecologically intelligent nutrient management

1. Optimal fertilization
2. Nitrogen-fixing species

Conventional fertilization

Increase foliar N
Increase photosynthesis
Increase leaf area
Increase aboveground biomass

control

fertilized

Conventional fertilization

Increase foliar N
Increase photosynthesis
Increase leaf area
Increase aboveground biomass

Belowground?


control


fertilized

Reduced fine root biomass

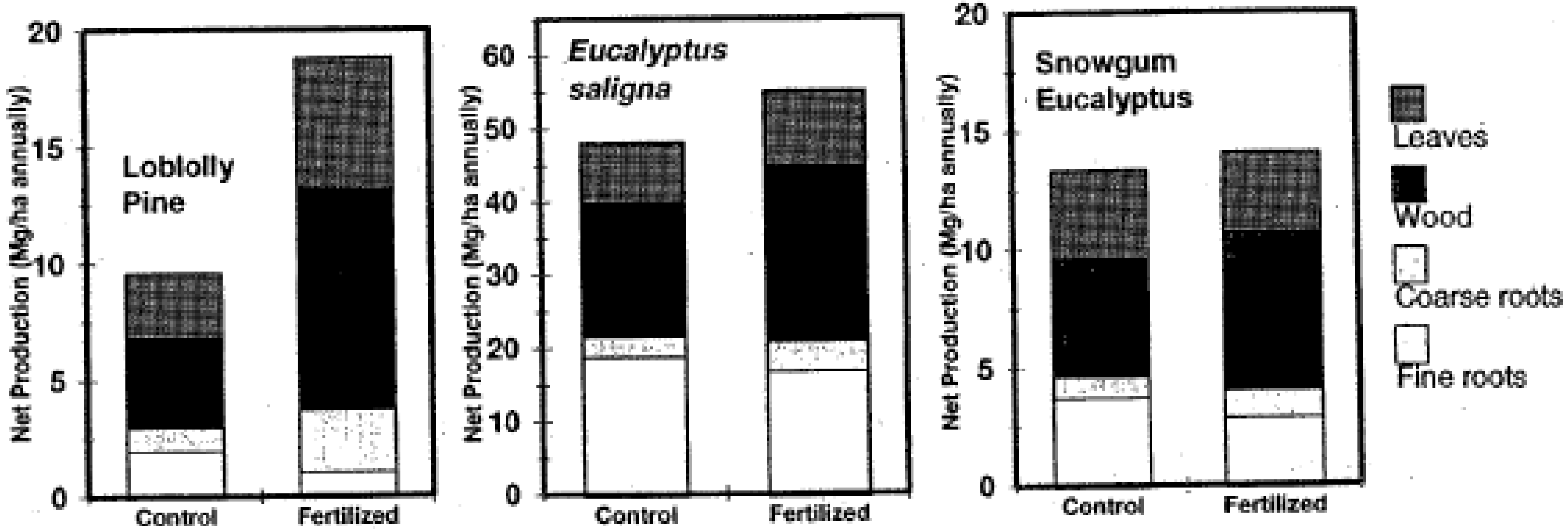
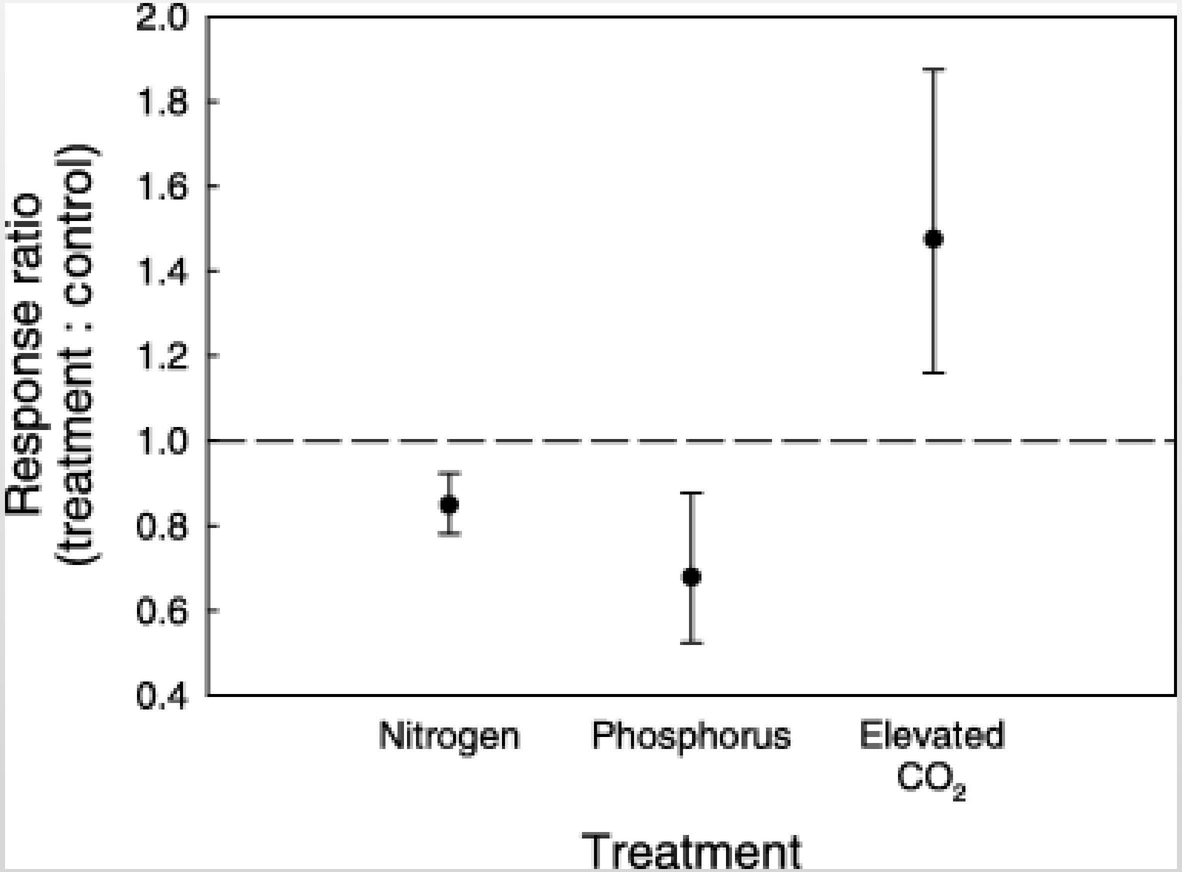


