A Tale of Nature's Collaboration - 40 Years of Simard's Scientific Research - The Wood-Wide Web

Keys and Excerpts of Simard, Suzanne. Finding the Mother Tree. Canada: Allen Lane 2021. 350 pp.
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Suzanne Simard

[The numbers following a passage refer to page numbers in "*Finding the Mother Tree"*.]

Suzanne Simard was born in British Columbia. She came from a family of loggers, studied forestry, and, in the early 1980's, began work as a forest technician. Simard later worked for the Forest Service, researching and working on ecosystem classification (83) before becoming a full time researcher. 93. Suzanne had always been curious and devoted to finding how forests work.

Suzanne's father was Earnest Charles (Peter) "Dad" Simard b @ 1935. Her mother was Ellen June "June" (Ferguson) Simard b @ 1937. Their children were: Robyn b @ 1959, Suzanne b @ 1961; and Kelly b @ 1962. 9, 22, 234.

Suzanne's grandparents lived during a previous rendition of logging, where trees were selectively cut, loggers opened only small areas that were reseeded naturally by the neighboring forest (19), and, through air, roots, and fungi, naturally connected to other plants, bacteria, soil, and all of their abilities and assets. The logs were hauled by huge horses or oxen (34), flumed to rivers (37), and finally were floated down to sawmills. (32, 37, and 39). Logger families lived in winter camps and sometimes even in houseboats. 29. That rendition of logging continued into the 1960s.

Two of Suzanne's grandparents were Henry Simard and Martha Simard b @ 1902. 27, 29, 39. Suzanne's other grandparents were "Grandpa Bert" and Winnifred Beatrice Ferguson "Grannie Winnie" b @ 1904. 11, 15, 21.

Suzanne's former husband, Don, had been an assistant professor on long-term soil productivity and investigated carbon in soils. Don would sometimes assist Suzanne with analyzing her data. 106-107, 108, 126, 131, 235-237. Their daughters are Hannah b. @ 1998 and Nava b. 2000 205, 209, 217, 223, 273, 295.

Suzanne Simard was educated at the University of British Columbia and Oregon State University [1987]. 100. As of the publishing of her book, Dr. Simard was a professor of forest ecology in the University of British Columbia's Faculty of Forestry. 210-211.

In her experiments, Simard had used glyphosates on clearcuts (88, 92- 93), a neutron probe to measure water within soil (109-111), and carbon isotopes to witness the underground flow of carbon and communication between plants. 148, 153, 157. Each tool had its moment of imperfect use. 263. Simard would require chemotherapy in 2013 and a mastectomy. 258, 246-250, 259, 263-267, 268, 273-277.

Dr. Simard began her experiments in 1987. 86. 89. She has since been published extensively in multiple journals with each article going through rigorous peer review. Journals include the prestigious *Nature*. https://suzannesimard.com/research/ Simard has given lectures and video talks worldwide including numerous universities, National Geographic, BBC, and the TED talk series. Many can be found on YouTube. Simard has given many interviews to the media including the CBC. https://suzannesimard.com/media/ . Her current book, "Finding the Mother Tree", is a best seller and is available in book stores in hardcover, paperback or on audio tape. Currently (2022) there is a movie, "Finding the Mother Tree", being produced by Amy Adams and Jake Gyllenhaal. https://www.cbc.ca/news/canada/british-columbia/amy-adams-ubc-forest-researcher-movie-1.6032379

Suzanne Simard: "Working to solve the mysteries of what made the forest tick, and how they are linked to the earth and fire and water, made me a scientist. I watched the forest, and I listened. I followed where my curiosity led me, I listened to the stories of my family and people, and I learned from scholars. Step-by-step – puzzle by puzzle – I poured everything I had into becoming a sleuth of what it takes to heal the natural world." 3.

Introduction

Earth is 4.56 billion years old. After Earth's first nearly 4 billion years of existence, life finally had the conditions to come to the surface of Earth. Cyanobacteria lichen's self-contained community and mosses, free-living nitrogen-fixing bacteria, and mycorrhizal fungi had special characteristics which allowed them to be the first life communities to surface.

Those ecosystems, and other Earth's surface life ecosystems to follow, required the ability to screen the sun's radiation and to use **sunlight's energy** to combine **water** and carbon into **carbohydrates** and oxygen. They required the ability to fix atmospheric **nitrogen** and to make **connections** with, **mine, salvage** and move mineral **nutrients** stored in Earth's mantle and soil. As other life evolved, surface life needed to create **defenses** against and **give warnings** of harmful competing life. Finally, surface life needed **generational connectivity** to sustain itself.

As Dr. Simard has said life needed Mother Trees.

The table of contents / keys, using Simard's observations, experiments and results, are divided up in those materials and abilities needed for sustainable life.

Table of Contents headings, besides helping to locate topics, are composed to help the reader's review later. They are hyperlinked so one only needs to tap a heading with either a mouse click or with a control mouse click.

Suzanne's Simard's book in hardcover and paperback is 350 pages. As it is safer to give quotes to avoid misinterpretation, the far majority of "Keys and Excerpts of Finding the Mother Tree" is excerpts. A page number from "*Finding the Mother Tree"* is given at the end of each excerpt. As there is so much more to be found in Simard's book, this writer recommends buying one.

Key parts of Simard's own written scientific process are noted within []. Those are **BACKGROUND**, **OBSERVATIONS**, **QUESTIONS**, **EXPERIMENT**, and **RESULTS**. To help understand the complexity of Simard's experiments or others' experiments [**TOOLS**] are also noted. To also make this booklet a faster review, background information, results, and organizer's clarifications have been specified also in [].

At MIT, the University of Rhode Island, Mount St. Vincent, Dalhousie University' Agriculture College, Acadia, and archives and libraries in Northeastern North America, this author has been fortunate to witness, in person, the meticulousness of scientists and historians at work. Scientists, using complex tools and machines, take years in data gathering and in analysing the data in their own or other's laboratories. Scientists and co-authors question themselves and each other, consult, and are supervised throughout their processes. Finished, their procedures and results are peer reviewed before making the results public. Peer-reviewed science doesn't work one way for one person and another way for another. Dr. Suzanne Simard has gone through these processes for thirty five years.

To help the reader relate to actual fungi, Simard has picture sections placed within her book. Those page numbers are listed in Appendix A and D with additional references with Au, indicating where pictures would be found in the *National Audubon Society Field Guide to North American Mushrooms*. Plant and lichen constituents, which help out the individual organism and consequently their co-evolved fungi-linked and aerosol-linked community, are found in Appendix E, F, and G. That constituent data is from author's own lengthy research on lichens and plants. Other sources are noted or linked.

Table of Contents (For use, see Introduction)

This table of contents may serve as a mental link for reviewing. Do a mouse tap and you will be at that section and its detail. 2022-11-01 1:53 PM Version

Contents

1. First Observations and Some Background Knowledge of Suzanne Simard

1a. How Plants Work – stomata, carbon & water joining; Tree rings; Tree root's strength; Mushroom halo

Ghosts in the Forests 7-25.

[**BACKGROUND]** Their stomata – the tiny holes that draw in carbon dioxide to join with water to make sugar and pure oxygen – pumped fresh air for me to gulp. 7-8.

Despite it being only a few hours before darkness, I paused at a log, a casualty of saws that had cleared the road right-of way. The pale round face of its cut end showed age rings as fine as eyelashes. The blond-colored early wood, the spring cells pump with water, were edged by dark-brown cells of latewood formed in August when the sun is high and drought settles in. 8.

Some rings were wider, having grown plenty in rainy years, or perhaps in sunny years after a neighboring tree blew over, and others were almost too narrow to see, having grown slowly during a drought, a cold summer, or some other stress. 8.

My fascination with tree roots had started from my growing up amazed at the irrepressible power of the cottonwoods and willows my parents had planted in our backyard when their massive roots cracked the foundation of our basement, tilted over the doghouse, and heaved up our sidewalk. 11.

I'd watched in awe each spring as a multitude of germinants emerged from cottony seeds amid halos of mushrooms fanning around the base of the trees, and I'd become horrified, at eleven, when the city ran a pipeline spewing foamy water into the river beside my house, where the effluent killed the cottonwoods along the shore. 11. The young tree looked to be a teenager, the whorls of lateral branches demarcating each year adding up to about fifteen. 14.

1b. Noting Mycena and Suillus Fungi: Their work, looks, size, adaptability to environment, fruit, hyphae, mycelium, and roots. Were fungi searching for particular nutrients and water?

[**OBSERVATIONS & BACKGROUND on various mushrooms & their mycelium**] I crawled over logs covered with moss and mushrooms, inhaling the evergreen mist. One had a river of tiny *Mycena* [Simard 116d] [Au 45, 52, 64, 68, 70, 76, 94, 98, 102, 104] flowing along the cracks down its length before fanning along a splay of tree roots that dwindled to rotten spindles. 11. These fungi [Mycena] had evolved a way to break down wood by exuding acids and enzymes and using their cells to absorb the wood's energy and nutrients. 12.

A *Suillus* mushroom [Simard 116b, 116f, 212c] [Pancake / Slippery Jack mushroom, *Suillus Lakei* Au 401] – tucked near a seedling that had established a few years back – was wearing a scaly brown pancake over a yellow porous underbelly and a fleshy stem that disappeared into the ground. 12.

In a burst of rain, the mushroom had sprung out of the dense network of branching fungal threads running deep through the forest floor. 13. I picked the mushroom, this fruit of the fungus that otherwise lived mainly below ground. The cap's underside was like a sundial of radiating pores. Each oval-shaped opening housed minuscule stalks built to discharge spores like sparks from a firecracker. Spores are the "seeds" of fungi, full of DNA that binds, recombines, and mutates to produce novel genetic material that is diverse and adapted for changing environmental conditions. 13.

The mushroom is the visible tip of something deep and elaborate, like a thick lace tablecloth knitted into the forest floor. The threads left behind were fanning through the litter – fallen needles, buds, twigs – searching for, entwining with, and absorbing mineral riches. 13.

But these root tips [of a sapling} were glowing yellow, like lights on a Christmas tree, and they ended in a gossamer of mycelium of the same color. The threads of this streaming mycelium looked close to the same color as those radiating into soil from the stems of the Suillus mushrooms, and from my pocket I took out the one I'd picked. I held the clump of root tips with its cascading yellow gossamer in one hand and the *Suillus* mushrooms with its broken mycelium in the other. I studied them closely, but I could not tell them apart. 14.

I began to dig into the forest floor. The yellow mycelium seemed to coat every minuscule particle of soil. Hundreds of miles of threads running under my palms. No matter the lifestyle, these fungal branching filaments, called *hyphae* – along with the mushroom fruit they spawn – appeared to be only a smattering of the vast mycelium in the soil. 15.

[**QUESTIONS**] [Questions so noted are Simard's questions.] I'd never seen such a rich bouquet of fungus - certainly not this brilliant a yellow, plus white and pink too – each color wrapped around a separate tip, bearded with gossamer. **<u>Roots need to reach far and in awkward spaces for nutrients</u>**. But why were so many fungal threads not only sprouting from the root tips but blazing with a palette like this? Was each color a different fungal species? Did each do a different job in the soil? 15.

<u>1c. Discovering Struggling Yellowing Seedlings, Discovering Successful Seedlings; More than one million species of fungi; Consideration of fungal connections for planting seedlings</u>

[OBSERVATIONS & QUESTIONS on struggling, starving, soil disconnected seedlings] "All the new seedlings were struggling – every single sad little planting. Why did they look so awful? Why, in contrast, did the wild firs germinating in that old-growth patch look so brilliant? 17.

The replanting was supposed to heal what we'd taken, and we were failing miserably." 17.

Maybe the seedlings symptoms would be easy to find in [**TOOLS**] the reference books, since yellowing can be caused by myriad problems. 17.

The seedlings shed yellow needles because they were starving for something. There was an utter, maddening disconnect between the roots and soil. 18.

[**OBSERVATIONS on successful seedlings and fungal threads**] I was amazed to see the same bright yellow fungal threads wrapped around the root tips as I'd seen in the old growth forest, the network of fungal hyphae growing out of the stems of ***Suillus*** pancake mushrooms [Simard 116b, 116f, 212c] [Pancake / Slippery Jack mushroom, *Suillus Lakei* Au 401]. Digging a little more around my fir excavation, I found the yellow threads infusing the organic mat that capped the soil, forming a network of mycelium that was radiating farther and farther afield. 18.

[**BACKGROUND on mushrooms and earth's numbers**] The Suillus mushrooms might be popping out of the subterranean fabric to spread spores when times were good. Or maybe these yellow threads weren't connected to Suillus mushrooms at all and were instead from a different fungal species. More than a million [fungal species] exist on earth, about 6 times the number of plant species, with only about 10 percent of fungal species identified. 19.

[QUESTIONS on getting fungal connection] Or we could plant them so their roots touched the yellow fungal web in the soil. Maybe the yellow gossamer would keep my seedlings healthy. [Indeed, now mycorrhizal fungi is available for purchase.] 19. Water, it was thought, was the most crucial resource that soils needed to supply roots so seedlings would survive. There seemed a very low chance of a change in policy so we could plant the roots in a way that they could reach the yellow fungal threads. 19.

Perhaps it was because my grandparents had cut only a few trees in a stand, opening gaps where nearby cedars and hemlocks and firs could readily seed in, the new plants easily connecting to the soil. I squinted to spot the timber edge, but it was too distant. 20.

1d. Noting mycelium; Soil life; Roots Securing the tree, tapping water, accessing minerals

[OBSERVATIONS on soil life, fungal threads, & roots' various purposes] **Hand fallers** 26-44. 1966 Jiggs and outhouse 27-32, Birch copious nutrients 28. Eating dirt 28-29. In Jiggs' rescue, Suzanne noted soil layers 26.

Obscuring these dismembered pieces of forest were brilliant yellow and snow-white fungal threads coating the collage of detritus, almost like the gauze covering my scraped knee. Through the pores in this fibrous quilt crawled snails, springtails, spiders, and ants. 28. Every root looked tenacious in its unique way, though their common job was to graft trees to the earth. 30.

Every root looked tenacious in its unique way, though the common job was to graft the trees to the earth. … Keeping the mammoths from tipping over. Tapping the water that ran deep. Creating pores for water to trickle through and bugs to crawl along. Allowing roots to grow downward to access minerals. To keep the outhouse hole from caving in. Making it hard as hell to dig through. 30-31.

He [Jiggs, the dog] had no idea, nor did I, that his adventure had opened up a whole new world for me. 31. Ancestors logging 32-35.

2. Water and Mycorrhizal Fungi

2a. Minimizing Water Loss; Drought Resistant Trees: Their Needles, Stomata, & Bark

Parched 45-63. See also 7a.

[**BACKGROUND]** I scrambled onto a knoll where a single ponderosa pine grew, its long needles in scanty bundles to save precious water. This afforded ponderosa the distinction as the most drought-tolerant of all the tree species in these parts. 46. [Possibly in 1982 47]

The Douglas fir and ponderosa pine were better than the spruce and subalpine fir at minimizing water loss, helping them cope with the drought – they did this by opening their stomata for only a few hours in the morning when the dew was heavy. In these early hours, trees sucked carbon dioxide in through the open pores to make sugar, and in the process, transpired water brought up from the roots. By noon, they slammed their stomata closed, shutting down photosynthesis and transpiration for the day. 46-47.

The brown furrowed bark [of the Douglas fir] absorbed the heat and protected the tree from fire. It was thick, too, to prevent water loss from the underlying tissue, the phloem which transported the photosynthetic sugar water from the needles to roots in an inch-thick ring of long tubular cells. 47.

See also https://phys.org/news/2022-09-tree-species-diversity-forest-drought.html

2b. Plants sharing water in dry areas with kin and ecosystems; Aspen's shared network; Deep-rooted fir with shallow-rooted fir; Hydraulic redistribution; Was mycorrhizal fungi iInvolved?

[BACKGROUND & QUESTIONS on aspens, sharing water with ecosystems, and coping with or succumbing to drought] Trembling aspen are unique in that many stems of the same individual spring from subterranean buds along a shared network of roots, and I wondered if the aspen copses [small groups of trees] were accessing water from the ravines and passing it upslope through their shared root systems. Under their crowns, wild roses sprouted, pale pink petals wide open to flaunt bright yellow stamens. 48.

Knots of purple silky lupines, golden heart-leaved arnicas, and rosy pussytoes spread from the shade into the sun. Was the root system of the aspen leaking some water into the soil for them to access? Maybe this was how the riotous plant community survived in the shallower, drier soil. 48-49. coral fungus getting water 49-50.

More puzzling was the question of whether the multitude of silky fungal threads fanning through the clay could explain how water moved from the big trees to the more shallow-rooted plants. Were those threads, which looked like an underground spider's web, joining trees and plants together to capture much-needed moisture for the whole community? Were the puffball and coral fungus involved? 50.

But that didn't make sense in this ecosystem where the trees and plants seemed to need one another for survival. One extremely dry season, a profound dryness the trees were not adapted to cope with, and they could succumb to the blistering heat. 50.

[BACKGROUND] I thought of new research on hydraulic redistribution by Douglas firs, where the deep-rooted trees lifted water to the soil surface at night and replenished shallow-rooted seedlings so they were vibrant during the day. 179.

[QUESTIONS] Had anyone examined whether firs spread water through mycorrhizal networks? Perhaps they shared water to keep their community whole, replenishing their companions through times of hardship. 179.

<u>2c. Two-Way Exchange – Trading hard-to-reach water & anything soluble in water for photosynthetic sugars; Mycorrhizal fungi apparatus: truffles, cords, strands, fans of ultrafine hyphae [like hollow pipes]; Fungal wall's special traits: thin, lacked cellulose and lignin, so used far less energy to make than plant's roots; Unique structures and abilities to acquire, transport and transmit; [Fungi extends plant's reach for water 10 X]</u>

[**BACKGROUND tree root tips and fungi's underground apparatus for accessing tightly held water**] I stared at the excavation, my mind whirling. The cord was linking the fungal-coated root tips of the Douglas fir to the truffle. The tips were also the source of the fungal threads fanning over the soil pores. 58.

Exhaling, I rocked onto my heels. Since the root tips were coated in the fungus, and water the roots would be accessing, or anything soluble in water for that matter for that matter, such as nutrients, would have to filter through the fungus, which looked as if it had all the tools to act as the joiner between the roots and the soil's water. Out of the fungus flowed a whole underground apparatus - truffles, cords, and strands that in turn grew fans of ultrafine hyphae that infiltrated the soil pores. These pores were where water was held so tightly that it would take a million of the microscopic threads to suck up enough to make a drop. The fans could be soaking up the water from the soil pores, then funneling it to the strands that formed the cord, which then passed it to the attached fir root. 58-59.

[**QUESTIONS of why and how**] But why would the fungus give up its water to the tree roots? Maybe the tree was so parched, with such a deficit from transpiring water through its open stomata, that its roots sucked the water from the fungus like a vacuum cleaner. 59.

This exquisite underground mushroom system sure looked like the lifeline between the tree and the precious water in the soil. 59.

[**BACKGROUND fungal walls' special traits, exchange of sugar for water and nutrients, how plants and fungi trade, reason fungi is more energy efficient and has better access**] All three of my odd-duck mushrooms were the fruiting bodies of this group of fungi, which gathered water and nutrients from the soil in exchange for sugars made through photosynthesis from their plant partners. A two-way exchange. A mutualism. I read the words again, fighting the need for sleep. 59-60.

<u>It was more efficient for the plant to invest in cultivating the fungi than growing more roots because the fungal walls were thin, lacked cellulose and lignin, and required far less energy to make</u>. The mycorrhizal fungal threads grew between the cells of the plant roots, their spongy cell walls pressed against the thicker plant cell walls. The fungal cells grew in a web around each plant cell, like a hair net covering a chef's head. The plant passed photosynthetic sugars through its cell walls to the adjacent fungal cell. The fungus needed this sugary meal to grow its network of fungal threads through the soil to pick up water and nutrients. In return the fungus delivered these resources back to the plant, through the layers of pressed-together fungal and plant cell walls, in a two-way market exchange for photosynthetic sugars. 60.

Myco like fungus, and rhiza like root. 60.

Scientists had recently figured out that mycorrhizal fungi helped food crops grow because the fungi [with finer hyphae than the plant's roots] could reach scarce minerals, nutrients and water that plants couldn't. 60. With a little effort, we could apply a more sustainable method by encouraging the development of the highly co-evolved mycorrhizal. 60-61.

<u>2d. Not removing or removing alders (cutting, browsing, using glyphosates); Affects to pines, water, nitrogen & soil loss - short & long Term. (Continued at nitrogen sections 7b and 7c.)</u>

[This set of experiments are continued at 6b & 6c in both places as the experiments are questions on water, Chapter 2's theme and of nitrogen, Chapter 6's theme. Nitrogen-fixing plants are listed in Appendix E]

[**BACKGROUND on eradication on alders, cost, and evidence for**] Across the province, alders were being cut and sprayed into near oblivion so that pine plantations could be declared free to grow. This ambitious eradication program, costing millions, was being applied with zero evidence that it helped the pines grow, but it was a response – a dramatic one – to the fear that the alder shrubs suppressed and killed commercially valuable trees. 101.

[**EXPERIMENT**] To evaluate the competitive effect of the herbaceous layer, I'd create three separate alder-free herbaceous treatments: 100 percent herb cover, where I'd leave the natural cover of herbs to grow freely. 50 percent herb cover, where I'd reduce the natural cover by half; and 0 percent herb cover, where I'd completely get rid of all the herbs. In each of these, [**TOOLS**] I'd cut and paint the alder first, then spray [**TOOLS**] herbicides (glyphosates) to kill the assigned portions of herbs. In the total-annihilation treatment, I'd spray everything in sight – shrubs, herbs, grasses, and mosses – creating bare earth. 103.

To measure the water in the soil, we used [**TOOLS**] a neutron probe. It was as deadly as its name implied, a yellow metal box that looked like a dynamite detonator – with a radioactive source of neutrons for measuring how tightly water adhered to soil pores. The scarcer the water, the greater its adhesion to the soil particles and the more difficult it was for the pines to take up - something the neutron probe would tell us. 109.

[**BACKGROUND on alder, pine, and herbs water needs**] Alders, pines, and herbs all required water to carry out photosynthesis, but alders needed the most in order to make enough energy to transform (fix) atmospheric nitrogen to ammonium, which the alders could then use. To accomplish this energy-demanding process, I expected them to suck up the most soil water. That was my hunch. The grasses and herbs, with their mat of fibrous roots, were also likely to be very thirsty. 109.

The more water alder took up, the higher its photosynthetic rate and the more energy it could invest in the nitrogen-fixing process. But at the same time, the less water it would be leaving for the pine seedling. A trade-off. 109.

[**EXPERIMENT continued**] Waiting for us [Suzanne Simard and her Dad] at the timber edge was [**TOOLS**] a pontoon-sized high-pressure cylinder of nitrogen. I'd explain we had to use this gas in the middle of the night to see whether the seedlings were recuperating from any daytime stress. I was guessing, based on the great amount of water in the soil measured by the neutron probe that the pines in the bare-earth treatment would recover more fully in the night than those growing among the water sucking alders. After the midnight measurement, we'd reassess the seedling at noon to see how stressed they got in the heat of the day. If they were water-stressed in the day *and* the night, then I'd know which seedlings were in big trouble and could even die before the summer was out. It could explain why my seedlings in bare earth were starting to grow faster than those among alders. 112. [Lots more on explaining procedures to the experiment.] 113-114.

The xylem pressure reading at night should be higher because the stomata are shut and the taproots are still accessing the ground water. Leaving the xylem saturated and not under any water stress. If there is a strong midday drought, however, the seedlings might not completely recover in the night, and the cells in their xylem might still be dry at midnight. 114

[**RESULTS immediate (early June) on soil's water, alder, & pine seedlings,**] Robyn and I returned every two weeks from early June to late September to repeat the soil-water measurements with the probe. With the biweekly digital readouts, I analyzed the trends in soil water over the recently melted snow had left the soil pores full of water. It didn't matter a hoot whether alder sprouted or not, no amount of alder could diminish the dampness left after two meters of winter snowpack had melted. 111.