Figure 13.3 Fertilization of loblolly pine in North Carolina (470 kg/ha of nitrogen, 135 kg/ha of phosphorus, 275 kg/ha of potassium) doubled net primary production, and wood production was 2.4 times the control value (Albaugh et al., 1998). Fertilization of *Eucalyptus saligna* in Hawaii (390 kg/ha of nitrogen, 170 kg/ha of phosphorus, 455 kg/ha of calcium, 60 kg/ha of potassium) increased wood growth by increasing total production and decreasing root production (M. Ryan, D. Binkley, and J. Fownes, unpublished data). Fertilization of snowgum (500 kg/ha of phosphorus, no nitrogen added) increased net primary production by just 6 percent and wood production by 30 percent (Keith et al., 1997). In all three cases, the relative and absolute allocation to fine root production declined, contributing to the increased production of wood.

Binkley 1986

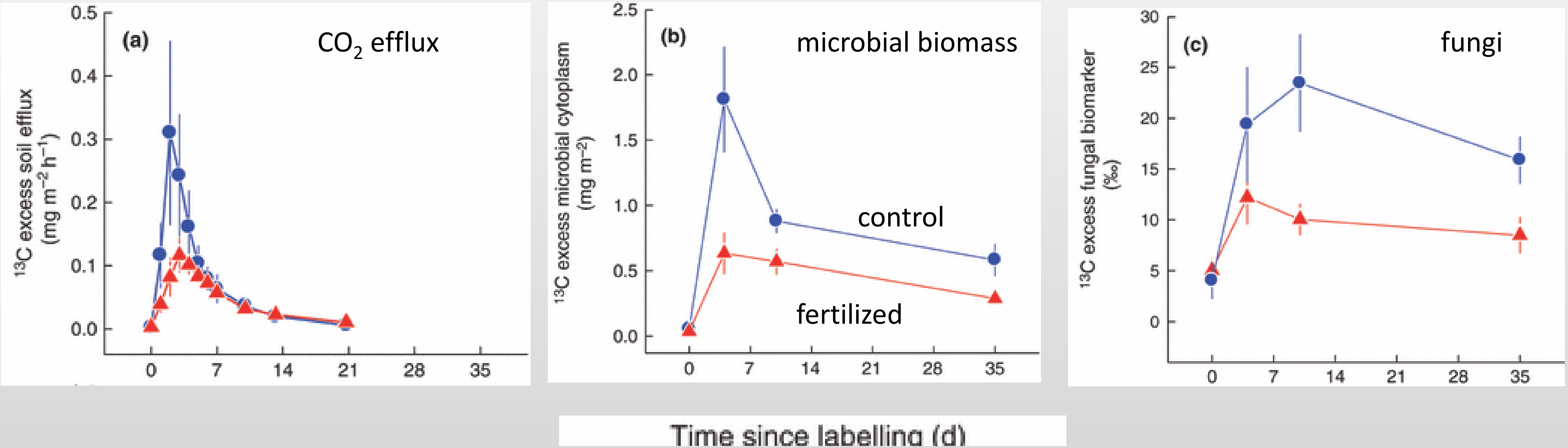
Reduced mycorrhizal abundance



Treseder 2004. A meta-analysis of mycorrhizal responses to nitrogen, phosphorus, and atmospheric CO2 in field studies. https://doi.org/10.1111/j.1469-8137.2004.01159.x

Responses of mycorrhizal fungi to nitrogen fertilization, phosphorus fertilization, and elevated CO_2 in field studies. A response ratio > 1 indicates an increase in abundance relative to the control, and < 1 indicates a decrease. Responses were significant.

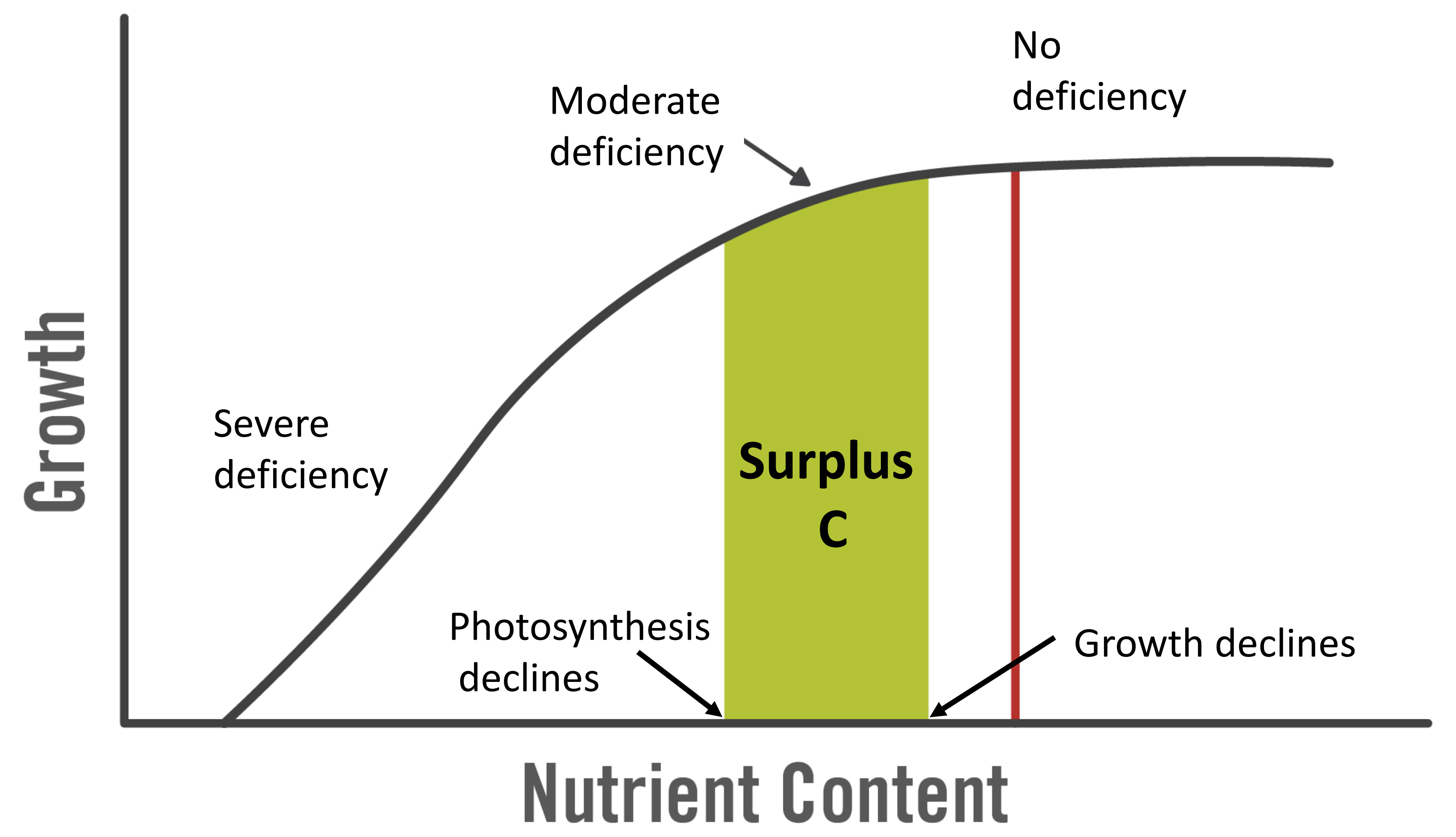
Reduced soil microbial biomass and activity



Effects of added N on tree below-ground allocation of labelled 13C. (a) Soil respiratory efflux (b) Soil microbial cytoplasm (c) fungal fatty acid biomarker phospholipid fatty acid (PLFA) 18:2ω6,9.

Hogberg et al 2010. Quantification of effects of season and nitrogen supply on tree below-ground carbon transfer to ectomycorrhizal fungi and other soil organisms in a boreal pine forest. New Phytologist 187: 485-493.

Optimize fertilization to encourage aboveground growth while maintaining C flux belowground



Prescott, CE, Rui, Y, Cotrufo, F, Grayston, SJ 2021. Managing plant surplus carbon to generate soil organic matter in regenerative agriculture. Journal of Soil and Water Conservation 76(6):99A-104A

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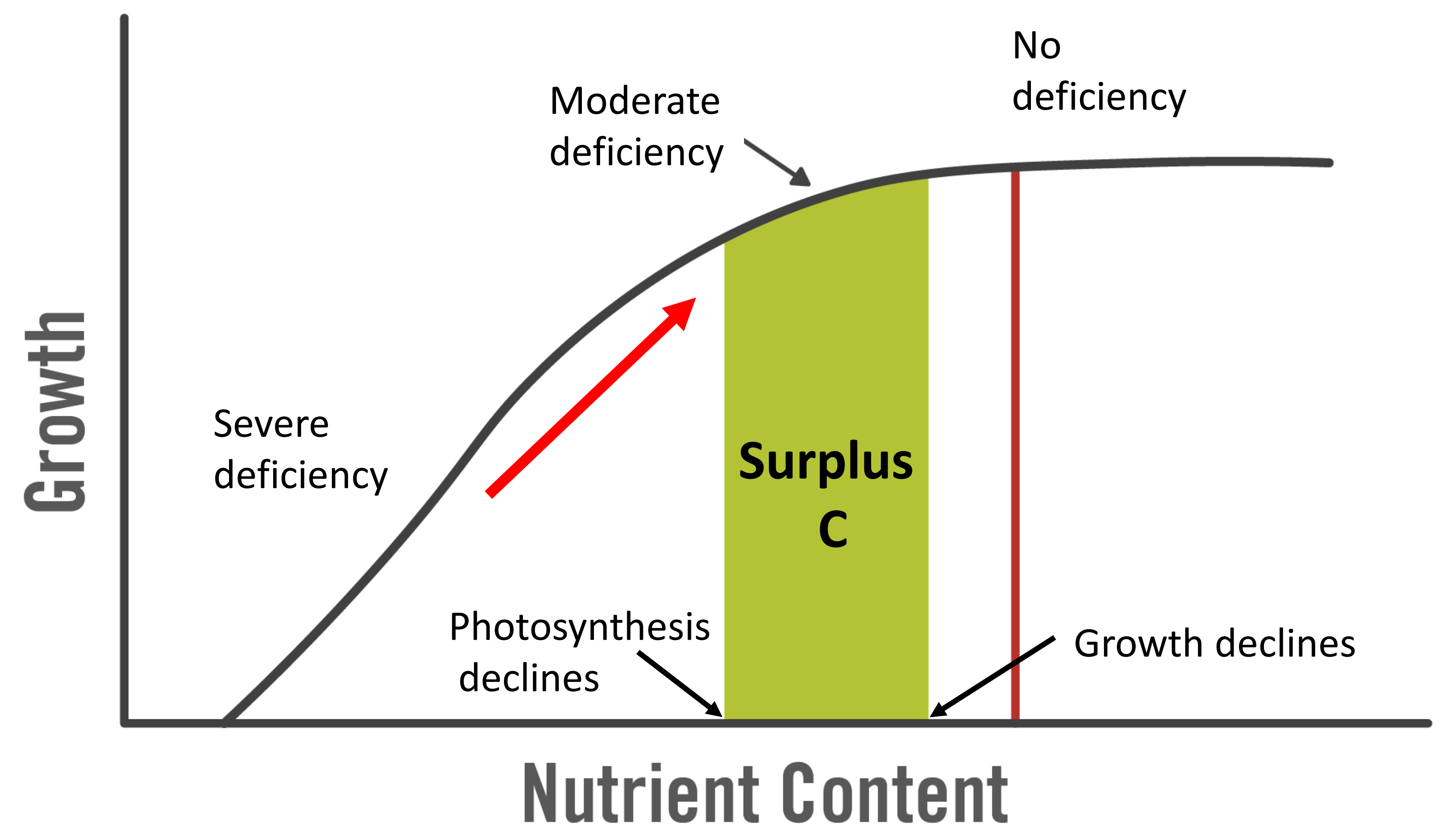