[**RESULTS early August on soil's water, alder, & pine seedlings]** But by early August, the soil pores had dried out where the alder grew back thickly. The flourishing alder leaves had been so eager to transpire gallons of water through their open stomata that they'd used up most to the free water. Where we'd completely eliminated the alder, however, the rootless soil pores remained full of water throughout the summer. Ugh, maybe the weed zealots were right. 111. To answer this, I needed to measure how much water was ending up in the pine seedlings in the middle of the summer. I enlisted my dad to help me. 111.

We left town at midnight on August seventh when, according to the reading Robyn and I had taken with the neutron probe, the alder-covered soil was the driest. 111.

[**BACKGROUND on xylem pressure (xylem for water ^, phloem for sugar V), stomata, and transpiration**] I took it anyway and stripped the needles and phloem, leaving only the central xylem, an inch long. 113 The xylem transports water from roots to shoots in response to the water deficit created by transpiration – the water emitted from the stomata of the needles into the air during photosynthesis. During the day, water pressure in the xylem should be low as the roots struggle to pull water from the drying soil to meet the vapor deficit created by transpiration. The xylem pressure reading at night should be higher because the stomata are shut and the taproots are still accessing the ground water, leaving the xylem saturated and not under any water stress. If there is a strong midday drought, however, the seedlings might not completely recover at night, and the cells in their xylem might still be dry at midnight. 113-114.

[**EXPERIMENT continued**] A bubble of water would emerge from the twig's cut end when the pressure I applied equaled the resistance of the water held in the xylem. 114.

[**RESULTS**] The seedling was thirsty, not recovering fully at night. 114.

The soil data also told me the alder was releasing a lot of nitrogen back to the soil when its leaves senesced [died] and decomposed in the fall. The pine roots could then snatch up the released nitrogen. "This seeding should have lots of nitrogen in its needles." I said, "even though it's thirsty." 114-115. The seedlings where the alder had been removed were recovering at night because more water was in the soil. 115.

Robyn and I returned to measure soil water with the neutron probe three more times. Each time, Dad and I again followed at midnight to see how well the seedlings were responding to the water fluctuation in the soil. I was surprised at what we discovered. 115.

[RESULTS by late August on soil's water & pine seedlings, hydraulic redistribution, eventual erosion, inorganic compounds in soil water] By late August, the neutron probe showed the soil under dense alder had filled with water again. There was now - already – as much water in the dense-alder treatments as in the bare-earth patches. Not only were the soil pores refilling with late summer rains and dewdrops, they were being inundated with ground water at night, when the alder taproots pulled water from deep in the soil and exuded it through lateral roots into the dry surface in a process called **hydraulic redistribution. Water rerouting**. 115.

And something else was happening in that denuded, pine-seedling-only soil. When the raindrops hit it, the water ran off the surface, carrying tiny particles with it. Silt, clay, and humus grains got transported away in rivulets because there were no living leaves or roots to stop them. **As the alder-dense plots began gaining water from late August and over the next few months, the bare earth started losing it.** 115-116

Dad and I used the pressure bomb to test whether the seedlings were sensing the changes in soil water content. As water refilled the soil, the stress the pines had experienced among the alders completely disappeared. **Except for that brief period in early August**, the pines were experiencing no more water stress than the ones in bare soil. **It turned out that getting rid of alder so pines could be free to grow provided only a fleeting advantage in water uptake. Not only that, its side effect was a loss of soil** 116.

The inorganic compounds, dissolved in soil water, were then readily available for the pine seedlings to take up, **briefly** boosting their growth. 116.

[**RESULTS after a year on nitrogen after dead alder had since decomposed**] After about a year, however, after the dead alder had long since decomposed and the mineralized nitrogen had been consumed by seedlings or plants or microbes, or leached through the groundwater, the total amount of nitrogen in the bare-earth treatment plummeted compared to where the alder grew freely. The **short-term pulse of nitrogen** as ammonium and nitrates released during decomposition **was quickly used up**, and there was no alder left to replace or augment that nitrogen. It went missing in action, 116-117.

It was clear that pines get nitrogen from the soil after it's been enriched by nitrogen-fixing plants like alder. Foliar nitrogen data – Pine seedlings growing among alder were rich in nitrogen, and those without were depleted. Even though the pines among the dead alder roots in the bare-earth treatment were taking up more phosphorus and calcium released from decomposition, they were more depleted in nitrogen in particular because of the absence of new nitrogen additions to the soil. 117.

This suggested to me that for most of the time, other than the most stressful weeks in August, alder was replenishing both water and nitrogen in the soil. 118.

[This is continued in Section 6b. It is in both places as it is a question of water and of nitrogen. Nitrogen-fixing plants are listed in Appendix E]

2e. Water Loss around Dead Trees; Lost soil structure; Drought's ecosystem changes; Taproots key to those that lived

[**OBSERVATIONS about water loss around a dead mother tree and structure loss]** I checked for seedlings around the bony skirt of the dead Mother Tree and found a few two-year olds huddled in a crevice. These siblings were all that remained to carry the Mother Tree's genes. I knelt to examine them, grasshoppers jumping from under the drooping awns of cheatgrass – a native plant run amok in the barren soil. If whitebark pine seedlings would live in the cold soil of the subalpine, surely these ponderosa seedlings would survive down here. At this age they should be firmly clasping the earth, but fungi and bacteria were no longer gluing the sand and silt grains into clumps, giving the soil structure to hold water. 244.

[**RESULTS on low soil moisture]** I pushed [**TOOLS**] the metal probes of my new soil-moisture sensor - a great advancement since the neutron probe – into the loose dirt to measure the soil water content. Only 10 percent registered, barely enough. It seemed incredible that these seedlings were surviving. 244.

Perhaps their mycorrhizas were drawing scant water from the dry grains. The broken bones of the Mother Tree still cast some shade, and I wondered if she'd been around long enough to help. I'd read that dying grasses shuttled phosphorus and nitrogen to their off-spring through arbuscular mycorrhizal networks and wondered if this Mother tree did the same as she died. Sending them her last drops of water, along with some nutrients and food. 244-245.

[**OBESERVATIONS drought changes to ecosystems, sacrificed for human convenience, gene change as temperature increased**] The ponderosa-pine woodlands were turning to grasslands, while Douglas fir forest was being overtaken by the ponderosas. 245.

Was this the best the forest could hope for? More likely, the cheatgrass – along with the spotted knapweed and common burdock – would be more successful than the trees at filling the parched earth, at least down here in the valley. These plants, with their prolific seed production and rapid growth rates, could easily invade a forest weakened by fire suppression and extreme climate. These trees seemed sacrificed for the sake of human convenience. Ironically, the very weeds and insects that were killing the forests might be the ones with the genes to persist as the temperatures rose and the rains changed. 245.

[**OBSERVATIONS drought, taproots, infestations, changes to ecosystems**] I guessed it was less stressful for the pines upslope where rainfall was more plentiful. But unlike the pines in this ecotone – this transition area between the lower and upper forest communities – the firs were feeling the drought, their taproots not reaching as deeply into the parent material, reducing their ability to resist infestation by their own coevolved herbivores. Maybe this was why they seemed so heavily defoliated by the budworm. 245.

Were the ponderosa doing well because of their deep taproots and more plentiful rainfall up there, or was it because of links to their Douglas-fir neighbors? My old doctoral supervisor, Dave Perry, had already found that the two species were likely joined in a mycorrhizal network in the forest of Oregon, and he'd thought that Douglas fir shared enough nutrients to affect the growth rate of ponderosa pine. I figure that was going on here too. 245-246.

3. Cyclic Fires, Melting Cone's Resin, Stimulating Aspen, Natural Responses; Preventing Fire with Mixed Forests, Natural Firebreaks; Saving Carbon in Soils, Fungi Adaptability, Replenishing Nitrogen Lost to Fire, Preventing Disease; Clear Cutting Amplifying Earth's Carbon Emissions

[**BACKGROUND on cyclic fire, nitrogen being replenished, coevolved, restoring nitrogen]** Lodgepole-pine cones only open when the resin holding shut the scales starts to melt. These mountain forests burn every hundred years because of the cool but dry climate and frequent lightning strikes, combusting the whole stand and consuming the overstory. The scattered alders help replenish the nitrogen gassed out by the wildfire. 68.

Lodgepole pine had coevolved with beetles in this landscape, naturally succumbing after about a century to create space for the next generation. As the trees declined, fuel accumulated as a matter of course, and wildfires were ignited by lightning or people. Flames released pine seeds from resinous cones and stimulated aspens to sprout from thousand-year old root systems, their moist leaves reducing the flammability of the young forest. As fire fingered through the landscape, it petered out in these aspen-clad glades, leaving a mosaic of different-aged forest that was itself resistant to future fires. But in the late 1800s European settlers … 181-182.

Maybe even more important was the fungi's ability to reproduce rapidly. Their short life cycle would enable them to adapt to the rapidly changing environment – fire and wind and climate – much faster than the steadfast, long-lived trees could manage. 185.

Shrubs such as alder and soapberry, I explained, were beneficial to their needle-leaved neighbors because of their ability to host symbiotic bacteria that fixed nitrogen. Not to mention, I thought to myself, their role in providing food for birds and medicine for people and carbon for soil in preventing erosion, and fire, and disease. 197.

Overestimating the threat of a few birch neighbors could bring unexpected consequences, potentially setting the forest for a vulnerable future, where lowered biodiversity might reduce productivity, increase the risk of poor health, and augment the spread of fire. 198.

[**BACKGROUND Mixed forests least vulnerable; Methods of prevention; Carbon needs to be stored in soil; Clear-cutting amplifying emissions**] We're going to need birch and aspen to grow quickly and put a lot more carbon in the soil, where it will be safe from fire." I went on to explain that, in most years in Canada, more carbon is lost to wildfire than from the burning of fossil fuels, and we should be trying to reduce the risk [of fire] by planning for landscapes of mixed forest instead of coniferous forests, and for corridors of birch and aspen to serve as firebreaks, because their leaves were moister and less resinous than those of conifers. 202, 207. These forests experienced fire every few decades or so. 220. Even though the beetle and fungus had coevolved with the pines, the past few decades of fire suppression had created a vast landscape of aging pines ripe for an epic infestation. 240. Fire risk has increased rapidly in the small towns of British Columbia due to climate change. 243.

The dead trees have been considered at fire risk, but more likely a convenient commodity. This salvage clear-cutting has been amplifying emissions, changing the seasonal hydrology in watersheds and in some cases causing streams to flood their banks. 288.

See also Lindsay, Bethany. Nov. 17, 2018 "'It blows my mind': How B.C. destroys a key natural wildfire defence every year. CBC News https://www.cbc.ca/news/canada/british-columbia/it-blows-my-mind-how-b-c-destroys-a-key-natural-wildfire-defence-every-year-1.4907358 "Provincial rules require spraying of fire-resistant aspen trees to make way for valuable conifers."

4. Soil - Need for the Right Fungal Connections

4a. Exposed soil; Weeding treatments, including glyphosates, to kill competition for water and light; But killing necessary fungal connections and necessary collaborators; Killing food, homes, cover for animals; Killing plants which: prevent erosion, provide Nitrogen, and provide shade to protect tender seedlings; *Armillaria* pathogenic fungi with or without birch; Glyphosate alarm

Killing Soil 78-100.

[**BACKGROUND on glyphosates / Roundup**] Monsanto had invented an herbicide in the early 1970s – glyphosate, or Roundup – that would poison the native plants without affecting the conifer seedlings. Roundup had become so popular that many people used it casually on their lawns and gardens, Grannie Winnie a stubborn exception. 85-86.

[**EXPERIMENT**] [Around 1987] With Alan's [Vyse's] help, I devised four weeding treatments, testing three volumes of Roundup, one, three, and six liters per hectare, plus one manual-cutting application. We also added a control, where we'd leave the shrubs untouched. We needed to repeat these five treatment ten times each so we could be sure which worked best. We randomly assigned the replicated treatments, one to each of fifty circular plots. 87.

With Alan's guidance, I'd designed my first experiment! Though I loathed its purpose, which I was sure was the opposite of what we should be doing, I felt one step closer to having the skills to solve the puzzle of my little yellow seedlings. 87.

The moment I'd been dreading had arrived. I'd bought [**TOOLS**] the liters of glyphosate over the counter at the farmer's supply store in Kamloops, unnerved that anyone could just go in and buy it, but was glad that I'd at least had to apply for a permit to spray it on government land. Robyn's fear was partly subdued by her frown. 88.

Now we had to wait a month before measuring how effective the treatments were at killing the plants. I loved learning how to conduct an experiment in the forest, but hated turning these plants into ghosts. For a forest management purpose that I already felt was mistaken. 89.

[**RESULTS of 'free to grow' - what was actually killed which included connective fungi, shade plants, leafy alders, plants which subdued pathogens**] When we returned, the rhododendron, false azaleas, and huckleberries in the highest-dose treatment had shriveled and died. Not just the shrubs, but all the plants, even the wild ginger and orchids. The lichen and mosses were brown, and the mushrooms were rotting. 89-90. At the lowest dose, most of the plants were still alive, but injured and suffering. 90. The stems of the shrubs that had been cut were already sprouting back and over topping the seedlings. 90.

On the verge of tears, wanting to know how the glyphosate had killed the plants, Robyn said, "I know what we did. But what happened?" She always carried the brunt of our emotional pains, bearing the injustices, wanting to fix them. 90.

I stared at my feet, because both of us crying would hurt too much. These plants were my allies, not my enemies. 90. I looked at a thimbleberry plant trying to survive, its stems bare as they hunched over some pale seedlings newly revealed, but all it had managed to do was sprout a tiny basal pincushion of yellow leaves. The herbicide wasn't supposed to harm birds or animals, because the poison targeted the enzyme only the herbs and shrubs produced to develop protein. 90.

But the mushrooms had shriveled and died.

Our favorite chanterelles - gone.

In my bones I knew the problem with the ailing seedlings was they couldn't connect with the soil. That they needed the fungi to help them do that. 90.

Alan shook his head at the results – the highest dose of herbicide [glyphosates] was best at killing the plants. **As solace, he pointed out that this evidence still had nothing to do with detecting if the killing plan would help the seedlings. All it did was prove that a heavy dosage got rid of the so-called weeds.** 91.

It didn't matter that the plants provided nests for birds and food for squirrels, hiding cover for deer and shelter for bear cubs, or that they added nutrients to the soil and prevented erosion – they simply had to go. Of no concern was the nitrogen added to the soil by the leafy-green alders, now clear-cut and burned to make way for seedlings. Or that the bunchy pinegrass provided shade for the new Douglas fir. 92.

[**BACKGROUND on glyphosate alarm**] The doctor at the clinic was gentle and could tell we were scared, and he took us into the examination room together. "Your throat is really red," he told Robyn, "but your glands aren't swollen. What have you been doing"? When I told him we'd been spraying glyphosate, Robyn awarded me a stare as he inclined his head while asking, "Were you wearing a mask?" When I said yes, he asked to see it. I fetched one from the truck, and he unscrewed the black plastic caps and whistled. "No filters," he said. 93. We had been breathing in glyphosate spray all day. 93.

[**RESULTS growth, survival, Armillaria pathogenic fungus without or with birch]** All but one of the treatments would end up failing to improve conifer growth and, no surprise, native plant diversity was lowered. In the case of the birch, killing it improved the growth of some of the firs, but caused even more to die – opposite of expectation.

When the birch roots had become stressed by the hacking and spraying, they had been unable to resist the *Armillaria* pathogenic fungus living naturally in the soil. The fungus infected the suffering birch roots and from them spread to the roots of the neighboring conifers. Where white-barked birch was left untouched in the control plots, and continued to grow intermingled with the conifers, however, the pathogen remained subdued in the soil. It was as though the birch were fostering an environment where the pathogen existed in homeostasis with the other soil organisms. 93.

[**BACKGROUND for being a permanent researcher**] A permanent job as a silviculture researcher with the Forest Service opened. 93. I couldn't believe my good fortune when I landed the job. Alan would be my direct supervisor. 94.

I won a research grant to test whether conifer seedlings needed to connect with mycorrhizal fungi in soil to survive. 94.

[**QUESTIONS about mixed forests**] Could a single species thrive on its own? If planted seedlings were mixed with other species, would that make for a healthier forest? Would planting the trees in clusters with other plants improve their growth, or should they be spaced far apart in checkerboard grids? These tests, too, might help me get at exactly why the old subalpine firs up high, and stately Douglas firs down low, grew in clumps. They could help me understand whether native plants growing next to conifers improved connections to the soil. Whether conifers had more colorful fungi on their root tips when growing next to broadleaf trees and shrubs. 94.

<u>4b. Examining communities & types of connectivity between birch & fir (ectomycorrhizal fungi EMF); Luxuriant grasses (arbuscular mycorrhizal fungi AMF); No fungi, wrong fungi, or adding old forest mycorrhizal fungi to the soil; Starving plants - Accidently killing mycorrhizal fungi also killed trees. [See also Appendices C & D]</u>

[**EXPERIMENT**] I picked paper birch as my test species, because from childhood that it made rich humus that should be helpful to conifers as it had been delicious in my dirt-eating days. I was also intrigued that it seemed to keep root pathogens at bay. <u>**But birch was only a weed to timber companies.**</u> To everyone else, it was a gleaming provider of sturdy waterproof white bark, shady leaves, and refreshing sap. 94-95.

[**OBSERVATIONS on which plants lived in certain communities**] I planned to test how three lucrative tree species - larch, cedar, fir – fared in different mixtures of birch. 95.

After hundreds of days in plantation and in weeding experiments observing how plants and seedlings grow together, I sensed that trees and plants could somehow perceive how close their neighbors were – and even *who* their neighbors were. Pine seedlings between sprawling, nitrogen-fixing alders could spread their branches farther than if they were under a thick cover of fireweed. Spruce germinants grew beautifully nestled right up to the wintergreens and plantain but kept a wide berth around the cow parsnips. Firs and cedars loved a moderate cover of birch but shrank when a dense cover of thimbleberry also grew overhead. Larch, on the other hand, needed a sparse neighborhood of paper birches for the best growth and least mortality from root disease. 96.

[**EXPERIMENT**] To be prepared as possible to look at the roots, to track if the conifers were connecting with the soil better when they were grown near paper birch than when they were alone, I ordered [**TOOLS**] a dissecting microscope and [**TOOLS**] a book on identifying the features of mycorrhizas and practiced with birch and fir roots collected on my way home. 96.

I'd disappear into my cave-office until midnight, excising root tips, taking cross sections, and mounting them on slides. Before long, I was getting good at identifying Hartig nets, clamp connections, cystidia, and the many parts of the mycorrhizal root tip that helped distinguish one fungal species from another. 96.

[**OBSERVATIONS about which fungi helped birch and fir**] Some of the species of fungi on the soft-needles firs seemed the same as those on paper birch. If this was true, maybe the birch mycorrhizal fungi jumped onto fir root tips, cross-pollinating them. Maybe this co-inoculation or sharing of fungi or symbiosis helped newly planted Douglas-fir seedlings avoid having naked roots, perhaps letting them escape the same death sentence that befell my early yellow seedlings in the Lillooet Mountain. If fir somehow needed birch, birch wouldn't be hurting fir, as foresters assumed. 96-97.

Quite the opposite. 97

[**RESULTS with no fungi, wrong fungi; species demise order based on sensitivity to water and light needs - birch, fir, then cedar, only grasses lived**] It turned out that he [a local rancher] did get it. He very much got it. Furious at losing his grazing site, he'd seeded the clear-cut with dense grasses. 98.

The plantation failed again – each of the mixtures. The white-barked paper birch died first, then the soft-brushed fir, and finally the braided cedar. Following the order of the sensitivities to light and water shortages. 98.

A third try the next year. Another failure. A fourth replanting. Again all the seedlings died. The site was a black hole where nothing would live. Nothing except luxuriant grass. 98.

I was quick to blame the rancher, but I secretly knew that my aggressive site preparation had displaced the forest floor and scraped the topsoil away. That couldn't have helped. 98.

The Douglas fir and western larch form symbiosis only with ectomycorrhizal fungi, the ones that wrap the outside of the root tips, whereas the grasses formed relationships only with arbuscular mycorrhizal fungi that penetrate the cortical cells of their roots. **The seedlings starved to death because the kind of mycorrhizal fungi they needed had been replaced by the kind only the damned grasses liked.**

[**QUESTIONS right kind of fungi**] It dawned on me that the rancher had helped me get at my deepest question: **Is connection to *the right kind of soil fungi* crucial for the health of trees**? 98.

[**EXPERIMENT continued with adding old forest mycorrhizal fungi**] I replanted a fifth year, but this time I collected [**TOOLS**] live soil from beneath old birch and fir trees in the adjacent forest. I placed a cup of it in each of one-third of the planting holes. I planned to compare these seedlings to another batch planted straight in another third of the razed ground without any transferred soil. For good measure, I placed old-growth soil that had radiated in the lab to kill its fungi in the final third of the planting holes. This would help me figure out if the living fungi or the soil chemistry alone accounted for any seedling improvement with the soil transfers. After five tries I felt on the cusp of a discovery. 98-99.

[**RESULTS after a year in transferred old growth's soil]** I returned to the site the following year. The seedlings planted in the old-growth soil were thriving. 99.

[**RESULTS after a year without transferred old growth's soil]** As predicted, the seedlings without transferred soil, or with the dead, radiated transferred soil, were dead. They had met the usual morbid fate that had been plaguing them - and us – for years. I dug up samples of the seedlings and took them home to [**TOOLS**] my microscope. As I expected, the dead seedlings had no new root tips. 99.

[**RESULTS after a year in transferred old growth's soil]** But when I looked at the seedlings grown in the old-growth soil, I jumped out of my chair. 99.

Merde! The root tips were covered with a dazzling array of different fungi. Yellow, white, pink, purple, beige, black, gray, cream, you name it. It *was* about the soil. 99.

[**CONCLUSIONS**] The death of fungi in the soil, and the breakdown of the mycorrhizal symbiosis, held answers about why the little spruce in my first plantations had been dying. I'd figured out that *accidently killing the mycorrhizal fungi also killed trees*. Turning to the native plants for their humus, and putting the fungi in the humus back into the plantation's soil, helped the trees. 100.

4c. Examining conifer clustering with other species; Effects of cutting, grazing, and application of glyphosates on growth for short term – minimal temporary gains; Long term: infested with insects or pathogens, blights, and loss of severe weather protection

[**EXPERIMENT**] [I] continued with my surfeit of experiments in other plant communities. One hundred and thirty, to be exact. All replicated, randomized, and with solid controls, all coming to similar conclusions. 132.

[**RESULTS short term of removing competitors or collaborators**] Cutting or spraying willows did not improve spruce growth or survival.

Cutting, spraying, or grazing fireweed with sheep did not improve performance of either spruce or lodgepole pine.

Neither cutting nor grazing thimbleberry helped spruce.

Cutting aspen did not increase the girth of pines.

Whether we sprayed, cut, or grazed the rhododendron, false azalea, and huckleberry communities in the high-elevation plantations, the growth of spruce didn't budge. I thought back to Robyn spraying the rhododendrons, and how we'd suspected even then **it was a waste of time**. 132.

[**RESULTS over time of removing competitors or collaborators, infestation**] True enough that 20 percent more seedlings survived where the non-cash-crop shrubs were weeded than where they were left untouched – *but only for the short term*. In the same subalpine environment, spraying ferns into pincushions did not improve the long-term survival rate of spruce but the short-term height growth of the prickly seedlings was more than where the ferns were left alive. These minimal, temporary yields were enough to satisfy the policy makers. 133.

[I said] "And I've thought about why many of the free-to-grow trees are becoming infested with insects or pathogens – and are worse off. For one, I think we're overestimating how competitive these native plants are with the conifers. 133. I also suspect the plants are protecting the trees against blights and severe weather." 133.

5. Fungi Sharing Carbonhydrates between Different Plants

5a. Pine with Pine Carbon Exchange and Effects of Shade (1984 Dr. David Read's Work Published)

[**EXPERIMENT sharing carbon in the lab]** I'd been intrigued by the possibility that birch and fir might trade sugar through mycorrhizal fungi ever since I'd read of a discovery in the early 1980s by Sir David Read, a professor at the University of Sheffield, and his students, who found that a pine seedling had transmitted carbon below ground to another pine. He had established pines side by side in [**TOOLS**] transparent root boxes in the lab. He'd inoculated the seedling roots with [**TOOLS**] mycorrhizal fungi to link them in a below ground fungal network, then tagged the photosynthetic sugars produced by one of the pines – the donor - with radioactive carbon. To do this, he'd sealed the shoots of the pines in [**TOOLS**] transparent boxes and replaced the naturally occurring carbon dioxide in the air of one of the seedling with radioactive carbon-dioxide. 144-145.

Then he placed [**TOOLS**] photographic film over the side of the root box in hopes of recording any radioactive particles that might be transmitting through the network from the donor pine to the receiver pine. 145.

[**RESULTS of pine seedling to pine seedling, and effects of shade]** Upon developing the film, he saw the path the charged particles had taken as they moved from pine to pine. They had traveled through the underground fungal network. 145.

The pine donor in Sir David's experiment sent carbon to a receiver seedling, and even more when the receiver was shaded,

[**QUESTIONS**] but he did not know if the receiver sent any carbon back. 145.

Francis, R., Read, D.J. The contributions of mycorrhizal fungi to the determination of plant community structure. *Plant Soil* **159**, 11–25 (1994). https://doi.org/10.1007/BF00000091
https://link.springer.com/article/10.1007/BF00000091#citeas

5b. Birch with Fir – Sharing water, carbon and nitrogen – making up for the other plant's lack of sunlight; Evolving for collaboration; From water received from fungi or directly from root tips > xylem > foliage. From leaf source of photosynthates (chemical energy) > phloem > root tips > used, shared, or stored by fungi.

Radioactive 142 – 163

[QUESTIONS competitors or collaborators for light, how did they collaborate?] I wanted to know whether these birches were simply competitors – reducing the resources Douglas fir needed for survival and growth – or whether they were also collaborators, enhancing the conditions under which the whole forest could thrive. And if the leafy native plants did collaborate with their needle-leafed neighbors, I wanted to know how. 142.

As the birches intercepted light for their own sugar production, did they make up for the reduced photosynthetic rate of understory Douglas firs by sharing their riches? My investigation would help me figure out how in the world could fir survive and even prosper in spite of living among birch neighbors considered by foresters to be strong, unwanted competitors. And if birch did spread this bounty – the large amount of sugar it was able to produce in full light – maybe it was delivered to the shaded Douglas fir through a belowground pathway, mycorrhizal fungi linking the two species together. Birch cooperating with fir for the greater health of the community. 142 -143.

[**QUESTIONS on connections between species, in real forests, selfish interests to keep community alive evolving to collaborate]** I wondered if this could be detected outside the lab, in real forests. Sugar might transmit from the root of one tree to another. If so, maybe the added radioactive carbon-14 traveled only between trees of the same species – as Sir David found – but what if it got conveyed between different species of trees mixed together, as they're often found in nature? 145.

If carbon did transmit between tree species, this would present an evolutionary paradox, since trees are known to evolve by competing, not cooperating. On the other hand, my theory was entirely plausible to me, because it made sense that they would have selfish interests in keeping their community thriving, so they could get their needs met too. 145.

The pine donor in Sir David's experiment sent carbon to a receiver seedling, and even more when the receiver was shaded, but he did not know if the receiver sent any back. 145.

[**BACKGROUND leaf source of photosynthates (chemical energy) > phloem > root tips > shared by fungi. Water at root tips > xylem > foliage]** I thought back to my plant physiology classes, imagining a birch leaf photosynthesizing – converting light energy to chemical energy (sugar) by combining carbon dioxide from the air with water from the soil. Because of their ability to photosynthesize, the leaves were the source of the chemical energy, the engines of life. The sugar – carbon rings bonded with hydrogen and oxygen would accumulate in the cells of the leaves and the sap then load into the leaf veins like blood being pumped into arteries. From the leaves, the sugar would travel into the conducting cells of the phloem – the blanket of tissue encircling the birch trunk under the bark and forming a pathway from leaves to the root tips. 146.

Water taken up by the roots from the soil would travel up the xylem – the innermost vascular tissue linking roots to foliage. 146. While leaves are the source of photosynthate, roots are sinks. 146.

The sugar train in my imagination didn't stop at the roots. I'd read that photosynthate was unloaded from the root tips into mycorrhizal fungal partners, like freight unladed off boxcars onto truck. 147.

[**EXPERIMENT controlling shade with various tents, watching photosynthate**] My plan was to cover one-third of the Douglas firs with [**TOOLS**] the heavy green tents and another third with [**TOOLS**] the light black tents, while leaving third [**TOOLS**] in full sun. This would create a gradient of light reaching the firs, from very little in the deep shade to the most possible in full sun. I was emulating the variety of shady and sunny spots that young fir experience when growing in the shifting shadows of naturally occurring overlapping birch saplings. 144.

But unlike naturally growing birches, which normally seed in or sprout from cut trees immediately after clear-cutting, and thereby have a height advantage over planted conifers, my birches were the same height as my planted firs. They cast no shade at all in my experiments, so I needed to create it artificially, with these tents. Unlike in nature, however, the tents would only provide shade and not simultaneously change the availability of soil water or nutrients. They would help me pinpoint the effect of shading as an isolated factor unaffected by other unseen relationships. 144.

My plan was to label paper birch with [**TOOLS**] the radioactive isotope carbon-14 so I could follow the photosynthate traveling to Douglas fir, and at the same time I'd label Douglas fir with [**TOOLS**] the stable isotope carbon-13 to trace photosynthate moving to paper birch. That way I could tell not only if carbon was passing from birch to fir but also distinguish if it was moving in the opposite direction, fir to birch, like trucks on a two-lane highway. By measuring how much of each isotope ended up in each seedling, I could also calculate whether birch gave more to fir than it got in return. Then I would know if trees were in a more sophisticated tango than just a competition for light. I'd discover if my intuition was right – that trees are tightly attuned, shifting their behaviours according to the functioning of their community. 147.

[**OBSERVATION on cedar**] The cedar were glowing where the birch cast a cool shadow, protecting their delicate chloroplasts from the high sun. Where the birch leaves could not reach, the cedars were tanned red to prevent damage to their chlorophyll. 148.

Barb asked why I'd include cedar next to the birch and fir. 148.

Cedar can't form mycorrhizal fungal partnerships with the birch and fir for the simple reason that it forms arbuscular mycorrhizas, not ectomycorrhizas like the other two. 148.

I'd planted cedar as a control, to tell me how much carbon was leaking into the soil versus how much might be transmitting through the ectomycorrhizal network linking birch and fir. 148.

Using [**TOOLS**] a portable infrared gas analyzer, a contraption the size of a car battery with a see-through barrel-shaped chamber, Barb and I check that the shade tents were doing their job of depressing the photosynthetic rates of the fir seedlings. 148.

I returned the next day to collect [**TOOLS**] foliar samples from the birch and fir to be tested for nitrogen concentrations. A couple of weeks later, this data came back from the lab. The birch had double the concentrations of nitrogen in its leaves compared to the fir needles. 149 [This story continues in 6b.]

[**RESULTS on birch-fir carbon exchange**] "I shouted the firs grown with birch looked like decorated Christmas trees. While the firs grown all alone had fewer mycorrhizas 158-159, **Douglas fir with ponderosa pine** 159. **fir with birch** 7 fungi, were but a fraction of dozens of their fungal species. Douglas fir received far more carbon from paper birch that it donated in return. 158-160.

<u>**Quid Pro Quo**</u> 164-180.

[Nature decided to publish the new version as the cover story in August 1997.]

Suzanne W. Simard, David A. Perry, Melanie D. Jones, David D. Myrold, Daniel M. Durall & Randy Molina August 1997 Net transfer of carbon between ectomycorrhizal tree species in the field *Nature* **volume 388**, pages 579–582 (1997) https://www.nature.com/articles/41557 https://www.jstor.org/stable/2559035 https://www.researchgate.net/publication/229192240_Net_transfer_of_C_between_ectomycorrhizal_tree_species_in_the_field

Sir David Read wrote an independent review https://www.nature.com/articles/41426

"The study of Simard et al. [addresses] these complex questions in a field situation and for the first time … shows unequivocally that considerable amounts of carbon – the energy currency of all ecosystems – can flow through the hyphae of shared fungal symbionts from tree to tree, indeed, from species to species, in a temperate forest. Because forests cover much of the land surface in the Northern Hemisphere, where they provide the main sink for atmospheric CO_2, an understanding of these aspects of their carbon economy is essential." 165.

Nature called my discovery the *wood-wide web* and the flood gates opened. 165

5c. Douglas fir ancients & birch with shaded fir seedlings without and with fungi; Noting specific fungal fir seedling connections: *Rhizopogon* fungi to adult fir, *Piloderma* fungi to birch

[**EXPERIMENT under forest canopy**] At the old growth forest next to the mixtures experiment, I waded through foot-deep snow, rain pants heavy. 166.

Deep inside these woods, I'd established the second of my doctoral field experiments. I'd planted twenty clusters of five Douglas firs each under the dense forest canopy to see how the seedlings might survive in the deep shade, how long they might live in the gloom. In half the clusters, the roots of the five little seedlings were free to interlace with mycorrhizal network of ancient trees. 166.

In the other ten clusters, I'd block the roots from the elders by encircling the fledgling group with [**TOOLS**] a meter-deep band of sheet metal. Just as I'd done with the triplets of fir, birch, and cedar for my wood-wide experiment, though here in the dark shadow of the canopy, I'd planted fir. Inside the timberline, the possibility of fir seedlings connecting and communicating with their neighbors was even greater. 166.

[**RESULTS under the canopy, seedlings without fungal connections**] At the first cluster of firs inside the thick forest, there was only one survivor, its sickly yellow leader barely sticking above the cover of snow. 167.

[**RESULTS under the canopy, seedlings free to get fungal connections: Rhizopogon from old firs, Piloderma from old birch**] A group of green leaders emerged from the snow. I'd planted these seedlings without a barrier, leaving them to connect with the rich fungal network of the elders. All had put on a centimeter of new growth since last summer, and each had a fat new terminal bud. I scraped away the snow, shallow here because of the warming stems, and peeled back the centimeters-deep litter. Thick, richly colored mycorrhizas like a Renaissance painting wended through the organic horizon, and I suddenly felt lighter, hopeful. I uncovered the root of a seedling and traced a dark Rhizopogon strand connecting it to a giant Douglas fir a few meters away. Another root was coated in a shimmering yellow mycorrhizal fungus, a Piloderma, and I followed the fleshy yellow threads to an old birch. I sat back, startled. This little seedling was entwined in a prosperous mycorrhizal network with both the mature fir *and* the paper birch. 167.

I tugged my hat over my ears. The network did indeed seem to be sustaining the seedling. The old trees could be sending it sugars or amino acids through the fleshy fungal mats. To compensate for the minuscule rates of photosynthesis the tiny needles could muster in the dim light and the sips of nutrients the fledgling roots were pulling from the soil. Or maybe the old trees just inoculated the seedlings with their own diverse suite of mycorrhizal fungi so the youngsters could get at the tightly bound soil nutrients without additional assistance. 167-168.

[**QUESTIONS**] But it didn't make sense that birch always gave more carbon to fir than it received in return. 169. I was testing whether birch continued to help fir through the childhood years, and whether fir eventually gave back – perhaps in the off-seasons of early spring and late fall, when birch had no leaves – and did so even more as fir slowly, naturally overtook birch in early childhood. 170—171.

[Follow the continuation of these experiments with the anti-fungal uses of birch with fir at 12d]

5d. Birch with Fir - seasonal change exchange direction (Dr. Melanie Jones' work)

[**EXPERIMENT adding in spring and fall**] [Dr. Melanie Jones, of Okanagan University, with her student Leanne] repeated my Nature experiment, this time including not just [**TOOLS**] one shot of isotopes in summer, but additional doses in in the spring and fall, to see whether the direction of the net transfer shifted over the seasons. Whether fir gave more to birch in the spring and fall, when fir was growing and birch was leafless, the opposite of what I'd observed in summer.

The first labeling took place in early spring, when the buds on the fir had broken and started to sprout needles but the birch leaves had not flushed. At this time, fir was a source of sugar, and birch was the sink.

The second labeling took place in midsummer, as with my Nature experiment, when the birch leaves were full expanded and sweet with sugar and the firs grew more slowly in the shade. In this case, we expected to find the same result: carbon moving down the source-sink gradient from birch to fir.

The third labeling was in the fall, when fir was still putting on girth and roots while the birch leaves had yellowed and stopped photosynthesizing. Fir was again the source and birch the sink. 175.

[**RESULTS of seasonal exchange of carbon between birch and fir**] Our hunch was right. The way carbon flowed between the trees changed over the growing season. Unlike what happened in the summer, when birch sent more carbon to fir, Douglas fir in spring and fall sent more carbon to birch. This trading system between the two species, shifting with the seasons, suggested that the trees were in a sophisticated exchange pattern, possibly reaching a balance over the course of a year. Birch was benefiting from fir, just as fir was benefiting from birch. 175 Quid pro quo 175.

5e. Other Sharing Relationships

[EXPERIMENTS] I investigated whether these relationship with birch varied with the identity of the conifer species – whether it was Douglas fir or western larch or western red cedar or spruce – and discovered that they did 177. As I ate, I wondered why trees – these **aspens and pines** – would support a mycorrhizal fungus that provides carbon (or nitrogen) to a neighboring tree. A later study would show that the roots of **at least half of the pines in a stand are grafted together**, and the larger trees subsidize the smaller ones with carbon. Blood runs thicker than water. 184.

Fir with fir seedlings 207. **Hemlock with crumbling logs**, hazelnuts, Sitka mountain ash, false box tracking elder Douglas fir to truffle. 221. **Old to young.** 221. **Old trees** sharing. 271.

6. Carbon Storage in Trees, Roots, Soils, & Microbes, or Vaporizing with Clear-Cutting compounding Climate Change; Planting of mixed forest to put carbon in soil and serve as fire breaks; Climate Change > Migration of species

[**BACKGROUND storage in roots, soils and microbes**] 130. 146, I returned to the site with university research associate, Dr. Dan Durall, an expert, an expert at labeling trees with carbon isotopes. He was also my next-door neighbor in Corvallis. Dan had just finished a project for the Environmental Protection Agency where he'd labeled trees with [TOOLS] carbon-14 and learned that half of the carbon was shuttled and stored below ground – in roots, soils, and microbes such as mycorrhizal fungi. The EPA needed this information so they could start figuring how best to store carbon in forests for mitigating climate change. 150.

Don was working on his own dissertation, examining clear-cutting effects on forest composition and carbon storage patterns across a portion of British Columbia the size of Oregon, <u>**soon to discover that clear-cutting was causing carbon dioxide to pulse into the atmosphere at unprecedented rates**</u>. 158.

[BACKGROUND on birch, aspen, wildfires, mixed forests, losses to air] When it's young, though, birch photosynthesizes at higher rates than the conifers and sends more sugars to its roots, and eventually large amounts are stored in the soil. If we start managing forests for increased carbon storage – to slow climate change – birch might be a good choice. 202.

"We're going to need birch and aspen to grow quickly and put a lot more carbon in the soil, where it will be safe from fire." I went on to explain, that in most years in Canada, more carbons is lost to wildfire than from the burning of fossil fuels, and we should be trying to reduce the risk planning for landscapes of mixed forests instead of coniferous forests, and for corridors of birch and aspen to serve as firebreaks, because their leaves were moister and less resinous than those of conifers. 202.

[**BACKGROUND on new networks; species migration isn't keeping up**] The new grant would eventually show us that the complex mycorrhizal network unraveled into chaos with clear-cutting. With the Mother trees gone, a forest would lose its gravitas. But within a few years, as seedlings grew into saplings, the new forest would slowly reorganize into another network. Without the pull of the Mother Trees though, the new forest network might never be the same. **The carbon in the trees, and the other half in the soil and mycelium and roots, might vaporize into thin air.**

Compounding climate change. Then what? **Wasn't this the most important question of our lives?** 232-233.

If all this could be revealed, we could better predict how tree species would migrate northward or upward in elevation as temperature warms – that is, to locations that would better fit their genes. As climate heats up, the forests will become sick and many trees will die, as was already happening, but new species preadapted to the warmer conditions should move in to take their place. Likewise the seeds of the species in the dying forest should disperse into new areas that now matched their genes. One of the problems with the predictions was that this assumed trees would migrate at record speed – over a kilometer per year, rather than the fewer than a hundred meters we'd seen in the recent past. 251.

[NW This author has compiled a history of the Earth's atmospheric and soil's carbon intermingled with nature's reactions – migration, adaptation, or extinction. It will be posted at the NS Wild Flora site. The author also has written pieces for the public on atmospheric carbon.

http://nsforestnotes.ca/2019/01/28/my-little-bit-wont-hurt-carbon-emissions-biomass-burning/ (With a large bibliography at the end.)

https://www.nsenvironmentalnetwork.com/blog/isnt-417-ppm-of-atmospheric-carbon-enoughnbsp (hyperlinks links within article)

https://www.hikenovascotia.ca/filemanager/files/Whiston_%20More%20Than%20Just%20Trees%202020-06-18.pdf (hyperlinks within slideshow.)

https://www.invernessoran.ca/top-story/columns-and-letters/1796-my-ancestors-part-of-problem]

7. Nitrogen - Fungi Sharing Fixed Nitrogen with Plants

(See also Appendix E) **Alder Swales** 101-126 & **Bar Fight** 127-141 Alder with Pine 117-122.

7a. Nitrogen's Purpose: Chlorophyll ($C_{55}H_{72}O_5N_4Mg$), Amino Acid (R-CH(NH2)-COOH), Protein (R-CH(NH2)-COOH), Enzymes, DNA ($C_{15}H_{31}N_3O_{13}P_2$); Deficit of Nitrogen effect on growth and dealing with local climate extremes; Loss of nitrogen to fires [and also to soil warming]

[**BACKGROUND on nitrogen's purpose**] Nitrogen is essential for the building of proteins, enzymes, and DNA, the stuff of leaves and photosynthesis and evolution. Without it plants can't grow. It is also one of the most crucial nutrients in temperate forest because it frequently goes up in smoke in wildfires. Deficits in nitrogen, along with cold temperatures, are known to limit tree growth in northern forests. 116. [And chlorophyll ($C_{55}H_{72}O_5N_4Mg$). See also Appendix E.]

[**BACKGROUND on nitrogen loss in fires]** After fire, scattered alders replenish nitrogen gas gassed out by wildfires. 68.

7b. Alder with Pine – Alder's *Frankia* bacteria and effects of removing alder during the first year (Continued from Water 2d and continued at 7c)

(Continued from 2d. This experiment is in two chapters 2d and 6b, as it is a question of water and, more significantly of nitrogen.)

[**QUESTIONS on war on alder and its Frankia**] In the distance, helicopter were spraying the valleys with chemicals to kill the aspen, alders, and birches in order to grow cash crops of spruces, pines, and firs. I hated this sound. I had to stop it. 100.

I was especially puzzled by the war on alder, because Frankia – the symbiotic bacteria inside its roots – had the unique ability to convert atmospheric nitrogen into a form the small shrub could use to make leaves. When the alders shed their leaves in the fall and decayed, the nitrogen was released into the soil and became available for the pines to take up with their roots. The pines relied on this transformation of nitrogen because these forests burned every hundred years, sending much of the nitrogen back into the atmosphere. 100.

[**EXPERIMENT**] To evaluate the competitive effect of the herbaceous layer, I'd create three separate alder-free herbaceous treatments: 100 percent herb cover, where I'd leave the natural cover of herbs to grow freely; 50 percent herb cover, where I'd reduce the natural cover by half; and 0 percent, where I'd completely get rid of all the herbs. In each of these, I'd cut and [**TOOLS**] paint the alder first, then spray [**TOOLS**] herbicides [glyphosates] to kill the assigned portions of herbs. In the total-annihilation treatment, I'd spray everything in sight – shrubs, herbs, grasses, and mosses – creating bare earth. 103.

[See also 2c for this experiment's water and sun results.]

[**RESULTS in growth by fall**] By fall of the first year, the short-term increases in water and nutrients – released during decomposition – resulted in enhanced growth of the planted pine seedlings compared to where the alders resprouted. This is what policymakers saw. 117.

[**QUESTIONS**] **<u>But would the seedlings always be fine, or would the looming nitrogen shortage catch up to them</u>**? 117.

… I wasn't sure. I thought about the papers I'd read. It was clear that pines get nitrogen from the soil after it's been enriched by nitrogen-fixing plants like alder. 117. [For that process see Simard 120-121.]

[**RESULTS by fall growing with nitrogen-fixing alder**] By October, I had [**TOOLS**] the foliar nitrogen data in my hands. Pine seedlings growing among alder were rich in nitrogen,

[**RESULTS by fall growing without nitrogen-fixing alder**] and those without were depleted. Even though the pines among the dead alder roots in the bare-earth treatment were taking up more phosphorus and calcium released from decomposition, they were more depleted in nitrogen in particular because of the absence of new nitrogen additions to the soil. 117.

This suggested to me that for most of the time, other than the most stressful weeks in August, alder was replenishing both *water and nitrogen* in the soil. How this forest functioned was turning out to be much more complex than the blunt free-to-grow policy presumed. 118.

Policymakers, I thought, saw only the data of depletion. The short-term, the first roadside glance. Alder preempting resources that otherwise would be available to pine seedlings.

But once I stood back and took in the longer sweeps of time and season and scene, I could see that this was clearly not the whole story. It seemed data were revealing a story of bounty.

Where I'd eliminated all of the alder, I also lost far more pine seedlings to voles and rabbits, which had made a beeline for the needles. 118.

[**RESULTS after a year in bare earth, after alder decomposed**] After about a year, however, after dead alder had long since decomposed and the mineralized nitrogen had been consumed by seedlings or plants or microbes, or leached through groundwater, the total amount of nitrogen in the bare earth treatment plummeted compared to where alder grew freely. The short-term pulse of nitrogen as ammonium and nitrates released during decomposition was quickly used up, and there was no alder left to replace or augment that nitrogen. It went missing in action. 116-117.

[**QUESTIONS**] If a nitrogen transforming plant like alder could send nitrogen to a tree like pine, the forests might not be as nitrogen limited as we thought. We chattered about the implication for farms: if legumes passed nitrogen to corn, for instance, we could mix crops and stop having to pollute the soil with fertilizers and herbicides. 122.

My mind was wound up like a clock, pendulum swinging. The direct link between alder and pine, explain the rapidity with which pine could sense the availability of newly transformed nitrogen in alder, could be the mycorrhizal fungi. 122.

They missed what we could not yet fully see: how the symbiotic bacteria and mycorrhizal in the roots of the alder, and the other invisible creatures in the soil, helped the pine. 123.

I had lots of experiments where I sprayed alder with herbicides [glyphosates] showing no improvement in pine growth. But what I really needed was evidence that alder helped pine. 123.

[**RESULTS immediate on light, water, growth and nitrogen**] "You can see in this slide that removing alder somewhat increases the amount of light the pines received, as you'd expect, as well as water for a week in the middle of the summer, but this is at the cost of lowered nitrogen availability once the piles of dead plants have decomposed." 130.