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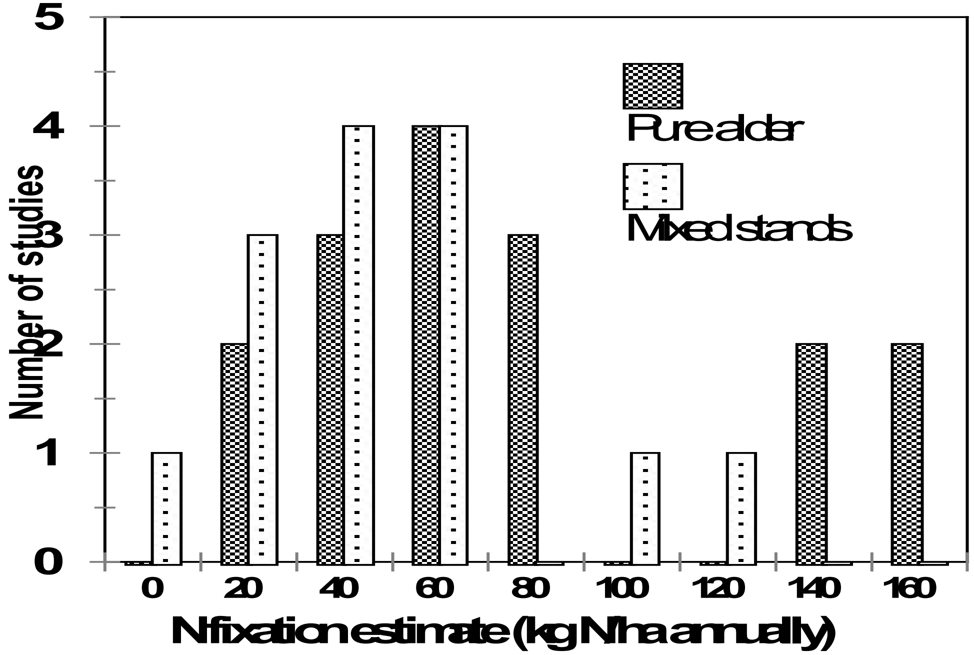
Principle 2. Reduce inputs