<u>7c. Alder with Pine – Alder's *Frankia* bacteria and effects of removing alder after 5 years and longer on: local climate extremes, growth, survival; increased degree of infestation, lowered concentrations of nitrogen in pine needles (Continued from 2d and 7b)</u>

[**RESULTS after five years on local climate extremes**] The end result is that there is little net improvement in stand growth after five years." I said, moving on to the data from my weather station, showing how killing all the plants made local climates more extreme – blistering hot during the day and frosty at the soil surface during the night. 130.

[RESULTS after 15 years on nitrogen, growth, and survival] In fifteen years, there'd be three times more nitrogen than where the alder had been killed. Within one year of planting, the effects of alder weeding on soil nitrogen had already become evident in the lowered nitrogen concentrations in the pine needles. On top of that, even though the pines free of alder were growing at faster rates, more than half had died. 118-119.

[**RESULTS after 30 years on nourishment, infestation, survival**] Eventually I would learn that these alderless pines would become so malnourished that they'd be infested by the mountain pine beetle, and most of the rest would die. Three decades later, only 10 percent of the original seedlings planted in the bare-earth treatment would remain. 120.

[**QUESTIONS / RESULTS on nitrogen in pine needles**] The weeding proselytizers kept overlooking the fallout from the longer-term loss of nitrogen and eventual decline of the plantations. How could we ignore this? I needed to convince them that the alder was necessary for replenishing the soil and, over the longer haul, was complementary, not detrimental, to pine growth. I needed more evidence that alder was a facilitator, not just a competitor. But it would take decades for the impacts of alder removal – the downturn in nitrogen fixation, decomposition, and mineralization – to show up in lost productivity of the forest. I couldn't wait that long. Besides, the seedlings seemed to sense nitrogen depletion almost immediately. The needles of pines in bare earth had less nitrogen than hose among the alder after only one year. There had to be a more direct pathway between alder and pine. 120.

Pine got nitrogen from alder not through the soil at all but thanks to mycorrhizal fungi. As though alder were sending vitamins to pine directly through a pipeline. After mycorrhizal fungi colonized alder roots, the fungal threads grew toward the pine roots and linked the plants. 121.

Maybe the alders have more nitrogen than they need" "Or the pines give something back to the alders?" 121.

[RESULTS during and after a century on productivity, by half] [TOOL] Don's model had forecast that productivity of century-old pine forest would dwindle by half where alders were no longer present to add nitrogen back to the soil. And that the vitality of the forest would slide further and further with removal of alder at each successive cutting cycle. The model showed how pines needed alder neighbors … especially when nitrogen capital was depleted right after a disturbance such as logging or fire. A young women's hand shot up, and she didn't wait for a gesture from me before asking, "Then why are we spending so much to spray alder when it doesn't improve the performance of our plantations and might even make them worse off?" 131

7d. Alder with Pine - Nitrogen transfers (1993 Kristina Arnebrant Study) & Birch with Fir: concentrations of nitrogen, growth, and infestations with and without birch

[**BACKGROUND Arnebrant's lab research of nitrogen transfer from alder to pine]** At the end of the day, we loaded [**TOOLS**] the gas analyzer back in the truck. Sitting on the tailgate, I checked to make sure we hadn't forgotten anything. Barb had marked down the concentrations of carbon dioxide, water, and oxygen, the amount of light shining on the needles, and the temperature of the air inside the chamber. 149.

When I remembered the lab study of Kristina Arnebrant, the young researcher for Sweden who showed that alder delivered nitrogen to pine through mycorrhizal connections. 149.

[1993 Arnebrant, Kristina et al. 1993 "Nitrogen translocation between Alnus glutinosa (L.) Gaertn seedlings inoculated with Frankia sp. and Pinus contorta Doug, ex Loud seedlings connected by a common ectomycorrhizal mycelium." *PubMed.gov* (see also 121) https://pubmed.ncbi.nlm.nih.gov/33874350/]

7e. Frankia nitrogen-fixing bacteria host plants with other plants (See also Appendix E for other *Frankia* hosts.)

"Could selection also operate at the group level? Individual species organized into complex."

Shrubs such as **alder** and **soapberry**, I explained, were beneficial to their needle-leaved neighbors because of **their ability to host symbiotic bacteria [Frankia] that fix nitrogen**. Not to mention, I thought to myself, their role in providing food for birds and medicine for people and carbon for the soil. In preventing erosion and fire and disease. Toward making the forest a lovely place to be. 197.

"It's partly because birch provides a lot of nitrogen to the coniferous trees, which they're short of. They [birch] also protect the firs against Armillaria root disease, which slows the trees down if it doesn't outright kill them." 199.

[See also Appendix E for other nitrogen-fixing bacteria: Bayberry, Sweetfern, Sweet Gale, with Alder and Soapberry]

7f. Birch with Fir: Effects on fir on concentrations of nitrogen, guards against root disease, growth, and infestations with and without Birch

[**EXPERIMENT**] I returned the next day to collect [**TOOLS**] foliar sample from the birch and fir to be tested for nitrogen concentrations. 149.

[**RESULTS couple of weeks later comparing nitrogen in birch to fir**] A couple of weeks later, this data came back from the lab. The birch had double the concentration of nitrogen in its leaves compared to the fir needles. Not only did this help explain the higher photosynthetic rates of birch compared to fir (nitrogen is a key component of chlorophyll), it also meant there was a nitrogen source-sink gradient between the two species. Like between the nitrogen-fixing alder and non-fixing pine in Kristina's study. 149.

[**RESULTS later on fir growth, nitrogen and infestation with and without birch**] Without the companionship of birch, with its microbes transforming nitrogen along mycorrhizal networks and bacteria helping guard against root disease, the growth of pure Douglas-fir stands declined to half of that evidenced in mixtures with birch. Birch, on the other hand, maintained its productivity without fir.

<u>7g. Paper Birch with Douglas Fir – Communicating, immediate (Geiger counter results); Fungi on each tree's roots separately: *Cenococcum*, *Laccaria laccata* [Au254, 255, 335], *Phialocephala*, *Thelephora terrestris* [Au437, 442] and *Wilcoxina*; Those fungi growing when both trees present: *Lactarius* [milk fluid in caps Au240, 244, 247 …] and *Tuber* (which houses Bacillus bacteria nitrogen-fixer) (See Also Appendix D Ectomycorrhizal Fungi)</u>

[**QUESTIONS creating amino acids, birch shuttling more**] I wondered if this nitrogen source-sink might be as important as the carbon source-sink gradient in driving the flow of carbon from birch to fir. Or if the source-sink gradients in the two elements worked hand in hand. Instead of carbon flowing in whole sugar molecules through the fungal pipelines, the sugars might break down into their bare elements (carbon, hydrogen, and water) and the free carbon could join up with nitrogen from the soil to form amino acids simple organic compounds ultimately used to make proteins), for example, in leaves and seeds. The newly formed amino acids, and any lingering sugars would then shoot through the network. With gradients in both carbon and nitrogen – carbon in sugars and nitrogen plus carbon in amino acids – birch was perfectly equipped to shuttle more food to fir that it received in return. 149-150.

[**EXPERIMENT**] I returned to the site with university research associate, Dr. Dan Durall, an expert, an expert at labeling trees with carbon isotopes. 150.

Labeling the seedlings would take us six days – ten triplets per day. In each triplet, we'd place [**TOOLS**] one garbage-sized clear plastic bag over the birch and one of the fir. In half the triplets, we would inject the bag over the birch with carbon dioxide tagged with [**TOOLS**] the carbon-14 isotope, and we'd inject the bag over the fir with [**TOOLS**] carbon-13-tagged isotope, and we'd inject the bag over the fir with carbon-13-tagged carbon dioxide, which they'd absorb over a couple of hours through photosynthesis. This would allow us to detect carbon moving in both directions between the trees. 151

Carbon-13 and carbon-14 are slightly heavier forms of the common element carbon-12 – atomic weights of thirteen and fourteen instead of twelve – but they are naturally very rare and can therefore be used as tracers of how carbon-12 behaves in photosynthesis and sugar transport. In the other half of the triplets, I'd switch which tree got what – tagging birch with carbon-13 and fir with carbon-14 – case the different isotopes were distinguishable by birch and fir and therefore affected how much they took up through photosynthesis and how much the transmitted to their neighbor. 151

If trees did detect the tiny difference in the mass between the two isotopes, I could calculate the relative magnitude of transfer of each isotope and then correct for their subtle discrimination differences to be sure it didn't mess with my ability to detect how shading affected the carbon fluxes. 151.

Besides, cedar was my control and it would pick up a mix of aerial and soil transfers of carbon, and it would tell me in total about any errant escapees. 151.

But Dan insisted we could do better than that. Before removing the bags, we could]**TOOLS]** vacuum out the unabsorbed isotope carbon dioxide and capture it in tubes. Then we would largely eliminate potential aerial transfer. 151-152.

We perfected our techniques for injecting the isotopic gases into the bags, and the day came when we were ready to label the seedlings. It was warm out in the clear-cut, and even hotter inside my plastic suit. Since carbon-14 is radioactive, I was worried about exposure, so I wore a rainsuit, a respirator, giant plastic goggles, and rubber gloves sealed to my sleeves with duct tape. Dan thought I was nuts as he donned his simple white lab coat, knowing that carbon-14 was not very dangerous in the way we were using it. 153. The scariest thing about carbon-14 is that if it does manage to stick to you, maybe lodge in your lung, it hangs around for long time, given its half-life of 5,730 (+ /- 40) years. Carbon-13, on the other hand, was a nonradioactive isotope and of no concern. 153.

[**RESULTS immediately on the connected birch and fir**] Dan said, "Maybe." We still needed to check the seedlings with [**TOOLS**] the Geiger counter. 154.

I flicked on the switch. A crackle sang from the wand. Dan's face lit up. The hand on the meter swung hard to the right, showing a high radiation count.

"Oh good. I did it right." Dan said, relieved.

"Do you think we'll be able to detect anything in the fir neighbor?" I asked.

"I doubt it. It's only been a few hours since we started the labeling," he said. 155.

… But what the heck. It cost nothing to try. 155.

Tilting my ear toward its stem, I ran [**TOOLS**] the Geiger counter over the fir's needles. My wrist lifted slightly in an upbeat, and my Geiger counter wand crackled faintly as the dial on the meter swung up a tad. 155.

I was part of something much greater than myself. I shot a look at Dan, his mouth frozen open.

"Dan!" I cried. "Did you hear that?"

He stared at the Geiger counter. He had wanted with his whole heart for the labeling to work, and what we were hearing from the fir was beyond anything he'd expected. [As it was immediate.] We were listening to birch communicate with fir. 155-156.

[**EXPERIMENT continued**] We wouldn't know for sure until we properly analyzed the tissue samples with [**TOOLS**] a scintillation counter, more sensitive at detecting radioactive carbon-14, and [**TOOLS**] a mass spectrometer, for measuring carbon-13. These would quantify accurately how much labeled photosynthate had traveled between birch and fir. 156.

[**RESULTS immediate continued**] Yes! Deep down, in our own ways, we both knew that we'd picked up something miraculous happening between the two tree species. Something otherworldly. Like intercepting a covert conversation over the airwaves that could change the course of history. 156.

[**RESULT on unconnected cedar**] I stepped to the cedar in the triplet, my palms sweating. I seemed to own the answer already. I lifted the wand and ran the Geiger counter over its braids. Silence. Cedar was in its own arbuscular world. Perfect. 156.

[**EXPERIMENT**] How long the isotopes would take to move fully, to complete their journey from seedling to seedling, was a mystery, so I planned to wait six days. 156.

I put my arm around Dan's shoulder and whispered, "We've found something really cool here." 156.

After the six-day wait, we dug the trees out of the ground. The roots of the birch, fir, and cedar were massive, intertwining, and covered with mycorrhizas. 156.

The next day, I drove to Victoria with the samples in coolers. I was using a designated lab facility to grind my tissue samples into powders, which I would send to [**TOOLS**] a lab at the University of California, Davis, for analysis to detect the amount of carbon-14 and carbon-13 in each sample. I ground my radioactive samples in [**TOOLS**] the fume hood. 157.

It took five ten-hour days to grind all the sample. On the last day, I was vacuuming out the fume hood and fiddling with my dust mask when I noticed the metal tab on the top covering my nose. When I squeezed the sides, it miraculously tightened the mask over my nose. My heart sank. I hadn't been squeezing the nosepieces on the dust masks properly. 157.

[**RESULTS same fungi on both fir and birch grown separately: Phialocephala**, **Cenococcum**, **Wilcoxina**, **Thelephora terrestris** and **Laccaria laccata**] Even though the birch and fir had been grown separately, most of the mycorrhizal fungi colonizing the roots were *the same ones*. Not just one species of fungus, but five. Fungi as varied as the mushrooms they spawned. 158-159. [See Appendix D]

[**RESULTS which fungi added to the list on fir and birch grown together: Lactarius** and **Tuber**] When I got the fir roots from the mixed pots under the microscope, I almost fell off my lab stool. … Not only that, two brand-new species emerged on the fir *and* the birch: Lactarius … and Tuber … 159.

I shouted that the firs grown with birch looked like decorated Christmas trees. While the firs grown all alone had fewer mycorrhizas. 159.

The seven shared fungi, we'd later discover, represented a fraction of the dozens of fungal species in common between birch and firs. The cedars, as I expected, were colonized only by arbuscular mycorrhizal fungi and were not part of the network joining paper birch and Douglas fir.160. [The lists are fully in the book, but alphabetically arranged in the Appendices.]

<u>7h. Garry Oak with Douglas Fir</u>

He [Don] told me about a study from California showing the same mycorrhizal fungal species colonizing Garry oak and Douglas fir, and scientists were trying to figure out whether the tree species were linked. And whether nutrients moved between them. 122

<u>7i. *Rhizobia* nitrogen-fixing bacteria within legumes with garden plants - Three-Sisters (Also on barrens roadsides, lawns, meadows, or forests</u>)

My garden's transmitting carbon to the beans and squash it was shading. And the squash sending water it had network shuttling nitrogen from the nitrogen-fixing beans to the corn and squash. And the tall, sunny corn saved to the thirsty corn and beans. 179. The wolves had given me a sign, as had my three sisters garden. 190. Grasses, herbs, and shrubs 221. Ensuring the community in which they were raising their kin was healthy 270.

"The next day, we sowed beans, corn, and squash. When the seeds germinated, their radicals would signal the arbuscular mycorrhizal fungi, which would join the plants in an intimate web, as I imagined was happening among the yews, cedars, and maples across the lake. The tall waking cedars would be starting to infuse the sleepy little yews with sugars, which would use the energy to grow their shaggy bark and make drops of paclitaxel. As the maple leaves opened, they'd send sugary water to the cedars and yews in the shadows, helping them get enough to drink on the dry summer days. The yews might return the favors to the maples in late fall, sending sugary reserves from their green cells to help the neighbors slumber through the winter. Mycorrhizal fungi would begin to wrap around the mineral grains, waking up the mites and nematodes and bacteria. 277-278.

8. Humus - Nitrogen and Minerals - Fungi and Other Microbes Mining for Minerals and Salvaging Nitrogen and Minerals from the Decay; "Blood of Bugs and Guts of Fungi"

8a. Creating Humus; Sand drained of nutrients by heavy rains; Earliest soil creation had Earth's first fungal connections: Lichen's rhizines exuding enzymes for rock break down, working with fungi to build humus; Evolutionary collaboration with fungi necessary for surface life beginning 450 – 700 million years ago

[**OBSERVATIONS on sand & its nutrients**] A thin bleached layer of sand gleamed, so white it looked like snow. I would later learn that most soils in this mountain country had surface layers like this, as if drained of all life by heavy percolating rains. Maybe beach sand is so pale because storms quench it of the **blood of bugs and guts of fungi**. Among these blanched mineral grains, an army of roots was threaded with an even denser thicket of fungi, sapping the upper soil horizon of any other nutrients that might remain. 30.

[**OBSERVATIONS** on humus] I stared at the clump of roots in my fist. Clinging to them was glistening humus that reminded me of chicken manure. Humus is the greasy black rot in the forest floor sandwiched between the fresh litter from fallen needles and dying plants above and the mineral soil weathered from the bedrock below. Humus is the product of plant decay. It's where the dead plants and bugs and voles are buried. Nature's compost. Trees love to root in the humus, not so much above or below it, because there they can access the bounty of nutrients. 14.

[**BACKGROUND on lichen's enzymes and building up soil**] "Look at the lichen on this rock, Mum." A red pie-shaped crust was bordered with whitish fungal filaments radiating outward. A symbiosis. "A fungus took a likin' to an alga." I said. 80. The roots of the lichen – the rhizines – exuded enzymes to break down the rock, while the lichens' bodies contributed organic material, and together made humus for plants to root and grow. 80. Come to think of it, the lichen and mosses and algae and fungi were also steady as could be, gradually building up the soil, quietly in tandem. 81.

I landed two interviews. The first involved sitting across the vast desk from a manager at Weyerhaeuser who told me he couldn't wait to cut down all the old-growth forest so they could reconfigure the mill for small plantations. At the second, the guy at Tolko Industries told me they were trying to mechanize as much as possible. Neither offered me a job. 82.

"There's a new silviculture researcher at the Forest Service, named **Alan Vyse**. You should try him," Jean said. 82.

[**BACKGROUND of evolutionary history, requiring fungi plant coevolved connection; Unique structures, abilities to acquire, transport, and transmit information chemicals]** I read a little further and found another startling passage. The mycorrhizal symbiosis was credited with the migration of ancient plants from the ocean to land about 450 to 700 million years ago. Colonization of plants with fungi enabled them to acquire sufficient nutrients form the barren, inhospitable rock to gain a toehold and survive on land. These authors were suggesting that cooperation was essential to evolution. 61.

8b. Creating Humus: Litter's processors (including for Nitrogen): earthworms, slugs, snails, spiders, beetles, centipedes, springtails, millipedes, enchytraeids, tardigrades, mites, pauropods, copepods, bacteria, protozoa, nematodes, archaea, fungi, viruses; 90 million critters in each teaspoon of soil.

[**BACKGROUND on leaf / wood processing, and access to inorganic nitrogen**] I puzzled over how the pine seedlings received the nitrogen so rapidly from alder. The conventional thinking was that the transformed nitrogen was stored in alder leaves, which were shed during the waning days of fall and decayed by a food web of bugs. A pyramid of creatures, the bigger ones eating the littler ones. Earthworms, slugs, snails, spiders, beetles, centipedes, springtails, millipedes, enchytraeids, tardigrades, mites, pauropods, copepods, bacteria, protozoa, nematodes, archaea, fungi, viruses, all munching and crunching one another. More than 90 million critters living in each teaspoon of soil. As they ate the leaves, they made smaller and smaller bits of litter. As they consumed the litter, and one another, they excreted excess nitrogen into the soil pores, making a nutritious soup of nitrogen compounds accessible to the pine roots. But in this decomposition and mineralization process, faster growing plants like grasses could grab the inorganic nitrogen before the pines and this didn't square with the great amount that ended up in the needles of the pines growing alongside the alders and grasses. [See above Alder with pine 8b & 8c.] 120.

<u>8c. Fungi salvaging nitrogen from aging wood, humus, and mineral particles</u>

Others [fungi] were [salvaging] nitrogen from aging wood. 168. [See also chapter 9.] They [The fungi] unlocked essential nutrients that had been held tightly for centuries, in tenacious complexes of humus and mineral particles. Atoms of **ancient nitrogen and phosphorus** that were sequestered on **phyllosilicate** clays and bound in carbon rings linked together like chicken wire. 168.

I wondered why trees – these aspen and pines – support a mycorrhizal fungus that provides carbon (or nitrogen) to a neighboring tree. 184.

{See also Mycena 1b.]

<u>8d. Fungi salvaging nitrogen from live springtail</u>

[**BACKGROUND on sourcing from springtail**] One particularly gruesome study showed that the mycorrhizal fungal threads growing plants from the tips of roots could invade the stomachs of soil-dwelling springtails feeding on decaying plant litter. The fungal treads sucked the nitrogen straight out of the springtail stomachs and delivered it directly to their plant partners. The springtails, of course, suffered a horrible death. The fungi supplied one-quarter of plant nitrogen simply with the stomach contents of springtails! 120-121.

<u>8e. Fungi salvaging nitrogen from decaying salmon</u>

[**BACKGROUND examination of tree rings for specific nitrogen**] Scientists before me have discovered that the nitrogen from decayed salmon lives in the rings of trees along the rivers from where they came. 289.

[**QUESTIONS**] I wanted to know whether salmon nitrogen was absorbed by mycorrhizal fungi of the Mother trees and transmitted through their salmon nutrients in the trees declining with the reduction in salmon populations and habitat loss, causing the forests to suffer? If so could this be remedied? 289.

[**EXPERIMENT**] We were search of the bones of salmon carried into the forest by bears and wolves and eagles. The bones were all that were left once the flesh was eaten and the residual tissue decayed, nutrients seeping into the forest floor. 289.

With me were Allen Larocque, my new doctoral student who would investigate the patterns of the fungal networks, and postdoctoral fellow Dr. Teresa "Sm'hayetck" Ryan of the Tsimshian Nation, the people of the Skeena River to the north. 289.

Each bear preying on the spawning salmon transported some 150 fish per day into the forest, where the roots of the trees forage for the decaying protein and nutrients, **<u>the salmon flesh providing more than three-quarters of the tree's nitrogen needs</u>**. The nitrogen in tree rings derived from salmon was distinguishable from the soil's nitrogen because fish at sea get enriched with [**TOOLS**] the heavy isotope nitrogen-15, which serves as a natural tracer of salmon abundance in the wood. Scientists could see the year-by-year variation in tree-ring nitrogen to find correlations between salmon populations and changing climate, deforestation, and shifting fisheries practices. An old cedar tree could hold a thousand-year record of salmon runs. 290.

[At this time, 2016, Simard did her TED talk. 290. "How Trees Talk to Each Other" / Suzanne Simard posted August 30, 2016 18:25 https://www.youtube.com/watch?v=Un2yBgIAxYs Another TED talk with the same name. Feb 2 2017 19:32 https://www.youtube.com/watch?v=breDQqrkikM

"Look!" Under the boughs of the old Mother Trees was a cozy, mossy bed large enough for a mama bear and her cub. Dozens of salmon skeletons gleamed from the carpet, the … 291-292.

Allen and I collected soil from under the bones and, for comparison, from places where there were no bones. 292.

[**RESULTS of mycorrhizal fungi transporting salmon's nitrogen-15**] This study is ongoing, but our early data show that the mycorrhizal fungal community in the salmon forest differs depending on the number of salmon returning to their natal streams. We still don't know how far into the forest the mycorrhizal network is transporting the salmon nitrogen, and if – or how – restoration of the tidal stone traps might affect forest health, but we are starting new research and reconstructing some of the stone walls to find answers. 293.

<u>8f. Fungi salvaging and sharing Phosphorus</u>

She said, "But why are the mycorrhizas on grasses different from those on trees?" 68.

I shrugged. My [fungus] book said that the **arbor-shaped membrane** [arbuscular Fungi] has a huge surface area **<u>so fungus can trade phosphorus and water with the plant for sugar</u>**. Good for **<u>helping plants in dry climates and where soils are low in phosphorus</u>**. 68.

There was **a short term pulse of other nutrients** (phosphorus, sulfur, calcium) to the soil as the dead roots and stems decomposed, [See above] 116.

Some [mycorrhizal fungi] were good at acquiring phosphorus from humus, others nitrogen from aging wood. 168. Knapweed stealing phosphorus 226.

<u>9. Fungi Generalists and Specialists – Fungi Finding and Sharing Water Sources, Nitrogen, Phosphorus, Spring, Fall, Exudate Producers, Bacteria Supporters, Fungal Setting for Bacterial Nitrogen Fixers, & Fungal Setting for bacteria which are Disease and Pathogen Fighters (See also 2d and 4a)</u>

[**OBSERVATIONS**] I dug through the forest floor encasing another of the seedlings and found a half-dozen more mycorrhizas on its roots. By now, I knew that there were more than a hundred species of mycorrhizal fungi in this forest. About **half were generalists**, colonizing both **paper birch and Douglas** fir in a diverse network. An intricately woven rug. **The other half were specialists**, with fidelity to either birch or fir but not both. Each of these specialists was thought to have its own niche. [1] **Some were good at acquiring phosphorus from humus**, others [2] **nitrogen from aging wood**. [3] **Some sopped up water from deep in the soil**, others [4] **from shallow layers**. [5] **Some were active in spring**, [6] **others in fall**. There were [7] **some that produced energy-rich exudates [plant excretions] that fueled bacteria** performing other jobs, **such as breaking down humus** or [8] **transforming nitrogen** or [9] **fighting disease**, while other fungi produced [10] **fewer exudates because their jobs required less energy**. [11] The glossy sheen of the ***Piloderma*** mycorrhiza I'd seen linked the birch suggested that it held a rich supply of carbon, supporting a biofilm of the luminescent ***Pseudomonas fluorescens*** **bacteria, whose antibodies could shrivel the growth of the root pathogen *Armillaria ostoyae.*** [12 see 8] The ***Tuber*** mycorrhiza turned out to **host *Bacillus*** bacteria that transformed nitrogen, helping explain why birch leaves had so much more nitrogen than fir needles. 168.

I talked about the Bacillus bacteria on birch roots that fix nitrogen and the florescent ones that produce antibiotics and reduce the pathogenic infections on nearby firs. 204.

The thick fungal strands of the tough *Rhizopogon* truffles and the fine mycelial fans of the fragile Wilcoxina mushrooms, and the hundreds of other fungal species in this old forest, had unique structures and abilities to acquire, transport, and transmit. Their long threads reached for treasure, their tendril fingers wrapped around the prizes. The information chemicals must transmit through these fungal highways along the various roots. Following the source-sink gradients between rich and poor. 230-231.

<u>10. Defense: Anti-Fungal Protection - Alder with Pine Fungi Sharing; Effects of Free-To-Grow on *Armillaria* Pathogen (Simard's Third Doctoral Field Experiment) (See also Appendix F & G)</u>

<u>10a. Alder with Pine –Affects With or Without Fungi to Rabbits and Voles (herbivores); Frost Protection; Sun-Protection</u>

[**RESULTS]** [See also Alder swales] Where I'd eliminated all of the alder, I also lost far more pine seedlings to voles and rabbits, which had made a beeline for the needles. The critters Robyn and I had worried about has reproduced like crazy in the clipped alder piles. The seedlings, the only green plants left in the bare plots, were like magnets, and the rodents merrily clipped off the luscious shoots in the first season. All that was left of most of the planted seedlings were brown nubs. Still other seedlings succumbed to frost damage leaving short yellow needles and eventually nothing but pale, dead stems. A number were sunburned, with scars at the bases where there was no shade – protection normally provided by leafy plants around them. By the end of the summer, more than half of the seedlings stripped of their alder neighbors were dead. 118.

[**RESULTS among kept alders**] Almost all the pines among the alders, on the other hand, were alive. They were growing at a slightly slower pace compared to the few remaining in the bare-earth treatment, but their needles were healthy and deep green. 118.

<u>10b. Noting Plants with Infection</u>

[**OBSERVATIONS row planting; ½ free-to-grow pines now have infection or injury**] Same rationale as my Grannie Winnie planting her garden in rows, but she worked the soil and varied her crops over the years. 17, 18.

<u>**Pathogenic fungi**</u> ***Armillaria*** honey-brown flat capped 28.

Instead, foresters ignored the mycorrhizas, or – worse – killed them with fertilizer and irrigation in the seedling nursery, and focused only on those fungi that damaged or killed big trees the pathogens. 61

"But whether sprayed with herbicide or cut with brush saws, whether on dry or wet sites, down south or up north, or whether the crop is pine or spruce, stand growth doesn't improve even though they can be declared free to grow sooner. What bothers me is that half the free-to-grow pines now have some infection or injury that will eventually kill or maim them." 130.

<u>10c. Investigations into *Pseudomonas fluorescens* bacteria found working with *Piloderma* fungi to Protect against *Armillaria* (1999 Rhonda Lynn DeLong)</u>

{**EXPERIMENT**] I'd convince Rhonda, my summer field assistant at the Forest Service to do her master's continuing my investigation of *Pseudomonas fluorescens*, the fluorescing bacteria I'd found antagonistic to *Armillaria ostoyae*. 171.

[**RESULTS**] She'd compared the abundance of the helpful bacteria between forest types and found four times more in birch stands than fir stands, probably because birch roots and mycorrhiza fungi, fueled by higher rates of photosynthesis, provide more food for the bacteria than firs can manage. She also found as many bacteria on firs as birches when the two species were mixed together, as though the tiny microbes were able to spread from the carbon-rich birches to fir when they were intimately mixed. 171.

Delong, Rhonda Lynn 1999 The role of fluorescent pseudomonad bacteria in the resistance of paper birch (Betula papyrifera Marsh.) to Armillaria ostoyae in the southern interior of British Columbia https://www.semanticscholar.org/paper/The-role-of-fluorescent-pseudomonad-bacteria-in-the-DeLong/eb63c15577eabedc83698e2012838e67af26d1da

<u>10d. Birch with Fir – Effects of Fungal Disconnected or Connected on Nitrogen; on Growth and on infestations from *Armillaria ostoyae or Armillaria sinapina* pathogenic fungi; Beetle infestations; Birch and carbon nitrogen support (Simard's third Doctoral Field Experiment)</u>

[**OBSERVATIONS**] Hacking and spraying the birch led to birch getting ***Armillaria*** pathogenic fungus which lives naturally in soil. Because it [the birch] was harmed, it infected the birch and spread to roots of conifers. When birch left untouched, the pathogen remained subdued. 93.

I picked paper birch as my test species, because I knew from childhood that it made a rich humus that should be as helpful to conifers as it had been delicious in my dirt-eating days. I was also intrigued that it seemed to keep pathogens at bay. But birch was only a weed to timber companies. To everyone else, it was a gleaming provider of sturdy waterproof white bark, shady leaves, and refreshing sap. 94-95.

My earlier experiments also suggested that birch somehow protected the conifers against early death from *Armillaria* root disease. 95.

If fir somehow needed birch, birch wouldn't be hurting fir, as foresters assumed. Quite the opposite. 97. [Without the birch] within a few weeks, all of the seedlings were dead 97.

There were some that produced energy-rich exudates that fueled bacteria performing other jobs, such as breaking down humus or **transforming nitrogen or fighting disease**, while other fungi produced fewer exudates because their jobs required less energy 168.

[**EXPERIMENT**] My third doctoral field experiment was here, where the rancher had spread the grass seed to carry out his revenge. I was lucky the trees had grown well in this little area in spite of the grass. The saplings, now five years old, I were already taller than I was. I crouched at one birch sapling surrounded by a [**TOOLS**] thick lip of plastic poking from the ground, part of the [**TOOLS**] meter-deep wall I'd sunk down to encircle its root system. This system was similar to the way I'd used sheet metal in the forest. Instead of building a moat around groups of seedling, though I'd built separate [**TOOLS**] ones [moats] around each of the sixty-four seedlings planted in a grid, a small forest. The plastic was still strong and intact, and it would maintain its integrity for many years. I was testing whether birch continued to help fir through the childhood years, and whether fir eventually gave back – perhaps in the off-season of early spring and late fall, when birch had no leaves – and did so even more as fir slowly, naturally overtook birch in early adulthood. 169-170.

To figure this out, I was comparing this trenched plot of trees with a nearby plot of sixty-four birch and fir left untouched, interwoven as one. Making the trenches was like conducting an archaeological dig in an ancient city of stumps. Barb and I had hired a fellow with [**TOOLS**] a miniexcavator and a crew of four young women with shovels to dig the meter-deep trenches. We'd clawed out sprawling root systems and edged out granite boulders to make nine trenches along the eight rows of trees, the ninth trench being on the outside of the last row. We'd excavated nine more in perpendicular rows, resulting in a crisscross. Popping out of the maze of trenches were the sixty-four islands of soil containing one tree each. When we'd lined the islands with [**TOOLS**] plastic – so the roots and mycorrhizas wouldn't burst through – and backfilled the maze with dirt, the only things left visible were the slivers of plastic breaking the surface. Hidden below was perfect eight-by-eight Latin square. 170.

[**RESULTS in the fungi disconnected plots**] I wondered if the firs really were smaller here than in the other plot where the roots were free to mingle with those of the neighbors. One sapling was dead, its red needles in the snow like drops of old blood. So I grabbed its flaking trunk and pulled it out of the ground. The rotting root stubs were covered with creeping black fungal strings – rhizomorphs. Flicking open my knife, I carved off the bark at the base of the stem and laid bare the woody xylem. Snow-white fungal hyphae formed a noose, confirming death by the fungal pathogen *Armillaria ostoyae*. I searched the plastic trenches for more corpses - a third of the firs had died. 170.

[**RESULTS in the fungi connected plots**] In the untrenched plot, all were alive, and I could have sworn bigger too. 170.

My guess was right. The firs connected with their birch neighbors were not only all living, they were larger than the trenched firs. The birches, on the other hand, were unaffected by their intimacy with the firs, not drained by the association. Birch was not being bled dry by transmitting some of its carbon. It was giving enough to boost the survival and growth of the fir without cost to its own vigor. 171

None of the firs showed any signs of *Armillaria* root disease. Growing enmeshed with birch seemed to protect fir from sickness – as I'd seen in many other experiments. 171.

[**OBSERVATIONS**] The beetles also infested plantations, especially those with fast-growing pines that had been weeded of their birch and aspen neighbors. 183. "It's as you thought." He said, pointing at [**TOOLS**] histograms proving that clear-cutting and removal of birch was detrimental to the long-term productivity of the forest. … 187-188.

I showed data on how many birches could be left in particular situations to ensure good conifer growth while minimizing root disease and maintaining biodiversity. My research was rigorous, it was also as young as I was. 197.

It's partly because birch provides a lot of nitrogen to the coniferous trees, which they're short of. They also protect the firs against the Armillaria root disease, which slows the trees down if it doesn't outright kill them." 199.

As birch reaches about fifty, near the end of its lifespan, it becomes more susceptible to *Armillaria sinapina*, with many risking infection of stem and roots *Armillaria sinapina* was like *Armillaria ostoyae*, but it infected mainly broadleaf trees like birch rather than conifers. Both fungal species occurred naturally in these forests … Weeding the clear-cuts of birch and aspen made the situation even worse because the new stumps provided a rich food base for this fungus [*Armillaria ostoyae*] to grow, increasing its potential to infect the planted conifers seedlings. 201.

A plantation where the birches had been cut to the quick and the stump soaked with herbicide [glyphosates] to attain free-to-grow status. 204.

When the birch had been clipped, the *Armillaria ostoyae* had infected the stressed roots and spread to the roots of the intermingled firs [Douglas fir]. Douglas fir, lodgepole pine, and western larch were heavily favored for planting but paradoxically were the most vulnerable to the type of infection. 204.

I talked about the *Bacillus* bacteria on birch roots that fix nitrogen and the florescent ones that produce antibiotics and reduce the pathogenic infections on nearby firs. Leaving a healthy mix of birches with its helpful bacteria, I argued, could enhance the health of the fir, like a public immunization program. "The bacteria are fueled by carbon leaked by the mycorrhizal networks as carbon passes back and forth between birch and fir," … "We can surgically remove a few birches to release the firs retain most of the birch to keep the infections down." 204-205.

[2010] My lab was busy, and I chased after grants and wrote more articles. I continued to teach and work on the free-to grow problem, and I published three journal articles in 2010 showing that free-to-grow lodgepole-pine plantations were in jeopardy with the warming climate. 235.

[Simard, S.W. and Austin, M.E. (2010). The role of mycorrhizas in forest soil stability with climate change. Sciyo, Chapter 15, pp. 275-302. *Climate Change and Variability*, Suzanne Simard (Ed.), ISBN: 978-953-307-144-2] https://www.intechopen.com/chapters/11448

Jean helped me collect the data and Don analyzed it, and we found that more than half the pines in the province were dying from insects and disease and other maladies like drought stress. 235.

Another independent study, though, had verified that the majority of pine plantations were in poor health. 235

Crisscrossing the mountains between Vancouver and Nelson, watching the beetle-killed forests turns into a mange of clearcuts, my anger with forestry practices grew. I co-authored a Vancouver Sun opinions editorial with Dr. Kathy Lewis, a colleague at the University of Northern British Columbia, that we titled "New Policies Needed to Save Our Forests." We highlighted the sea of clear-cuts, citing how they were "reducing landscape complexity and affecting broad-scale ecological processes such as hydrology, carbon fluxes, and abiotic damage, and said this would worsen with climate change. 235-236.

Over the course of the day, a hundred foresters wrote responses to the newspaper in agreement. 236.

Dr. Kathy Lewis, Dr. Suzanne Simard 2011 "New Policies Needed to Save Our Forests." Reprinted in https://forestindustries.eu/de/content/new-policies-needed-save-our-forests

They had better nutrition – the rich birch leaves building the soil 281. 284.

11. Defense: Warnings, Immuno Stimulants, and Defense-Enzyme Production; Monoterpenes (like Alpha Pinenes] - Fungi or Aerosols Sharing These

11a. Douglas Fir with Ponderosa Pine: dealing with beetles & blue-stain fungus; monoterpenes: Warnings and Implementing Defense Response (2015 YuanYuan Song et al.)

[**BACKGROUND on infestation, pathogen, thirst, and monoterpenes**] "What are these globs?" Mary asked, pointing to the drops of yellow pitch on the bark of the dead lodgepole pines lining the trail. … I explained that the pine tried to pitch out – eliminate – the beetle when it burrowed into its bark, but the ultimate cause of death was the blue-stain fungus carried into the wood on the bug's legs. The pathogen spread through the xylem [^], plugging the cells and cutting off the water coming up from the soil. "The tree died of thirst," I said. 239.

Even though the beetle and fungus had coevolved with the pines, the past few decades of fire suppression had created a vast landscape of aging pines ripe for an epic infestation. 240.

"Some will live, but most will die," I replied. The pines produced an array of defense compounds – monoterpenes – to inhibit the beetles. 240.

The sweep of dead trees throughout the West was disturbing to witness. Some individual pines could increase their defense through a greater production of the monoterpenes, but even so, not many had survived this outbreak. 240. Still, in spite of the worms burrowing in the buds of the firs and the beetles in the pines, the forest here was anything but dead. Many saplings were in good health, and plants were spreading into the gaps where the dead pines had fallen over. "**Survivors should produce new generations better adapted to pitch out the beetles**," I said. 240-241.

[**QUESTIONS on warning systems and defense**] "It's even possible the firs and pines can warn each other about infestations," I said as we continued along the trail. I explained how **Dr. YuanYuan Song**, a scientist from China, had been working with me to see if firs infected with budworms might warn neighboring pines to prepare themselves. Her query had arrived out of the blue, asking if she could come for a five-month postdoc to test whether the warning system she'd detected among tomato plants in the lab also occurred among coniferous trees in forests. YuanYuan had already found that tomato plants communicated their stresses to other nearby tomatoes, and we were both curious if similar signals might occur between trees. 241.

Integration of the two species in a mycorrhizal web would well provide more than just an avenue for swapping resources. If the Douglas firs dying in the drought were making way for pines better adapted to the warming temperature, were they still connected and communicating with the pines, even as they passed? Could the firs warn the pines that there were stresses in the new areas? Maybe they could send the pines information about sickness. 246

[**BACKGROUND tomato's transmission of warnings of pathogen infection, defense genes activation, and production of defense enzymes**] My colleague YuanYuan's tomato plant had not only transmitted warning signals though the interlinking arbuscular network to its neighbor about a pathogen infection, but the neighbor upregulated its defense genes in response. Even more, the neighbor's genes got to work and produced an abundance of defense enzymes. These enzymes must have subdued the pathogen, because when the fungus was applied to the eavesdropping tomato, it incredibly did not cause disease. YuanYuan had come to help me ask the same of ailing firs, to see if the pines stood a better chance in the new environment because the firs signaled the nature of their plight. 246.

She'd boldly advanced our knowledge on mycorrhizal networks, whizzing past historical handwringing over what constituted an interplant connection by inoculating her lab-grown plants with [**TOOLS**] a plenitude of networking hyphae Some scientists had still been puzzling over whether linking into networks affected the welfare of the recipient plants, and she'd gone well beyond this. She'd not only examined the receiver-tomato growth responses but had measured the activity of its defense genes, its production of the defense enzymes, and its resistance to disease. 250-251.

[**QUESTIONS**] If dying trees communicate with incoming species, we might use this knowledge to better assist the migration of tree species as the old forests become maladapted to their native places. A warning-and-aid system – those infested Douglas firs **telling pines to upgrade their defense arsenal**, for instance – might be important for the growth of the new species or race (genotypes) as the old forests were dying back. 251.

As the injured Mother Trees slowly folded their cards, did they transmit their remaining carbon and energy to their offspring? As part of the active dying process. Like senescing grasses, handing over their remaining photosynthates to boost the next generation. Maybe they just dispersed the content of their dying cells randomly to the rest of the ecosystem, since energy is neither created nor destroyed. 251

[**EXPERIMENT**] At the university greenhouse, we placed 90 one-gallon pots on benches and filled them with the forest soil. In each pot, we planted one Douglas-fir and one ponderosa-pine seedling, but to alter the degree to which pine attached to the mycorrhizas of the fir, we planted one-third of the ponderosa in soil-filled mesh bags with pores large enough for any mycorrhizal hyphae, but not any roots, to grow through. We planted another third in mesh bags with pores so fine that only water could pass between the fir and pine. In the final third, we planted the ponderosas directly into bare soil so their mycorrhizas could freely connect with the firs, roots intermingling. [35 µm, 0.5 µm and no mesh treatments.] Our plan was to infest one-third of the firs in each of these soil treatments with western spruce budworms, snip the needles off another third with scissors, and leave the remaining third untouched as a control. Nine treatments all told, the soil and defoliation treatment fully crossed, with ten replicates of each. 252

We waited. … After four months, we'd checked some seedling roots under [**TOOLS**] the dissecting microscope, YuanYuan panicky when I said they looked bare. I then took some thin cross sections, squashed them on a slide, and looked under the compound scope: There were Hartig nets. The roots of Douglas firs and ponderosa pines had both become colonized with the single mycorrhizal fungus Wilcoxina. This told us that the fir and the pine were connected by Wilcoxina mycorrhizal network, except in the fine mesh, and we could go ahead with our defoliation treatments. 252-253.

YuanYuan raced to the bug-rearing lab and grabbed her wriggling budworms. I ran to the mycorrhizal lab for scissors and sterilizing alcohol. We went into the greenhouse together to divest the seedlings of their needles. She put a breathable bag over a third of the seedlings and inserted in each a couple of budworms to feast on the needles. I clipped the needles off another third, leaving a few species to carry out photosynthesis. The remaining third we left untouched. 253.

One day after the defoliation, we put gas-tight plastic bags over the firs and pulsed them with $^{13}C\text{-}CO_2$. The next day, YuanYuan and I sampled the pine needle, doing the same the next day and the one after that, to check for defense-enzyme production. After six days, we pulled up all of the seedlings, ground them to bits, and went the samples to a lab with [**TOOLS**] a mass spectrometer to see if the firs had sent the pines any carbon isotope through the fungal inks. 253.

[**RESULTS of defoliating on carbon exchange, defense-enzymes**] [A few months later the lab work came back and they looked at it. YuanYuan in Jinshan and Suzanne in Vancouver. They email each other and …]

A few minutes later, she [YuanYuan] added, "But I've never seen carbon after a defoliation migrate into the shoots of a neighbor." With defoliation, the firs became a large source of carbon, and the rapidly growing pines had drawn the carbon straight into their leaders. 253.

"This matches with the defense-enzyme data," she tapped, sending a graph five minutes later. <u>**The firs had increased defense-enzyme production with the budworm infestation**</u>, which was normal, <u>**but within a day, the ponderosa pine *had done the same thing***</u>**.** "But look," I wrote, "none of this happens unless the two tree species are linked in a network." 253-254.

The pine's defense enzymes – four of them – had dramatically increased in perfect synchrony with the carbon dump, and this occurred only it the pines were linked belowground to the firs. Even slight injury to the firs elicited an enzyme response in the pine. The firs were communicating their stress to the pines within twenty-four hours. 254.

What the trees were conveying made sense. <u>**Over millions of years they'd evolved for survival, built relationships with their mutualists and competitors, and they were integrated with their partners in one system**</u>. 254.

I was floored. 250.

The Douglas firs that YuanYuan and I had infested with western spruce budworm had dumped half of their photosynthetic carbon into their roots and mycorrhizas, and 10 percent of it had traveled straight to their ponderosa-pine neighbors. But what had me banging out an email to YuanYuan, now a professor at the Fujian Agriculture and Forestry University, was that only those pines connected by a mycorrhizal network to the dying firs, not those whose connection were restricted, were recipients of this inheritance. 250.

This was a triumph a full year in the making – and now an answer was here. 250

[See also: Song, Y., Simard, S., Carroll, A. *et al.* Defoliation of interior Douglas-fir elicits carbon transfer and stress signaling to ponderosa pine neighbors through ectomycorrhizal networks. *Nature's Scientific Reports* **5,** 8495 (2015). https://doi.org/10.1038/srep08495 https://www.nature.com/articles/srep08495]

[See also https://www.sciencedirect.com/topics/chemical-engineering/monoterpenes]

11b. [Added from Elsewhere] Alpha Pinene of Pine with Forest; Alpha Pinene (a monoterpene) scrubs the air, and antiviral, antifungal, antibiotic; anti-cancer. Alpha Pinene was found to boost immune response; (2016 Dr. Diana Beresford-Kroeger)

Though not in Simard's book the following is taken from Beresford-Kroeger relating to this topic. It is well-worth a full read:

Beresford-Kroeger, Diana. 1 April 2016. "Green Machines." *New Internationalist* https://newint.org/features/2016/04/01/forest-chemistry

From Bereford-Kroeger: "Each species of tree has its own chemical identity that is always true to its own genome. The greater the diversity within the forest, the more varied is the biochemistry and the more interactive the synergy between the released chemicals. Sometimes the aerosols are released under pressure like a landmine. More often it is the physics of the sun's heating that drives the release. Other times the aerosols require carrier compounds to aid in their lift.

Boosting immunity

[6] Aerosols have a unique ecofunction in the atmosphere. [1] Many are 'scrubber' compounds, like detergent. Their aseptic character helps clean the air. [2] Some harbour hallucinogens or have gentle anaesthetic characteristics. [3] Many are antiviral, antifungal and antibiotic. [4] There are also complex, anti-cancer biochemicals that become airborne, like those of the pine family.