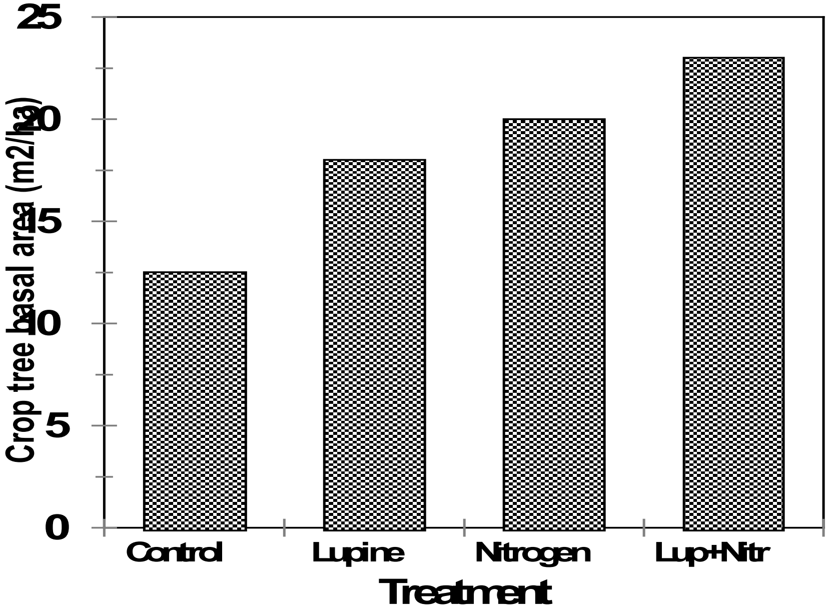
Ecologically intelligent nutrient management

1. Optimal fertilization
2. **Nitrogen-fixing species**

N-fixing plants can add significant amounts of N per year and increase productivity of crop trees



Estimates of nitrogen fixation rates for red alder in the northwestern US and BC using a variety of methods on a wide range of sites (from Binkley et al., 1994).



Basal area accumulation of radiata pine in New Zealand in relation to addition of lupines, nitrogen fertilizer, or both (from Gadgil, 1983).

- also increase soil C stocks

Fisher and Binkley 2000

N-fixing species build soil organic matter faster than other species

Root exudates from N-fixing plants have higher concentrations of N-rich

The release of compounds rich in both C and N stimulates SOM production

N-fixing trees have high stocks of soil organic matter, C and N, and build these stocks faster than other species.

Planting red alder on a site formerly occupied by Douglas-fir increased soil C content by 27% in only 7 years (Cole et al., 1995).

Nitrogen-fixing species – rapid growth

- 5 years of alder enough to increase SOM and N
- especially important following fire
- best in mixture with conifers

Bangor Rhizotron:

Biomass of alder vs other species at 5 months

Ribbons et al 2022. Roots and rhizospheric soil microbial community responses to tree species mixtures. Applied Soil Ecology https://doi.org/10.1016/j.apsoil.2022.104509

Principle 3: Encourage diversity

Soil biodiversity increases most in mixtures that contain plant species that are phylogenetically and functionally distinct.

Milcu et al. 2013. Functionally and phylogenetically diverse plant communities key to soil biota. Ecology, 94, 1878–1885. http://www.jstor.org/stable/23596990 (Jena)

Peng et al. 2022. Litter quality, mycorrhizal association, and soil properties regulate effects of tree species on the soil fauna community. Geoderma, 407, 115570, https://doi.org/10.1016/j.geoderma.2021.115570

High plant diversity = high soil microbial diversity

- linked to higher root exudate diversity
- adding diverse exudate cocktails like those in plant-diverse plots resulted in diverse soil microbial communities

Steinauer et al. 2016 Root exudate cocktails: the link between plant diversity and soil microorganisms?
https://doi.org/10.1002/ece3.2454