[7] There are 200 or so species of pine threaded through the global forest – from the Jack pine (*Pinus banksianna*) of the northern boreal to the Kauri pines (*Agathis australis*) of New Zealand. **Pines all produce *alpha* and *beta pinenesa*. Research in Japan has found that these aerosols protect the body against cancer by boosting the immune system**. Something similar happens in the warmer forests of the Americas, Asia and Tasmania with **another aerosol, *taxodione*, produced by the cypress family. Taxodione has strong tumour-inhibiting properties. And then there is *paclitaxel*, produced by a yew tree of the *Taxaceae* family and used routinely in the treatment of breast cancer.**"

11c. [Added from Elsewhere] Salicylic Acid ($C_7H_6O_3$) of Willows with Apple; Fresh Willow mulch implements 13 Defense Responses in Apple Trees, including causing the tree's increase resistance to pests, fungi, bacterial, and viral diseases and to thicken apple's leaves and produce phenolic acids, tannins, defensive enzymes, and antibodies (2019 Glynn Percival)

See also Szubert, Alicja 12 June 2020 "Tree Vaccination with Pure Mulch." *Canadian Organic Grower* https://magazine.cog.ca/article/tree-vaccination-with-pure-mulch/

Szubert, Alicja 2 July 2020 "How Willows Could be the Future of Tree Health." *Permaculture* Based upon research of Dr. Glynn Percival, a researcher at the Bartlett Tree Research Laboratory at the University of Reading. Since reshuffled or thinned from their site. https://www.permaculture.co.uk/

Szubert: "What's even more surprising is that whereas humans require a unique vaccine for each disease, just one dose of SA [Salicylic acid] increases a tree's resistance to a multitude of pests and fungal, bacterial, and viral diseases. Up to 13 defense mechanisms are activated, causing the tree to thicken its leaves and produce phenolic acids, tannins, defensive enzymes, and antibodies. … Because different willow species contain varying amounts of SA, this was also measured and is shown in the graph below. [From Szubert's Permaculture article:] Note that fresh, not composted, wood chips contain higher amounts of SA as decomposition leaches the chemical from the wood. And if willows are not a viable option, then poplars (*Populus alba*) also contain salicylic acid, albeit less."

Glynn Percival, Reading University. Nov 15, 2019 "Vaccinating trees? Willow mulch for control of apple scab." Organic Growers Alliance @ Organic Matters https://www.youtube.com/watch?v=-i1RFG8vzkY
https://www.youtube.com/watch?v=c_5YnkOw_aQ

It needs to be noted that lichens that live on apple trees each have their own defenses and likely would add to the apple tree's defense. For some additional background on Immunostimulants see Appendix F & G

12. Generational Connectivity - Mother Plants and Mother Trees

12a. Douglas Fir with Seedlings and Saplings – Tracking physically and using DNA, Rhizopogon's Mycelium and Its Hartig Net (2010 work with Kevin Beiler)

[**QUESTIONS**] Young [fir] trees were colonized by *Rhizopogon* as were the old, and this was crucial in my quest to understand whether the network helped young Douglas fir establish under the canopy of their elders. Whether the *Rhizopogon* network was key to the continual regeneration of the forest, the ability of the forest to rejuvenate, to sustain itself no matter what. Besides researchers had already [**TOOLS**] sequenced pivotal portions of the *Rhizopogon* DNA to distinguish one fungal individual – a genet – of singular genetic identity, like an individual person – from another, providing a crucial element for making a map of individual fungal strands linking one tree to another. 218-219.

Where perhaps the success of seedlings depended on tapping into mycelia that were flush with water, raised by the taproots of the old trees from the deep granite fissure. **Attaching to the mycelial networks of the elder [tree] could well be more urgent for seedlings where the soil was parched** compared to where it was damp, helping them quench their thirst and gain a foothold. 219.

[**OBSERVATIONS**] I tracked another root from the elder [Douglas fir] and found another truffle, and another. I raised each to my nose and breathed in its musty, earthy smell of spores and mushroom and birth. I traced the black pulpy whiskers from each truffle to the riggings of roots of seedlings of all ages, and saplings too. With each unearthing, the framework unfolded – this old tree was connected to every one of the younger trees regenerated around it. 221

[**EXPERIMENT**] Later another of my graduate students, Kevin, would return to this patch and [**TOOLS**] sequence the DNA of almost every *Rhizopogon* truffle and tree 221.

[**RESULTS on which trees were linked with which trees**] and find most of the trees were linked together by the *Rhizopogon* mycelium, and that the biggest, oldest trees were connected to almost all of the younger ones in their neighborhood. One tree was linked to forty-seven others, some of them 20 meters away. Roots of seedlings of all ages and saplings too. Old tree was linked to every one of the young trees regenerated around it. One tree bound to the next, and we figured the whole forest was connected - by *Rhizopogon* alone. 221.

We published these findings in 2010, followed by further details in two more papers. If we'd been able to map how the other sixty fungal species connected the firs, we surely would have found the weave much thicker, the layers deeper, the stitching even more intricate. 221.

[Beiler, K.J., Durall, D.M., Simard, S.W., Maxwell, S.A. and A.M. Kretzer. (2010). Mapping the wood-wide web: mycorrhizal networks link multiple Douglas-fir cohorts. *New Phytologist, 185: 543-553.*] See also Durall 150.

[**OBSERVATIONS on root and mycelium preparation and their exchange**] This courageous root was as vulnerable as a growing bone and it survived by emitting biochemical signals to the fungal network hidden in the earth's mineral grains [nutrients] its long threads joined to the talons of the giant trees. The mycelium of the old tree branched and signaled in response, coaxing the virgin roots to soften and grow in a herringbone and prepare for the ultimate union with it. 222.

On invasion, the fungus envelopes the root cells, forming a latticework – a Hartig net – the color of beeswax, or seawater, or rose petals. The fungus delivers nutrients, supplied by the vast mycelium of the old trees, to the seedlings through this Hartig net. The seedling in return provides the fungus with its tiny but essential sum of photosynthetic carbon. 222.

The roots of these little seedlings had been laid down well before I'd plucked them from their foundation. The old trees, rich in living, had shipped the germinants waterborne parcels of carbon and nitrogen, subsidizing the emerging radicals and cotyledons – primordial leaves – with energy and nitrogen and water. The cost of supplying the germinants was imperceptible to the elders because of their wealth – they had plenty. 222.

Once the Hartig net was firmly embedded in the radical of the new sprouts, and the old trees were dispatching sustenance, making up for the paltry rates of photosynthesis by the cotyledons [primordial leaves], the fungus could then grow new hyphal threads to explore the soil for water and nutrients. As the miniature crowns of the seedlings spawned new needles, they would feed the mycelium with their own photosynthetic sugars, so the fungus could travel to even more distant pores. 223.

Once on solid footing, life running as smoothly as a stock market exchange, the growing root could then support a fungal mantle – a coating – as though donning a jacket of mycelium, from which even more fledgling hyphae could grow into the soil. The thicker the mantle and the greater the number of fungal threads the root could feed, the more extensively the mycelium could laminate the soil minerals, and the more nutrients if could acquire from the grains and transport back to the root in trade. **Root begets fungus begets root begets fungus**. The partners keeping a positive feedback loop until a tree is made and **a cubic foot of soil is packed with a hundred miles of mycelium**. A web of life like our own cardiovascular system of arteries, veins, and capillaries. I wound two of my upended seedlings into my hair and started back up the slope. 223-224

A belowground network could explain why seedlings could survive for years, even decades, in the shallows. These old-growth forests were able to self-regenerate because the parents helped the young get on their own two feet. Eventually, the young ones would take over the tree line and reach out to others requiring a boost. 224-225

[See Simard's 2014 Mother Trees Connect the Forest https://www.youtube.com/watch?v=O_EJmEaT06I]

[**RESULTS on linkage to deep rooted trees**] But I already knew; these little seedlings were linked into the network of old trees, receiving enough water to get them through the driest of summers. My students and I had already learned that the **deep-rooted trees brought water up to soil surface at night by hydraulic lift and shared it with shallow-rooted plants**, helping the archipelago stay whole during prolonged drought. 227.

Without such attachment, death of a seedling can be nearly immediate … 227.

12b. Searocket: Detecting Relatives; Roots giving clues (2007 Dr. Susan Dudley of McMaster University)

[**BACKGROUND skyrocket experiment showing plants recognize kin**] I'd been mulling over the possibility that kin recognition, something we normally ascribe to humans and animals, might occur in Douglas fir. 258.

I'd read a paper by Dr. Susan Dudley of McMaster University in Canada about her discovery that an annual plant – the searocket, *Cakile edentula*, of the Great Lakes' sand dunes – could distinguish between neighbors that were kin (siblings from the same mother) and those that were strangers, from different mothers, and that the cues came from their roots. 259.

[See also Susan A Dudley and Amanda L File 13 June 2007 "Kin recognition in an annual plant" Biology Letters The Royal Society https://royalsocietypublishing.org/doi/10.1098/rsbl.2007.0232]

12c. Douglas Fir - Detecting Relatives, roots giving clues; Affecting signals, nutrients, fitness, and size (2013 Amanda K. Assay Experiments)

[**QUESTIONS**] I wondered if conifers could detect relatives too. A Douglas-fir forest was genetically diverse, with wind pollinated kin and stranger seedlings establishing around the Mother trees. *Could Mother Trees distinguish kin from stranger seedlings*? 259.

I'd figured if kin recognition were occurring, and if it involved root cues as Susan had found with her searockets, it would have to be signaled through fungal links, because all trees roots were coated in mycorrhizal fungi. Also, given that populations of Douglas fir were regionally distinct, with less genetic variation in local valleys than across mountain ranges, there should be lots of relatives in close proximity to Mother Trees. If relatives had lived closely together for centuries, surely, I thought there must be a fitness advantage to recognizing one another. To helping one another along, carrying forward the family line. Maybe the Mother Tree could alter her behavior – make some elbow room – to increase the fitness of her kin. Or transmit nutrients or signals to her offspring. 259.

[**EXPERIMENT**] I rested while Amanda checked more mesh. In the spring, she's installed twenty-four of them around each of the fifteen Mother Trees in this clear-cut. [**TOOLS**] Twelve of the bags had pores big enough for the mycorrhizal hyphae of the Mother Tree to grow through and colonize the germinants. [**TOOLS**] The other twelve had pores too small to form a network. In each of these mesh-bags, Amanda had sown with seeds from the Mother tree (kin) and six with seeds from different Mother Trees (strangers). The four treatments - the two mesh and two relation treatments fully crossed – were applied at each of the fifteen Mother Trees, a number meant to give us confidence in any trends. To ensure our finding were not an anomaly of this location, we'd repeated the experiment at two more sites. This clear-cut near Kamloops was the hottest and driest, and the two farther north were cooler and wetter. 261.

For sowing kin seeds, Amanda had collected cones from out total of forty-five Mother Trees were fewer than ten meters in height but hired a girl to use a shotgun where they were taller. 261.

[**RESULTS of kin survival**] She [Amanda] pointed to a cluster of red seedlings and said, "Many of the kin are alive,

[**RESULTS of strangers survival**] but the strangers are dead." Unrelated and unconnected to the Mother Tree, the strangers had perished in the summer drought. 260.

We walked toward the other fourteen Mother Trees, left by the loggers as habitat for wild life, as my thoughts slid into a dark corner. 260.

Under this Mother Tree, just as with the first, more kin were alive than strangers, especially in bags that allowed them to connect to the network. I chewed at the end of my pencil. It was possible birch also sent more carbon to related birches than firs in the mixed stands, but I hadn't tested this in my doctoral research. 260.

Even before adding up the numbers, I knew Amanda and I had gone beyond confirming that Douglas-fir seedlings tended to perform better if linked to a healthy, unrelated Douglas-fir Mother Tree: seedlings that were her kin survived better and were noticeably bigger than those that were strangers linked into the network, a strong hint that Douglas Mother Trees Douglas fir Mother Trees could recognize their own. I suggested following another year.

"I'd feel better if we could," Amanda said. 262.

[See Mycorrhizal facilitation of kin recognition in interior Douglas-fir (Pseudotsuga menziesii var. glauca) Asay, Amanda Karlene, University of British Columbia 2013 https://open.library.ubc.ca/soa/cIRcle/collections/ubctheses/24/items/1.0103374]

12d. Douglas Fir Greenhouse Experiment Kin versus Strangers. Kin greater mycorrhizal colonization, heavier root tips, more iron, copper, aluminium, more carbon (essential in photosynthesis and seedling growth) (2017 Brian J Pickles, Amanda Assay et al. Experiments)

[**BACKGROUND**] Amanda's Kin-Recognition Experiment in the three clearcuts was the just the beginning. Since I couldn't let her master's degree depend on a field study that might be bound for failure, we'd matched it with a greenhouse experiment. 267-268.

[**EXPERIMENT**] We'd matched it with a greenhouse experiment where she'd grown one hundred seedlings – what we called the "Mother Trees" for the purpose of this experiment – for eight month, then planted fifty of the pots with a side-by-side sibling and the other fifty with a stranger. With each type of neighbor – kin or stranger – twenty-five were grown in mesh bags with pores wide enough for signaling through mycorrhizal linkages, and the other twenty-five were grown in fine-pored bags where mycorrhizal networks could not form. We grew the pairs until the Mother Trees were a year old and the new neighbors were four months. 268

Amanda had emailed that she was ready to harvest her one hundred pots. "Before you do, you and Brian should label the Mother trees with $^{13}C\text{-}CO^2$ to see if they share more carbon with kin than strangers," I replied. 268.

[**RESULTS on nutrient exchange: greater mycorrhizal colonization, root tips size, more iron, copper, aluminium, more carbon (essential in photosynthesis)**] "Kin neighbors have more iron than the strangers," she said, tracing her cursor over the differences between the two types of neighbors and then showing me the same with copper and aluminum. "The Mother Trees could be delivering these nutrients to their youngsters," I said. 268-269 … These three micronutrients were essential in photosynthesis and seedling growth, I said and we bantered about whether iron, copper, or aluminum could also be part of signal molecules that move from the Mother Tree to her kin. 268-269.

Like passing a puck.

"Kin seedlings also have heavier roots tips than strangers and greater colonization by the mycorrhizas of Mother Trees," she said, her cursor hovering over the data points.

"Oh, that fits!" I said.

"Do you think it's important that we're seeing that Mother Trees are also bigger when they're next to their kin? Amanda asked. "It makes sense if they're passing signals back and forth." 269.

[Looking at the isotope data.] Brian was excitedly saying, "Look at this!"

"The amounts are small," Amanda said, "but the Mother Trees are sending more carbon to the mycorrhizal fungi of their kin than the others! Kin recognition molecules seem to have carbon and micronutrients." 269.

[Brian J Pickles, Roland Wilhelm, Amanda K Asay, Aria S Hahn, Suzanne W Simard, William W Mohn Apr. 2017 "Transfer of ^{13}C between paired Douglas-fir seedlings reveals plant kinship effects and uptake of exudates by ectomycorrhizas" New Phytol 2017 Apr;214(1):400-411. Epub 2016 Nov 21. DOI: 10.1111/nph.14325 https://pubmed.ncbi.nlm.nih.gov/27870059/]

[**OBSERVATIONS**] "Even a tiny amount moving into the mycorrhizal fungi o the seedlings could mean the difference between life and death when the little ones are small," I said.

Germinants struggling to survive in the deep shade, or during the summer dry spell, could live instead of die with the slightest boost, the smallest of advantages, if it came at the right time. 270

Forests are mosaics too. That's what makes them thrive. Birch and fir transmitted carbon to each other, even though they were different species, and to the cedar as in their unique arbuscular mycorrhizal network. These old trees were not only favoring their kin, they were also ensuring the community in which they were raising their kin was healthy. 270.

Kin appeared more dependent on Mother Trees in the dry rather than the wet climatic areas. The Mother Tree had especially stepped in to help at the driest site, perhaps by transporting water to her seedling through the network. 270-271.

[**QUESTIONS**] Maybe society should keep old Mother Trees around – instead of cutting most of them down – Maybe clear-cutting the old, even if they're not well, wasn't such a good idea. The dying still have much to give. We already knew the elders were habitat for old-growth-dependent birds and mammals and fungi. That old trees stored far more carbon than young ones. They protected the prodigious amounts hidden in the soil, and they were the sources of fresh water and clean air. Those old souls have been through great changes, and this affected their genes. Through the changes, they'd gathered crucial wisdom, and they offered this up to their offspring – providing protection, laps into which the new generations got started, the foundation from which to grow. 271

<u>12e. Old Trees Passing on Carbon and Nutrients to Those Who Would Remain</u>

[**QUESTIONS**] My unfinished business – my main lingering question – centered on this: Were the old Douglas-fir Mother Trees that were unhealthy – sick with disease, stressed from the drought of climate change, or just ready to pass on – using the their moments to transfer their remaining energy and substance to their offspring? With so many forests dying, we should figure out if the elders leave a legacy. YuanYuan and I had already seen that stressed firs passed more carbon to neighboring pines than did healthy firs, and Amanda had also discovered that, in the proximity of healthy Mother-Tree seedlings, kin seedling had better nutrition than strangers, and their mycorrhizal fungi received more carbon. But so far we hadn't seen whether dying Mother Trees passed their carbon legacy into the shoots, the lifeblood of her kin seedlings, beyond the fungal web. Therefore we couldn't verify that the carbon transferring into the fungi actually improved the kin seedlings' fitness. We didn't know if the fungus kept the carbon for itself, like a middleman, or if the carbon sent by the Mother Tree was truly to increase the survival of her children. 271.

It would take years for the full answer to arrive. 272.

[**OBSERVATIONS**] Our modern societies have made the assumption that trees don't have the same capacities as humans. They don't have the nurturing instincts. They don't care for one another, don't administer care. But now we know Mother Trees can truly nurture their offspring. Douglas firs, it turns out, recognize their kin and distinguish them from other families and different species. They communicate and send carbon, the building block of life, not just to the mycorrhizas of their kin but to other members of the community. To help keep it whole. They appear to relate to their offspring as do mothers passing their best recipes to their daughters. Conveying their life energy, to carry life forward. The yews too were in this web, in relationship with their lifelong companions, and with people like me recovering from illness or just walking through their groves. 277.

[**QUESTION**S] But that lingering question since my illness still haunted me. If we are equal to everything in nature, do we share the same goals in death? To pass the wand as best we can. Passing onward to children the most crucial material. Unless the essential energy went directly to a Mother's Tree's offspring, stem, needles, buds, and all – not just into the underground network – I couldn't be sure that the connection increased their fitness beyond that of the fungus. 286

[**EXPERIMENT**] Monika, a new doctoral student, had added another link in this chain of knowledge. In the fall of 2015, she started a greenhouse experiment with 180 pots. In each pot, she planted three seedlings: tow kin and one stranger, with one of the kin designated as her "Mother Tree." The idea was that, once injured, the Mother Tree would have a choice of where to send the last of her energy: to her kin, the stranger, or into the earth. Monika grew the seedlings in mesh bags with variously sized pores to allow or inhibit mycorrhizal connections, and she injured some of the Mother-Tree seedlings with shears or western budworms. She then pulse labeled the Mother Trees with caron-13 to trace where the carbon went. 286.

As if to remind us of the capricious nature of nature, a heat wave knocked out the greenhouse's ceiling fans, killing part of the experiment. 286-287.

Most of the seedlings were still alive. We were lucky. 287.

[**RESULTS on kin exchanging carbon and types of exchange**] Monika's Mother-Tree seedlings transmitted more carbon to kin than strangers, as Brian and Amanda had found. But unlike the earlier study, where we'd only detected carbon moving into mycorrhizal fungi if the kin seedlings, Monika now found that *it went straight into their long leaders.* The Mother-Tree seedlings flooded the mycorrhizal network with carbon energy, and it advanced into the needles of her kin, her sustenance soon within them, *Et Voila!* The data also showed that injury, whether by western spruce budworm or the shears, induced the Mother-Tree to transfer *even more carbon* to her kin. Facing an uncertain future, she was passing her life force straight to her offspring, helping them to prepare for changes ahead.

Dying enabled the living: the aged fueled their young. 287.

[**OBSERVATIONS**] The trees of the next generation with genes most adaptable to change – whose parents have been shaped by a variety of climatic conditions, those attuned to the stresses of their parent, with a robust defense arsenals and shots of energy – ought to be the most successful in rebounding from whatever tumult lies ahead. 288.

13. Alternative industries

Then we can build a cottage industries to make birch flooring and furniture instead of importing them from Sweden. Birch products, we can grow a straight, solid birch in a quarter the time of a conifer. 200.

14. Quotes (See beginning and throughout as well.)

Rachel Carson: "But man is a part of nature, and his war against nature is inevitably a war against himself." 1.

Introduction: Connections 3-6

Instead I discovered vast landscapes cleared of trees, soils stripped of nature's complexity, a persistent harshness of elements, communities devoid of old trees, leaving the young ones vulnerable, and an industrial order that felt hugely, terribly misguided. The industry had declared war on those parts of the ecosystem – the leafy plants and broadleaf trees, the nibblers and gleaners and infesters – that were seen as competitors and parasites on cash crops but that I discovered were necessary for healing the earth. 4

"I discovered that they are in a web of interdependence, linked by a system of underground channels, where they perceive and connect and relate with an ancient intricacy and wisdom that can longer be denied. I conducted hundreds of experiments, with one discovery leading to the next, and through this quest I uncovered the lessons of tree-to-tree communication, of the relationships that create a forest society. The evidence was at first highly controversial, but the science is now known to be rigorous, peer-reviewed, and widely published. It is no fairy tale, no flight of fancy, no magical unicorn, and no fiction in a Hollywood movie." 4.

When I followed the clandestine path of the conversations, I learned that this network is pervasive through the entire forest floor, connecting all the trees in a constellation of tree hubs and fungal links. … In it, the old and young are perceiving, communicating, and responding to one another by emitting chemical signals. Chemical identical to own neurotransmitters. Signals created by ions cascading across fungal membrane. 5

The scientific evidence is impossible to ignore: the forest is wired for wisdom, sentience [death], and healing. This is not a book about how we can save the trees. This is a book about how the trees might save us. 6.

Each unfolding the story of how everything was nourished 16. Spruce wood more valuable tightly grained resistant to decay, mature fir timber is weak and punky 16. This was because timber grown in grids of evenly spaced trees yielded more wood than scattered clumps. At least in theory. By filling in all the gaps, they figured they could grow more wood than occurred naturally.
With every corner chockablock, they felt justified in bigger harvests, in anticipation of future yields. And logical rows made everything more countable.

Ghosts in the Forest 7-25.

Replanting was supposed to heal what we'd taken, and we were failing miserably. 17. I kicked myself for glossing over the problem, taking the easy way out for the company. 17. Or we could plant them so their roots touched the yellow fungal web in the soil. Maybe the yellow gossamer would keep my seedlings healthy. I wished I had someone to talk to out here in the forest, to debate my growing sense that the fungus might be a trustworthy helper to the seedlings. Did the yellow fungus contain some secret ingredient that I – and everyone – had somehow missed? 19 "Perhaps it was because my grandparents had cut only a few trees in a stand, opening gaps where nearby cedars and hemlocks and firs could readily seed in, the new plants easily connecting to the soil." 20. I can't tell if my blood is in the trees or if the trees are my blood. That's why it was up to me to find out why the seedlings were fading into corpses 25.

Handfallers 26-44

[Simard:] I floated the suggestion that we could convinced the company to leave some firs in the middle of the block to spread their seed. I blurted, "You know, the way they sometimes leave the big seed trees in Germany." – [Ray:] "We only clear-cut around here." 43. [Simard] "My childhood was shouting at me: The forest is an integrated whole." 44.

Parched 45-63

Maybe the fungus *was* the key to my dying seedlings. The industry had figure out how to grow seedlings in the nursery and plant them, but totally missed that the collaborative relationships, needed nurturing as well. 62.

But I was missing part of the story and thought about today's clusters of trees. The old Douglas firs were clumped together in ravines in the deeply dry interior mountains. The soft-needled subalpine firs were huddled in clutches on mounds in the high-elevation mountains, though they were escaping the frigid sodden spring soil. How did this clustering – whether growing down low or up high – help them survive? Maybe the fungi played a role in the grouping of trees in the most trying environments, bringing them together for a common purpose – to thrive. 62.

Treed 64-77

Killing Soil 78-100

Enormous clearcuts had recently emerged on Simard Mountain, obliterating the old-growth forests. I had driven the new logging road along the shoreline where we used to moor Grampa's houseboat. Where the Jiggs outhouse used to be. And Grampa Henry's waterwheel, and his flume. Now one clear-cut morphed into the next. The cutting and monoculture planting and spraying had transformed my childhood forest. While elated with my revelation, I was heartbroken by the relentless harvesting, and it was my responsibility to stand up. To act against the government policies that I felt weakened the tree-soil links. 99.