Include broadleaves

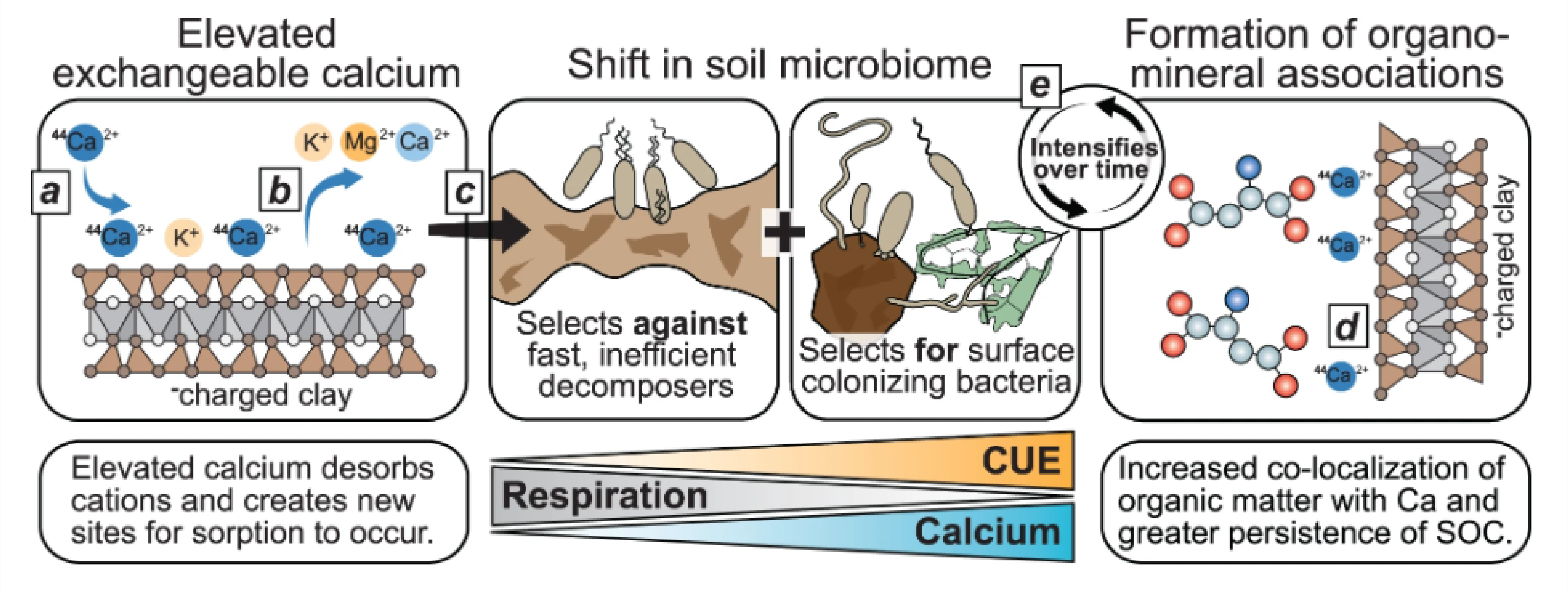
‘soil improvers’

change soil biota & humus form

increase organic matter in mineral soil

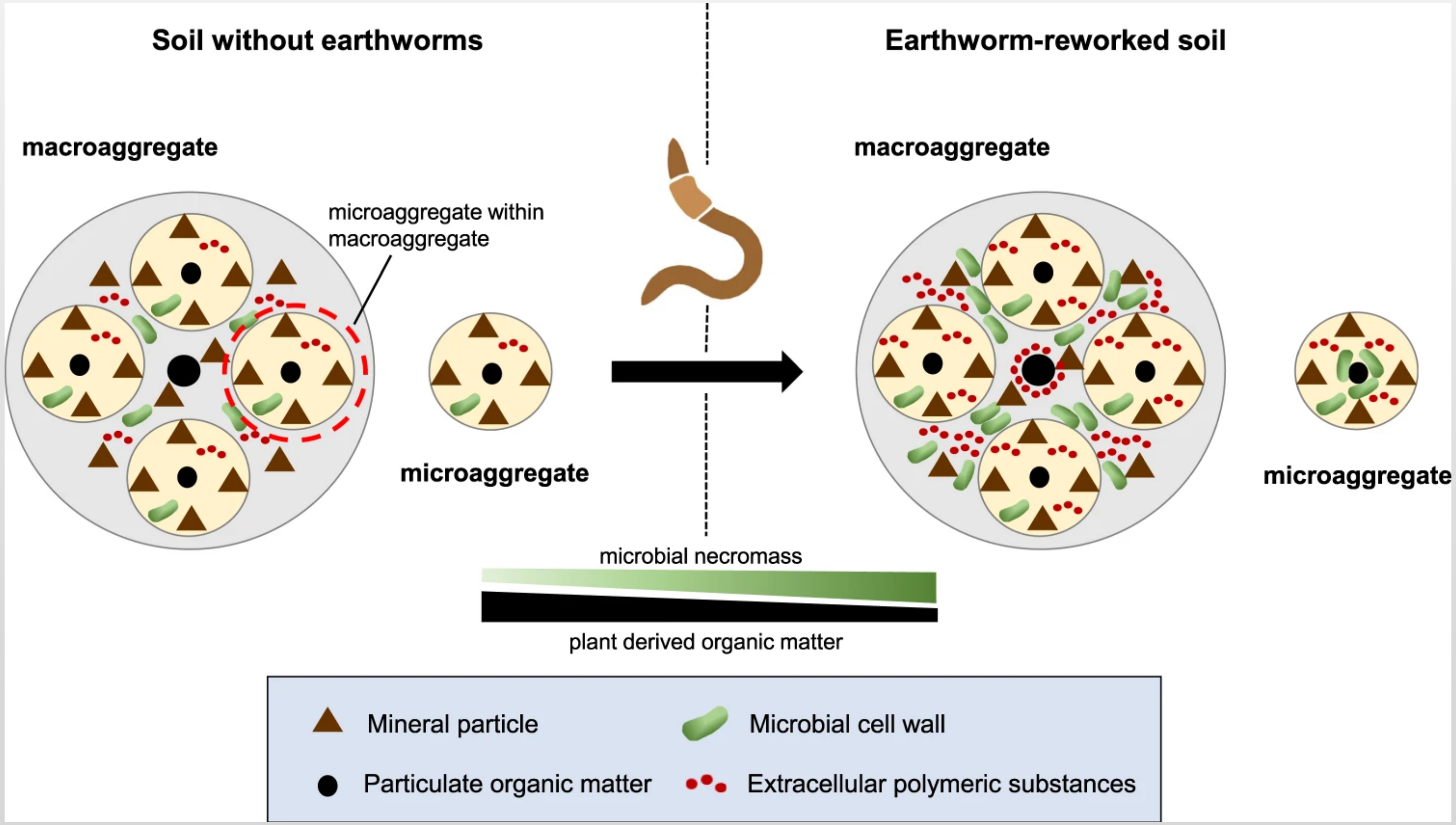
higher calcium

Calcium additions increase incorporation of litter into microbial biomass.
Calcium promoted associations between minerals and microbial byproducts of plant litter.



Shabtai et al. 2023. Calcium promotes persistent soil organic matter by altering microbial transformation of plant litter. Nat Commun 14, 6609 (2023). https://doi.org/10.1038/s41467-023-42291-6

Calcium promotes earthworms.
Earthworms convert labile plant compounds into stabilized soil microbial necromass.



Angst et al. 2019. Earthworms act as biochemical reactors to convert labile plant compounds into stabilized soil microbial necromass. Commun. Biol. https://doi.org/10.1038/s42003-019-0684-z

Include plant species with arbuscular mycorrhizae

AM trees exude more C into mineral soil where it becomes associated with minerals (MAOM) = slow-cycling

Root-derived C was 54% greater in AM versus ECM-dominated plots.

Nearly twice as much root-derived C in MAOM in AM compared to ECM plots.

Keller, A. B., Brzostek, E. R., Craig, M. E., Fisher, J. B., & Phillips, R. P. (2021). Root-derived inputs are major contributors to soil carbon in temperate forests, but vary by mycorrhizal type. Ecology Letters, 24(4), 626–581 635.
https://doi.org/10.1111/ele.13651

Embrace ‘complexity’

Kabzems et al 2016 Creating boreal mixedwoods by planting spruce under aspen: successful establishment in uncertain future climates. Can J For Res https://doi.org/10.1139/cjfr-2015-0440

Managing forests for soil life

1. Take some stems, just don’t take them all. Leave enough trees to keep the soil alive while the next generation of trees becomes established.
2. Add nutrients where and when they will improve the soil and foster soil life, and not just feed the trees, possibly at the expense of soil life. Aim for the sweet spot of nutrient supply where above- *and* belowground productivity are optimized.
3. Manage forests with more than one tree species. Embrace mixtures of conifers with broadleaves and N-fixing species. These species will rebuild soil life, soil organic matter and soil nutrients. Have a fallow period of alder and/or other broadleaves. Or grow them in mixtures -e.g. alder with cedar, aspen with spruce. Or simply allow them to be part of the forest.
4. Recognize that the belowground ecosystem is our most critical asset, our #1 ally in growing a resilient forest.

cindy.prescott@ubc.ca

The life beneath our feet – podcast - https://yourforestpodcast.com/episode-1/2024/2/1/146-the-life-beneath-our-feet-with-cindy-prescott-and-sue-grayston

The carbon flux of life - video - https://www.youtube.com/watch?v=Vdb08uyZw20

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Prescott, CE (2022). **Sinks for plant surplus carbon explain several ecological phenomena**. Plant & Soil https://doi.org/10.1007/s11104-022-05390-9

cindy.prescott@ubc.ca

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