Alder Swales 101-126

How this forest functioned was turning out to be much more complex than the blunt free-to-grow policy presumed.

Bar Fight 127-141

… Previous speaker, a fellow from Monsanto who'd just promoted brushing (weeding) with the herbicide Roundup, dwindled to silence. Still vivid were images of free-to-grow lodgepole pine surrounded by dead aspen. 127.

The weeding treatments meant to help plantations meet free-to-grow regulations – costing the companies millions of dollars – had not increased the performance of the trees. These weeded, free-to-grow pines, in spite of the money spent on them, grew at the same rate as the ones among the alders. 129.

But these brush-free individuals - the few that hadn't died from frost or sunburn, or become a meal for rodents – had turned into large gangly trees with big, awkward branches and swollen stems as they feasted on the flood of light, water, and nutrients from the rotting carcasses of their dead neighbors. I took a deep breath to explain. 129.

The audience murmured at the unusual-looking pines, with their twisted trunks pocked with sores and cankers. These foresters knew these fast-growing trees would have wide growth rings and big knots, much different from the slow-growing trees that naturally regenerated after fire. But their hope was that the cultivated trees would outgrow these defects and still be valuable in half a century, at the time of the next harvest. 129.

Gunning for fast early growth by weeding out native plants in hopes of future profits was not going to end well. For anyone. 130

Radioactive 142-163

Quid Pro Quo 164-180

There's been a dis course about whether the carbon sir David Read had seen move, between pines in his lab study amounted to anything in nature, and it had stoked controversies, including ones related to the importance of symbiosis in evolution. The question of whether it was mainly competition that shaped the forests was at stake, a long-held assumption based on recognizing that this was central to natural selection. The work with the arbuscular plants in the English lab suggested transmission through networks was irrelevant. My work, seemingly out of nowhere, suggested otherwise. I'd stepped into the middle of a firestorm. 174.

I was just a young woman from Canada who had fanned a fire already burning. I knew nothing of their flower-splashed English meadows, and they knew little of my cathedral forests. 174.

Painting Rocks 181-192

I had growing evidence that forests have intelligence – that they are perceptive and communicating. – 183.

Miss Birch 193-217

Nine-hour commute 218-237

Core Sampling 238-257

The ponderosa-pine were turning into grasslands, while the Douglas fir forest was being overtaken by the ponderosa.

Birthdays 258-278

I was still so introverted, sensitive, stumbling too easily over what others thought. I'd been too agreeable when a forester has said to me, "I want to cut these Mother Fucking trees down because they're going to blow over anyway, and we might as well make money." I was still afraid to stand strong with my convictions, fight tooth and nail. But isn't this what my trees were showing me too? That health depends on the ability to connect and communicate. This cancer diagnosis was telling me I needed to slow down, grow a backbone, and speak about what I'd learn from the trees. 262-263

Passing the Wand 279-303

Making the transformation requires that humans reconnect with nature – the forests, the prairie, the oceans – instead of treating everything and everyone as objects for exploitation. 294-295.

Mowing down the forests and harvesting the waters to fulfill our wildest dreams of material wealth *just because we can* has caught up to us. 295.

Appendix A - Fungal Types

The Au stands for page numbers in the picture section of National Audubon Society's Field Guide to North American Mushrooms. The picture page number can be followed back to the mushroom's description. The page numbers are placed in [] so they can be separated from Suzanne Simard's references and excerpts. Simard has taken lots of time to learn her stuff.

Saprophytes

Armillarias – honey-brown flat-capped around white-barked birches 28. **Saprophytes** decomposed dead stuff, crucial to cycling of nutrients 61. ***Pleurotus*** - oyster mushrooms 48. ***Mycena***: (picture 116d) breaking down wood exuding acids and enzymes 11-12. Trees had been killed by the **pathogenic honey mushroom**, the **oyster mushrooms**, their decay skills so efficient, also killed and digested bugs to meet their needs for protein. Mushrooms were as varied as their roosts, and they were masters at multitasking. 48.

Saprophytes Named

Armillarias [Au 196, 205, 209, 210, 213] [https://en.wikipedia.org/wiki/Armillaria : ***Armillaria*** is a genus of fungi that includes the *A. mellea* species known as honey fungi that live on trees and woody shrubs. It includes about 10 species formerly categorized summarily as *A. mellea*. *Armillarias* are long-lived and form the largest living fungi in the world. The largest known organism (of the species *Armillaria ostoyae*) covers more than 3.4 square miles (8.8 km^2) in Oregon's Malheur National Forest and is estimated to be 2,500 years old. Some species of *Armillaria* display bioluminescence, resulting in foxfire.]

[https://en.wikipedia.org/wiki/Armillaria *Armillaria* can be a destructive forest pathogen. It causes "white rot" root disease (see Plant pathology section) of forests, which distinguishes it from *Tricholoma*, a mycorrhizal (non-parasitic) genus. Because *Armillaria* is a facultative saprophyte, it also feeds on dead plant material, allowing it to kill its host, unlike parasites that must moderate their growth to avoid host death.]
https://www.theatlantic.com/science/archive/2022/08/humongous-fungus-climate-change-biggest-organism/671109/?utm_source=feed

Mycena [Au 45, 52, 64, 68, 70, 76, 94, 98, 102, 104] [https://en.wikipedia.org/wiki/Mycena ***Mycena*** is a large genus of small saprotrophic mushrooms that are rarely more than a few centimeters in width. They are characterized by a white spore print, **a small conical or bell-shaped cap, and a thin fragile stem**. Most are gray or brown, but a few species have brighter colors. Most have a translucent and striate cap, which rarely has an incurved margin.]

Pleurotus - oyster mushrooms

[Au 433, 484, 486, 492, 495, 496, 497, 498, 500] [https://en.wikipedia.org/wiki/Pleurotus: The genus name *Pleurotus* literally means **side ear** in reference to the mushroom caps being laterally attached to the substrate.]

Endophytic mycorrhiza

Endophytic mycorrhiza attach to plants on the inside. These include orchidaceous mycorrhiza, ericoid mycorrhiza, and arbuscular mycorrhiza

Monotropoid mycorrhizas

Monotropoid mycorrhizas ghost pipe plant, parasites green plants as it has no chlorophyll itself. Grows inside plant cells like arbuscular and ericoids. It also grows on roots 68-69. Monotropoid mycorrhizas [of the ghost pipe plant] are like the ectomycorrhizas, in that they form a fungal cap on the outside of the root tips. But they also grow inside the plant cells, like the arbuscular and ericoid varieties – making them perhaps a type in between. 69.

Orchidaceous mycorrhiza

[See also Wikipedia] Orchid network. After treatment, "When we returned, the rhododendrons, false azaleas, and huckleberries in the highest-dose treatment had shriveled and died. Not just the shrubs, but all of the plants, even the wild ginger and orchids 90. and the orchids mycorrhizas with their own too. 221.

Appendix B - Ericoid fungi

Ericoid Fungi Traits

[Ericoids] Forms coils inside plant cells – **huckleberry** 68-69. Pink mountain heathers and crowberries had roots in the crust. Some even housed sprigs of shrubs. "Dwarf huckleberries," I said, indicating some short stems growing in the lichen humus, loaded with tiny blue berries. This species only grew in the alpine. 81. The heather formed a symbiosis with the coil-like ericoid, the same type I'd discovered on the huckleberries at Stryen Creek with Jean. These lichen-fungi turned rocks into sand and released minerals, slowly making soil that other plants could grow in. **heather** 80. **Huckleberries** 221,

[With small biomass and non-existent root hairs, members of the heath / heather family, have relatively poor ability to find their own nutrients 2021 report. That report describes as well the ericoid transport of **phosphorus**. Ericoid mycorrhizal fungi can be purchased for specific blueberries and cranberries.]

Ericoid Plants

Ericoid fungi Molecular clock estimates suggest that this symbiosis with ericoid originated approximately 140 million years ago. This group includes **Azalea**, **blueberry**, **common heather**, **cranberry** (Oxycoccus), **cranberry** (Vaccinium), **crowberry**, daboecia, gaultheria, Gaylussacia, **heather**, **huckleberry**, **lambkill**, **fetterbush**, **rhododendron** (**Labrador Tea** and **Rhodora**) NW] [See also https://www.gardenerspantry.ca/yes/wp-content/uploads/mycorrhizae-list.pdf]

Appendix C - Arbuscular fungi

Arbuscular Mycorrhizal Fungi Traits: permeates root cells where cytoplasm and organelles are, often dryer habitat

[**BACKGROUND**] The arbuscular mycorrhizal fungi of grasses only grow inside the root cells. They're invisible. Not like the ectomycorrhizal fungi, which grow on the outside of the root cells of trees and shrubs, like toques. The arbuscular … grows straight through the grass cell wall and permeates the insides where cytoplasm and organelles are. It's as if they grow through skin and invade guts. … The fungus can trade phosphorus and water with the plant for sugar. Good for helping plants in dry climates and where soils are low in phosphorus. 67-68.

[**OBSERVATIONS**] The seedlings starved to death because the kind mycorrhizal they needed [ectomycorrhizal fungi] had been replaced by the kind [arbuscular fungi] only the damned grasses like. 98.

Cedar can't form mycorrhizal fungal partnerships with the birch and fir for the simple reason that it forms arbuscular mycorrhizas, not ectomycorrhizas like the other two. **If cedar roots acquire any of the sugars fixed by the fir or birch, they would have picked it up after it was leaked from their roots into the soil**. 148. **Cedars**, as I expected, were only colonized by arbuscular mycorrhizal fungi and **were not part of the network joining paper birch and Douglas fir** 160.

Even the western red cedar and yews, and the ferns and trillium which by now I knew were arbuscular mycorrhizal, probably formed a network. A seamless arbuscular web entirely separate from the ectomycorrhizal one. 169. They were probably confusing the arbuscular mycorrhizal meadows of England, 173. 175

I followed the "three-sisters" technique developed by the Native Americans, who grow **corn**, **squash**, and **beans** as companions to enhance the growth of them all. Garden plants usually associate with arbuscular mycorrhizal fungi, unlike the ectomycorrhizal species on most trees. **There are only a couple of hundred arbuscular mycorrhizal worldwide**, compared to the thousands of ectomycorrhizal species. Arbuscular are generalists and should link most of the garden plants. Like **corn**, **squash**, **beans**, **peas**, **tomatoes**, **onions**, **carrots**, **eggplant**, **lettuce**, **garlic**, **potatoes**, **yams**. 178-179.

[https://en.wikipedia.org/wiki/Arbuscular_mycorrhiza : An **arbuscular mycorrhiza** (**AM**) (plural *mycorrhizae*, a.k.a. *endomycorrhiza*) is a type of mycorrhiza in which the symbiont fungus (*AM fungi*, or AMF) penetrates the cortical cells of the roots of a vascular plant forming **arbuscules**. (Not to be confused with ectomycorrhiza or ericoid mycorrhiza.) Arbuscular mycorrhizae are characterized by the formation of unique structures, arbuscules and vesicles by Glomeromycota and Mucoromycota, sister clades of the more well-known and diverse dikaryan fungi (all three are together called "symbiomycota"). AM fungi help plants to capture nutrients such as **phosphorus**, **sulfur**, **nitrogen** and **micronutrients** from the soil. It is believed that the development of the arbuscular mycorrhizal symbiosis played a crucial role in the initial colonisation of land by plants and in the evolution of the vascular plants. It has been said that it is quicker to list the plants that do not form endomycorrhizae than those that do. This symbiosis is a highly evolved mutualistic relationship found between fungi and plants, the most prevalent plant symbiosis known, and AMF is found in 80% of vascular plant families in existence today.

Arbuscular Fungi's Plants

[See also https://www.gardenerspantry.ca/yes/wp-content/uploads/mycorrhizae-list.pdf]

Arbuscular mycorrhizal fungi (AM/AMF) plants associated include: [From mention by Simard:] **red cedar**, **yew**, **ferns** and **trillium** 169. **Corn**, **squash**, **beans**, **peas**, **tomatoes**, **onions**, **carrots**, **eggplant**, **lettuce**, **garlic**, **potatoes**, **yams**. 178-179. **Grasses**, **herbs**, and **shrubs** 221 [from https://gestion.centreacer.qc.ca/fr/UserFiles/Publications/138_Fr.pdf and then looked up.]. For evolution see https://www.britannica.com/plant/Rosales/Characteristic-morphological-features#ref1009998

Aceraceae family leaves opposite **Sugar Maple**, **Manitoba maple** / box elder, **striped maple** / **moose maple**, **Norway maple**, **red maple**, **silver maple**

Amygdaloideae of the Rosaceae family which includes **plums**, **cherries**, **peaches**, **nectarines**, **apricots**, **serviceberry**, **almonds**. The Rosaceae family also includes

Maloideae of the Rosaceae family with pomes the **apple**

Oleaceae family characterize by mostly by opposite leaves (with one samara) (**ash**, **olives**, **privet**, **jasmine**, **forsythia**, **lilac**)

Rosaceae family - generally woody, some armed with thorns, spines, or prickles to discourage herbivores, most have alternate leaves

Rosoideae of the Rosaceae family: with achenes, about 5.3 mya to 2.6 mya - dry fruit that do not open **rose**

Rubus of the Rosaceae family small drupes fleshy stone fruits including **raspberries**, **blackberries**, and **dewberries**

Sorbus of the Rosaceae family: rowan / **mountain-ash**; subfamily *Crataegus*: **hawthorn**; sub family

Spiraeoideae of the Rosaceae family with follicles – dry fruits that open on one side includes **meadowsweet** and **steeplebush**

Appendix D - Ectomycorrhizal fungi

Ectomycorrhizal Fungi Traits

Not like the ectomycorrhizal fungi, which grow on the outside of the roots cell of trees and shrubs, like tuques. 67. When I pulled up the roots of a pine seedling, I was delighted to find a bouquet of purple and pink ectomycorrhizal root tips. 88; 98. > 116; 148; 169; 173; 178.

The mycorrhizal fungi with which the trees are in symbiosis could evolve much faster to acquire increasingly tightly bound resources. Perhaps the *Suillus*, and *Boletus* and *Cortinarius* fungi could respond more immediately to the warming winters that had spawned the mountain-pine-beetle outbreak and the trees still gather nutrients and water to maintain a level of resistance. 185-186.

If the fungus acquires more carbon from one tree than it requires for growth and survival, then it could supply the excess to the other networked trees in need, and in so doing diversify its carbon portfolio – insurance in acquiring resources. **The fungus could shuttle carbon produced by a rich aspen to a poor pine in the middle of the summer to ensure it had two different healthy hosts – sources of photosynthetic carbon – in case there was a calamity and one died**. 186.

The thick complex strands running out from the Mother Trees must be capable of efficient, high volume transfer to the regenerating seedlings. The finer spreading mycelia must help the new germinants, modify to accommodate pressing, rapid needs, such as how to find a new pool of water on a particularly hot day. Pulsing, active, adaptive in providing for the growing plants. 232.

Amanitas milk caps, some toxic [Au 112, 113, 114, 115, 116, 117, 119, 120, 123, 124, 125, 126, 127, 128, 129, 130, 132, 133, 134, 135, 136, 137, 138, 139, 140, 142, 143, 144, 145, 146, 147, 148, 149, 164, 165, 166, 167, 671, 672, 673, 674, 675, 677, 678, 680, 681] [https://en.wikipedia.org/wiki/Amanita The genus ***Amanita*** contains about 600 species of agarics, **including some of the most toxic known mushrooms found worldwide**, as well as some well-regarded edible species. This genus is responsible for approximately 95% of the fatalities resulting from mushroom poisoning, with the death cap accounting for about 50% on its own. The most potent toxin present in these mushrooms is α-amanitin.]

Boletus chubby stalks, pores instead of gills [Au 370, 383, 395, 396, 398, 399, 405, 408, 409, 412, 413, 414, 418] [https://en.wikipedia.org/wiki/Boletus : The genus *Boletus* was originally broadly defined and described by Carl Linnaeus in 1753, essentially containing all fungi with hymenial pores instead of gills.]

Clavaria Coral looking, saprotrophic [Au 737, 739] [https://en.wikipedia.org/wiki/Clavaria: *Clavaria* is a genus of fungi in the family Clavariaceae. Species of *Clavaria* produce basidiocarps (fruit bodies) that are either cylindrical to club-shaped or branched and coral-like. They are often grouped with similar-looking species from other genera, when they are collectively known as the clavarioid fungi. All *Clavaria* species are terrestrial and most (if not all) are believed to be saprotrophic (decomposing dead plant material). In Europe, they are typical of old, mossy, unimproved grassland. In North America and elsewhere, they are more commonly found in woodlands.]

Cortinarius has veil between cap and stem, some very toxic [Au 276, 298, 299, 300, 331, 332, 333, 340, 341, 342, 344, 347] [https://en.wikipedia.org/wiki/Cortinarius A common feature among all species in the genus *Cortinarius* is that young specimens have a **cortina** (veil) between the cap and the stem, hence the name, meaning *curtained*. Most of the fibres of the cortina are ephemeral and will leave no trace once gone, except for limited remnants on the stem or cap edge in some species. All have a rusty brown spore print. Due to dangerous toxicity of several species (such as *Cortinarius orellanus*) and the fact that it is difficult to distinguish between various species of the genus, non-expert consumption of mushrooms from the genus is discouraged.]

Laccaria widely spaced gills, [Au 254, 255, 335] [https://en.wikipedia.org/wiki/Laccaria *Laccaria* typically have thick, widely spaced, purple to flesh-colored gills that are adnate to slightly decurrent in attachment. The spores are white and ornamented in most species]

Lactarius milk fluid in caps, brittle, some edible **[Au 240, 244, 247, 248, 250, 251, 256, 284, 285, 288, 289, 290, 291, 292, 293, 295, 312, 337, 338, 349, 361, 362, 363, 364**] [https://en.wikipedia.org/wiki/Lactarius ***Lactarius*** is a genus of mushroom-producing, ectomycorrhizal fungi, containing several edible species. The species of the genus, commonly known as **milk-caps**, are characterized by the milky fluid ("latex") they exude when cut or damaged. Like the closely related genus *Russula*, their flesh has a distinctive brittle consistency. It is a large genus with over 500 known species, mainly distributed in the Northern hemisphere. Recently, the genus *Lactifluus* has been separated from *Lactarius* based on molecular phylogenetic evidence.]

Piloderma thick walled, nitrogen recycling [https://en.wikipedia.org/wiki/Piloderma ***Piloderma*** is a genus of fungi in the family Atheliaceae. The distinguishing characteristics of *Piloderma* are the thick-walled (roughly 0.25 µm) basidiospores, the club-shaped basidia with stalk-like bases, and the clampless-septate hyphae. The widespread genus contains six species. Piloderma is known to be a key ectomycorrhizal species in conifer forests, assisting in nitrogen recycling and assimilation.]

Pisolithus Dye-maker's False Puffball [Au 698] [https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/pisolithus-tinctorius Pisolithus tinctorius (Pers.) Coker and Couch (Syn.p P. arhizus [Scop.: Pers.] Rauschert) is an ectomycorrhizal fungus that interacts with some of the most important tree genera from temperate forests.]

Rhizopogon underground false truffles, stalkless [Au 660] [https://en.wikipedia.org/wiki/Rhizopogon ***Rhizopogon*** is a genus of ectomycorrhizal Basidiomycetes in the family Rhizopogonaceae. Species form hypogeous sporocarps commonly referred to as "false truffles". *Rhizopogon* species are primarily found in ectomycorrhizal association with trees in the family Pinaceae and are especially common symbionts of pine, fir, and Douglas fir trees. Through their ectomycorrhizal relationships *Rhizopogon* are thought to play an important role in the ecology of coniferous forests.]

Suillus slimy and sticky cap when moist [Au 371, 372, 376, 386, 387, 391, 392, 393, 394, 401, 406, 415, 416] [https://en.wikipedia.org/wiki/Suillus#Description ***Suillus*** is a genus of basidiomycete fungi in the family Suillaceae and order Boletales. Species in the genus are associated with trees in the pine family (Pinaceae), and are mostly distributed in temperate locations in the Northern Hemisphere, although some species have been introduced to the Southern Hemisphere. Structures of the fungi in this genus in common with other members of the order Boletales include the presence of a cylindrical stipe, cap, soft flesh and tubular hymenium. Specific characteristics common to most species in *Suillus* are the cap cuticle which is often slimy and sticky when moist, the presence of darkly staining, clustered, sterile cells called cystidia that give the tube mouths or the stipe surface a speckled or glandular appearance, spores that are usually cinnamon brown or chocolate brown in mass, and obligate mycorrhizal relationships primarily with members of the Pinaceae, especially with members of the genera *Pinus*, *Larix* and *Pseudotsuga*.]

Thelephora terrestris vase like, in radiating rosettes, coral to distinct caps, inedible [Au 437, 442] [https://en.wikipedia.org/wiki/Thelephora ***Thelephora*** is a genus of fungi in the family Thelephoraceae. The genus has a widespread distribution and contains about 50 species. Fruit bodies of species are leathery, usually brownish at maturity, and range in shape from coral-like tufts to having distinct caps. Almost all species in the genus are thought to be inedible, but *Thelephora ganbajun* is a gourmet fungus in Yunnan province of southwest China.

The generic name is derived from the Greek *thele* (θηλή) meaning *nipple* and *phorus* meaning *bearing*. Species in the genus are commonly known as "fiber fans" and "fiber vases".

Some *Thelephora* species are know [known] to accumulate or even hyperaccumulate trace elements in fruit-bodies. *Thelephora penicillata* hyperaccumulates cadmium and arsenic.

Tuber truffle underground, under Douglas fir [Au 659] [https://en.wikipedia.org/wiki/Tuber_(fungus) ***Tuber*** is a genus in the Tuberaceae family of fungi, with estimated molecular dating to the end of the Jurassic period (156 Mya). It includes several species of truffles that are highly valued as delicacies.]

Wilcoxina with conifers and deciduous such as pine, birch & Oak [https://en.wikipedia.org/wiki/Wilcoxina *Wilcoxina* species are mycorrhizal, and commonly infect a variety of conifers and deciduous trees such as *Pinus*, *Betula*, and *Quercus*.]

Ectomycorrhizal Fungi's Plants

[See also https://www.gardenerspantry.ca/yes/wp-content/uploads/mycorrhizae-list.pdf]

Alder (Endo/Ecto). Arborvitae; Arctostaphylos; **Aspen** (Endo/Ecto); **Basswood** / **Linden**; **Beech**; **Birch**; Chestnut, Chinquapin, Cottonwood (Endo/Ecto), Douglas fir, Eucalyptus, Filbert, **Fir, Hazelnut,** Hickory, **Hemlock, Larch,** Linden, Madrone, Manzanita, **Oak,** Pecan, **Pine, Poplar, Spruce,** Walnut, **Willow** (Endo/Ecto)

Ectomycorrhizal fungi (EMF) support This type of association is very important in boreal and temperate deciduous forests (Atlas and Bartha, 1993. Allen, 1991), as the Pinaceae (**spruce**, **pine**, and **fir**), Betulaceae (**birch**) and Fagaceae (**oak** and **beech**) are almost exclusively ectomycorrhizal families, (Smith and Read, 1997.)

Douglas fir (old) brown furrowed bark absorbed the heat and protected the tree from fire. It was thick, too, to prevent water loss from the underling tissue, the phloem which transported the photosynthetic sugar water from the needles to roots in an inch-thick ring of long tubular cells. Elder Douglas fir trees, important seed source, perch for birds, roots a bears den, habitat for owls 42. condemning ancients 42, 43. **ponderosa** Better at minimizing water loss during a drought. The distinction as the most drought-tolerant of all the tree species in these parts …Only its tap root could save it. 46. The orange bark of the ponderosas also protected the parasol-crowned trees from fires that swept through every twenty years of so. 47.

Ectomycorrhizal Fungi Named and Described

Amanitas, (picture 116d) morels; orangey-yellow funnel-shaped chanterelles – apricot aroma 28.

Boletus Perhaps the *Suillus*, and *Boletus* and *Cortinarius* fungi could respond more immediately to the warming winters that had spawned the mountain-pine-beetle outbreak (see below) 186.

Cenococcum jet-black coating a smattering of the birch and fir's root tips and emanating bristles 158.

Cortinarius In the same vein, why would a tree pass carbon to a generalist networking fungus – a *Suillus* or Cortinarius – that could then pass the carbon to an unrelated tree? 185-186.

Clavaria pink coral fungus white, pink, and black fans of fungal threads, thin and gritty in hard clay and getting water 49-50, 59.

Laccaria laccata isolated fir or birch bland root tips and snow white emanating hyphae with bald orange-brown mushroom caps 159.

Lactarius between fir and birch, white creamy mantle, gills of milky-cap mushrooms 159. Boletes,

Phialocephala isolated fir or birch translucent dark hyphae both inside and outside roots 158.

Piloderma fleshy yellow threads connecting fir seedlings to a paper birch 167. The glossy sheen of the ***Piloderma*** mycorrhiza I'd seen linked the birch suggested that it held a rich supply of carbon, [12] supporting a biofilm of the luminescent ***Pseudomonas fluorescens* bacteria, whose antibodies could shrivel the growth of the root pathogen *Armillaria ostoyae.*** 168.

Pisolithus puff ball 49, 59.

Rhizopogon chocolate brown truffle – a false truffle, [A squirrel] a squirrel held a chocolate truffle coated in a black rind, gnawing at it with the cadence of a hummingbird. He had excavated it from the soil of the [Douglas] fir. Several burrows were lined with fresh soil from his exhumations. 57. With about fifteen Actually a false truffle. One tree was linked to 47 others. Some of them 20 meters away. Roots of seedlings of all ages and saplings too. Old tree was linked to every one of the young trees regenerated around it. 220-221.

The thick pipelines of fungal species like Rhizopogon were designed for long-distance communication. … Maybe the long-distance Rhizopogon were analogous to the strong links in our brains arising from repetition, pruning, and regression, giving us long-term memory. 232.

Suillus scaly brown pancake cap, (pictures 116b, 116f, 212c) yellow underbelly, brilliant yellow root tips threads 12-13, reaching for nutrients 15. 19. (see also *Cortinarius*)

Thelephora terrestris isolated fir or birch white creamy root tips blooming fanning rosettes of tough brown flesh with white margins 159.

Tuber between fir and birch covering root tips with blond chubby fungal clubs and spawning black underground truffles 159. **Tuber** hosted the nitrogen-fixing bacteria ***Bacillus*** 168.

Wilcoxina Isolated fir or birch smooth brown mantle and see-through mycelia delicate beige mushroom caps. 159. Maybe the finer *Wilcoxina* hyphae, which grew faster and more abundantly, helped the mycorrhizal networks adapt to new opportunities, not unlike our own rapid, flexible responses to new situation, which Grannie was losing.232.

Appendix E - Nitrogen-fixing Bacteria and their Hosts

Nitrogen-fixing Bacteria and the Sponsoring Plants, Moss, Lichen or Fungi

Frankia nitrogen-fixing bacteria is found in modified root branches of all species of genus *Alnus* in the family *Betulaceae* (**alder** (Dwelly) Dwe74; Dwe75, Dwe73 / (Boland) Bol118, Bol119, & Bol120); in *Morella* (**bayberry** Dwe52 / Bol104); in *Comptonia* (**sweetfern** Bol27); in *Shepherdia* (**soapberry** Dwe192 / Bol.47); in *Myrica* (**sweet gale** Dwe51 / Bol87); in some species of *Dryas*; and in others.

Rhizobia Nitrogen-fixing bacteria is found nodules of the roots of the huge family of legumes. Within trees or shrubs Rhizobia bacteria is found in Robinia (**black locust** Dwe156 / Bol202), and Cytisus (**scotch broom** Dwe155 / Bol182.) This group also contains the many clovers which each having their own special ecosystems, with some able to explore deeply for water, others with ability to live within concrete cracks, besides roads, or to exchange with lawns, within tall pastures etc. Among them are lupine, white sweet clover, yellow hop clover, rabbit's foot clover, white clover, red clover, bird's eye trefoil, …

Bacillus nitrogen-fixing bacteria is found in Tuber fungus which has been found linking **birch** to fir. 168. 204. [There may be other bacteria hosting fungi.]

Nostoc is a cyanobacteria. It is photosynthetic and nitrogen fixing. They are black or brown and include *Collema* jelly lichens; *Leptogium* jellyskin; *Fuscopannaria* shingle, the black when wet *Lobaria* lungworts; the gray *Pannaria conoplea* - mealy-rimmed shingled lichen; the gray the brown *Parmeliella* – shingle lichens; the brown or green *Peltigera hydrothria* – waterfan; the gray or brown *Peltigera* – the pelt lichens or dog lichens (foliose); the brown *Polychidium muscicola* – moss thorn lichens

Cephalodia with Nostoc Lichens with cephalodia are often fast growing because they have two photobionts. They have brown freckles on thallus. These include *Lobaria pulmonaria* **lungwort lichen** {Andrsn31} {Wal110}; *Lobaria quercizans* **smooth lungwort** {Andrsn40} {Wal111}; *Peltigera aphthosa* veinless **freckle pelt lichen** {Andrsn108} {Wal29}; *Stereocaulon paschale* **Easter lichen, common foam lichen** {Wal53}; *Stereocaulon saxatile* **rock foam lichen** {Wal88}; and others.

Stigonema (Reddish in color); ***Chroococcus*** (black in color); ***Rivulariaceae*** (black in color); ***Anacystis*** (Olive brown in color); ***Gloeocapsa*** (reddish, brownish, yellowish). These tend to be rare or nonexistent in the Maritimes.

Cephalodia with Stigonema *Stereocaulon dactylophyllum* **fingerleaf lichen** {Andrsn155}; *Stereocaulon paschale* **Easter lichen, common foam lichen** {Wal53} [Note this lichen can have this Stigonema bacteria or Nostoc bacteria.]; and others

Appendix F - Plants' and Lichen's Defense Constituents

NOTE Appendix F has been created by Norris Whiston in his studies of plants, fungi, and lichen

Yes, plants and lichen are competitive - they all want light and water.

But, much like humans, plants have many other needs. Getting them is limited to the plant root's expanse. They get these and other needs more efficiently when they collaborate, in this case, with specializing plants, lichen, fungi, and others and through exploring, processing, transporting, exchanging, and storing fungi. [See Section 5 - Generalists and Specialists]

Plant and lichen's constituents defend the original plant but also defend and warn its community. Fungi, in turn, are grateful to exchange for the energy / carbohydrates that plants can only produce.

The following plant constituents are transported below the soil by mycorrhizal fungi and through air by winds etc. as aerosols. The list comes from modest research this author had done for many years, placed under the title Organic Compounds, and upgraded from time to time. The 60+ page manuscript is available to others. This list is far from complete. NMW

Among their needs, there is noted in various experiments how one plant has passed on to another nitrogen, anti-disease, anti-herbivores, anti-pathogens, immunostimulants, and many more. In various places in Simard's book is noted this sharing of protection. Simard's work noted how antifungal, insect repellent, etc. of one plant helped, in the long run, firs and pine. Experiments in England by Dr. Glynn Percival showed using mulched willows had apple trees kick in 13 of its own anti disease and pathogens. https://www.permaculture.co.uk/readers-solutions/how-willows-could-be-future-tree-health

Specific Defensive Constituents

In parenthesis are the plants which contain those constituents. This research is continuing. It is placed in alphabetical order except the initial three.

Glucose $C_6H_{12}O_6$ Glucose and Oxygen are a product of photosynthesis $6\ CO_2 + 6\ H_2O = C_6H_{12}O_6 + 6O_2$ (or some O_3, Ozone, – Earth's necessary atmospheric sunscreen). [HOW] Through stomata, using green chlorophyll ($C_{55}H_{72}O_5N_4Mg$), requiring magnesium and nitrogen, plants and others pull in atmospheric carbon. Glucose's water needs are obtained through roots, leaf, and stem surfaces and conveyed through plant's water transport system. To expand water sources plants roots are assisted by finer and finer roots, or up to a factor of 10, by mycorrhizal fungi which can access deeper or further away water. [USE] Glucose's evolving creation brought the earth's temperature down and released oxygen to the atmosphere. Glucose supplies energy for all plant's functions, of the plants themselves, their supportive fungi, their supportive bacteria, their needy seedlings, their neighbors, others, and eventually to animals. Our earth's glucose and oxygen are currently and mostly created in leaves and in the green stems and bark of certain plants. It is done most efficiently in old layered forests with lots of coevolved species, now being chopped down, with coevolved and ever evolving specialist species supporting the process. (Evolutionarily, glucose has been created in cyanobacteria, algae, cyanobacteria and algae within lichens, plants, and mosses, and some prokaryotes - things that are green. It is not created in the rest of fungi, and certainly not created in animals or ungrateful humans.)

Fructose $C_6H_{12}O_6$ Fructose supplies energy to the plants themselves or their needy neighbors, fungi, and eventually animals (honey, tree and vine fruits, flowers, berries, and most root vegetables)

Vitamin C ascorbic acid $C_6H_8O_6$ (placed here as its formula's similarities to glucose and fructose) (Wild Apple Fruit, Dark Leafy Green, Willow twigs and leaves, rose hips and leaves, strawberry leaves, Young leaves of Plantain, chickweed, berries, kiwifruit, broccoli, citrus fruits, tomatoes, Bell Peppers, papayas …)

Alectoronic acid depside $C_{28}H_{32}O_9$. (Lichens of Witches Hair, Concentric Ring, Sea-Storm, Fringed Wrinkle)

Alpha-pinene monoterpene (See Terpene) $C_{10}H_{16}$. Highly repellant to insects. Anti-cancer agent, anti-inflammatory, antiseptic, expectorant and bronchodilator properties. Boost immune system. [See 11a and 11b.] (Jack pine, red pine, Scotch pine, white pine, ironwort, sagebrush)

Andromedotoxins a glycoside $C_{22}H_{36}O_7$ Toxic, deters herbivores (rhodora) http://www.chm.bris.ac.uk/webprojects2001/gerrard/andromedotoxin.html

Anthocyanin a flavonoid $C_{15}H_{11}O_6Cl$. Antioxidant against reactive oxygen species caused by abiotic stresses, such as overexposure to ultraviolet light and extreme temperatures. Being red it attracts pollinators and attracts those eating its fruits to spread the seeds. (Visibly red. All higher plants, particularly red berries)

Anthraquinone aromatic organic compound. $C_{14}H_8O_2$. Used as a bird repellant on seeds, has laxative properties, induces vomiting, antiviral (Buckthorn, Firedot Lichen, Toadskin Lichen, Mustard Kidney Lichen)

Atranorin a depside $C_{19}H_{18}O_8$. Colorless Absorbs UV rays & re-emits them as fluorescence to be used for photosynthesis (hence causes photocontact dermatitis), antibacterial, anticarcinogenic, strong antimicrobial, antioxidant, cytoprotective, and pro-oxidant. (Many Lichens)

Barbatic acid a depside $C_{19}H_{20}O_7$. Inhibits 5-LOX, inhibits metabolite on biosynthesis of LTB4 (horse hair lichen, smooth beard lichen, British soldier lichen, boreal pixie cup lichen, lipstick powder horn lichen, Methuselah's beard lichen)

Betalain a class of red and yellow tyrosine-derived pigments, an amino acid $C_{24}H_{26}N_2O_{13}$. Plant physiologists are uncertain of the function in plants, but there is evidence of having fungicidal properties. Tyrosine used by cells to synthesize proteins (in some higher order of fungi, distinctive red to purple noticeable in flower petals but also colors fruit, leaves, stems, and roots beets, amaranth and many cactuses) https://en.wikipedia.org/wiki/Tyrosine

Betulinic acid pentacyclic triterpenoid $C_{30}H_{48}O_3$. Anti-retroviral, antimalarial, antifungal, and anti-inflammatory properties, potential as an anticancer agent, inhibits human melanoma. Its white reflects sunlight, guards against sunscald, keeping trunk from heating up. It is found to induce apoptosis [death of cells to allow for growth]. (white ash, speckled alder, gray birch, white birch, black birch, & yellow birch, dogwood, selfheal, ber tree, tropical carnivorous plants, flowering quince, and rosemary)

Calycin acid $C_{18}H_{10}O_5$ Serves as a sunscreen to protect delicate algae (Bright yellow lichens: candleflame, goldspeck, yellow specklebelly lichens)

Camphor $C_{10}H_{16}O$ terpenoid. Believed toxic to insects and a repellent used in moth balls; antimicrobial (Sagebrush, oil in rosemary leaves)

Carotene $C_{20}H_{30}O$ bright yellow and brown colors serve as alarm signal signaling readiness to defend themselves and to later producing toxins, important for growth and development (yellow and brown leaves of fall, young leaves of Plantain, Staghorn Sumac fruit) (See Vitamin A)

Chrysin a flavonoid $C_{15}H_{10}O_4$. Antiviral (trembling aspen, large toothed aspen)

Cornic acid – Cornin / Verbenalin $C_{17}H_{24}O_{10}$. Sleep promoting. (Vervain, Alternate Leaved Dogwood)

Cyanide compounds toxic: See Hydrocyanic Acid

Depside A depside is a type of polyphenolic compound composed of two or more monocyclic aromatic units linked by an ester bond. https://en.wikipedia.org/wiki/Depside antibiotic, antioxidant, anti- proliferative. Some have anti-inflammatory activity. Some are anti-HIV. (In many lichens, and members of the heath family, mint, sage, poppy, and myrtle families)

Digallates $C_{43}H_{32}O_{20}$ Antioxidant, antiviral (Red Maple. Needs more research for other maples.)

Ethylene a gas, the simplest alkene C_2H_4 ($H_2C{=}CH_2$). Essential for germination, senescence of flowers [deterioration with age], plant ripening, and abscission of leaves [natural detachment of leaves]. In thorn acacia ethylene is given off as a herbivore, and is given off to warn other plants of a herbivore. (All parts of higher plants, leaves, stems, roots flowers, fruits, tubers, and seeds)

Flavonoids See also Anthocyanin, Chrysin, Quercetin https://en.wikipedia.org/wiki/Flavonoid From the Latin word *flavus*, meaning yellow, their color in nature) are a class of polyphenolic secondary metabolites found in plants, and thus commonly consumed in the diets of humans. Anti-viral; (basswood / linden)

Folate B9 $C_{19}H_{19}N_7O_6$ necessary for production of new cells (dark leafy vegetables)

Gallic acid $C_7H_6O_5$ Phenolics Phenol. Inhibits the formation of amyloid fibrils, antiviral, insect repellent (Labrador tea, northern red oak, Sumac, Virginia Creeper, Grape, Strawberries, Bananas, Cloves)

Glycosides: https://en.wikipedia.org/wiki/Glycoside bonds with sugars. See elsewhere. Insect repellent: (red elderberry, rose)

Humulene a sesquiterpene (See terpene) $C_{15}H_{24}$. Emitted into the atmosphere (Aromatic plants: Hops, Pine Trees, Orange, Marsh Elders, Tobacco, Sunflowers, Sage, Ginseng, Ginger)

Hydrocyanic Acid cyanide in water HCN. Almond smell, toxic, interferes with iron containing respiratory enzymes, so poisonous to rodents and humans but not to herbivores with large intestines. (Pin Cherry, Black Cherry, Apple, Chokeberry, Common & Red Elderberry, Mountain Ash, Wild Raisin)

Isoprene volatile organic compound C_5H_8. Protects plants from heat stress, resists active oxygen species (oaks, poplars, some legumes, eucalyptus)

Lecanoric Acid a polyphenol and didepside $C_{16}H_{14}O_7$. (Antler Lichen, Speckled Shield Lichen, Brown Shield Lichen, Camouflage Lichen)

Leucine $C_6H_{13}NO_2$ one of 3 essential amino acids (Meats, dairy products, soy products, and beans and other legumes) https://en.wikipedia.org/wiki/Leucine

Methyl acetate aerosol $C_3O_2H_6$ (CH_3COOCH_3). Toxic (Black Locust, Apple, Grape, Virginia creeper, Banana)

Methyl salicylate benzoate ester that is the methyl of salicylic acid $C_8H_8O_3$. Bitter, anti-herbivore, recruits beneficial insects, warns other plants (Black and yellow Birch, white birch, meadow sweet, steeplebush, teaberry, checkerberry¸ wintergreen)

Monoterpenes (See terpenes) [See 11a, 11b} (firs,

Mucilage plays a role in the storage of water and food, seed germination, and thickening membranes (Cyanobacteria, Most plants, Basswood, Buckthorn, Slippery elm, particularly cactus and flax seeds)

Nitrogen: nitrous oxide (N_2O), nitric oxide (NO) ammonium (NH_4+), nitrate (NO_3−), nitrite (NO_2−), or inorganic nitrogen gas (N_2)

Oxalic acid the simplest dicarboxylic acid $C_2H_2O_4$ ($HO_2C{-}CO_2H$). Reducing agent, aids in solubility of metals, inhibits lactate dehydrogenase (so potential cancer treatment), enhances plant resistance to pathogenic fungi in small amounts but higher amounts cause programmed cell death of plants. (Jack-in-the Pulpit, Wood Sorrel, Umbellifers (like parsley), Spinach, Rhubarb, Virginia creeper) https://en.wikipedia.org/wiki/Dicarboxylic_acid https://en.wikipedia.org/wiki/Oxalic_acid

Parasorbic Acid cyclic lactone (esters) of sorbic acid $C_6H_8O_2$. Toxic, antibiotic, antimicrobial, anti-mold, anti-yeast, anti-fungal inhibits seed germination, (mountain ash, rowanberry) https://en.wikipedia.org/wiki/Lactone https://en.wikipedia.org/wiki/Sorbic_acid

Parietin a depsidone $C_{16}H_{12}O_5$. Absorbs UVB radiation, so protects against it. Weakens melanoma cells. Has anti-fungal (Orange colored lichens: Xanthomendoza and Xanthoria – ON POPLAR, ELM. CONCRETE, SHINGLES, Sunburst Lichens, ON CONIFER BRANCHES, EXPOSED WOOD, Rock cortical pigment in Caloplaca, roots of curled dock, rhubarb)

Phenolics Phenol Carbolic Acid. C_6H_5OH. Natural insect repellent (Includes Gallic Acid, Methyl Salicylate, Salicylic Acid)

Populin a glucoside $C_{20}H_{22}O_8$. Insect repellent, antifungal (Trembling Aspen, Balsam Poplar, Large Toothed Aspen)

Quercetin a flavonoid $C_{15}H_{10}O_7$. Antiviral, used as a defense against pests (American elder, apples, St. John's wort, berries, Ginkgo biloba)

Quercitrin a glycoside $C_{21}H_{20}O_{11}$. Antioxidant, immunostimulant (Northern Red Oak, White Oak, Beech)

Resin

Sabinene natural bicyclic monoterpene (See Terpene) $C_{10}H_{16}$, with scents, antioxidant, antifungal, antimicrobial (Oak, beech, spruce, Juniper bushes, clove plants, spices like black pepper and nutmeg)

Salicylic acid a glycoside (Phenolics Phenol) $C_7H_6O_3$ (ASA). Bitter, toxic, deters bacteria, antibiotic, antifungal, aroma repels insects, immunostimulant, pain reliever (Willow, Meadowsweet, Quaking Aspen, Big Toothed Aspen, Balsam Poplar)

Tannin a glycoside $C_{76}H_{52}O_{46}$.Toxic, bitter, antiviral, antifungal, anti-epiphytes, repels insects, anti-browser, decomposes slowly, plant growth regulation (basswood / linden, beaked hazelnut, black cherry, elm, hemlock, Labrador Tea, Northern Red Oak, Burr Oak, staghorn sumac, willow, and lots more)

Terpenoid organic chemical, terpene. https://en.wikipedia.org/wiki/Terpenoid

Terpene: $(C_5H_8)_n$. Terpenes are further classified by the number of carbons: monoterpenes (C_{10}), sesquiterpenes (C_{15}), diterpenes (C_{20}), as examples. The terpene alpha-pinene, is a major component of the common solvent, turpentine. (conifers, northern red oak) https://en.wikipedia.org/wiki/Terpene

Tetrochrysin (trembling aspen)

Thorns: protects from some herbivores, shelters certain birds and small animals from predators (hawthorn, rugosa rose)

Thujene a monoterpene (See Terpene) $C_{10}H_{16}$. Reduce inflammations, and protect against harmful germs and bacteria, Used to relieve minor aches and pains, soothe digestive issues (Beech, Sagebrush, summer savory)

Ulmic acid

Urushiol oily mixture of organic compounds with allergenic properties $C_{21}H_{32}O_2$. (Poison Ivy, Poison Sumac, Poison Oak) https://en.wikipedia.org/wiki/Urushiol

Usnic Acid a naturally occurring dibenzofuran derivative $C_{18}H_{16}O_7$. Shortwave UV protection. Inhibits photosynthesis in competing plants. Effective antibiotic. Anticarcinogenic, anti-inflammatory, antimicrobial, antioxidant, cardioprotective, cytoprotective, gastroprotective immunostimulant, and pro-oxidant (Found in several bluish green lichens includes ON ROCKS: concentric ring lichen, rock shield, pixie cups, greenshield, rock shield, reindeer lichen ON SOIl: horsehair, reindeer lichen, boreal pixie cup, British soldier, ON TREES: eastern candlewax, horsehair lichen, witch's hair, greenshield, Maple Dust, Lobaria textured lichen, starburst lichen, frayed ramalina, beard lichen, old man's beard, powdered sunshine ON WOOD: pixie cup, bristly beard lichen

Vitamin C: (rugosa rose plus many others)

Volatile Organic Compound Organic chemical that have high vapor pressure at room temperature, which correlates with a low boiling point. Responsible for the odor of scents and perfumes as well as pollutants. It attracts pollinators, protection from predation, and even inter-plant interactions. Some VOCs are regulated by law. https://en.wikipedia.org/wiki/Volatile_organic_compound

Appendix G - Plant's Personal and Collaborative Defense Constituents by Type

Immunostimulant **Salicylic acid** $C_7H_6O_3$ a glycoside (Willow, Meadowsweet, Quaking Aspen, Big Toothed Aspen, Balsam Poplar) **Quercitrin** $C_{15}H_{10}O_7$ a glycoside (Northern Red Oak, White Oak, Beech); **Monoterpene** $C_{10}H_{16}$ (firs, others) (See YuanYuan Song's & Simard's work, 11a.); **Alpha-pinene** monoterpene (See Terpene) $C_{10}H_{16}$. (See 11b.] (Jack pine, red pine, Scotch pine, white pine, ironwort, sagebrush)

Insect and herbivore repellents: **Alpha-pinene** $C_{10}H_{16}$ monoterpene (white pine, Jack pine, red pine, Scotch pine, ironwort, sagebrush), **Andromedotoxins** $C_{22}H_{36}O_7$ a glycoside (rhodora), **Camphor** $C_{10}H_{16}O$ (Sagebrush, oil in rosemary leaves), **Gallic Acid** $C_7H_6O_5$ a Glycoside (Labrador tea, northern red oak, sumac, Virginia creeper, grape, strawberries, bananas, cloves); **Glycosides** (red elderberry, rose), **Methyl salicylate** $C_8H_8O_3$ (Black and yellow birch, white birch, meadow sweet, steeplebush, teaberry, checkerberry¸ wintergreen), **Populin** $C_{20}H_{22}O_8$ a glucoside (Trembling Aspen, Balsam Poplar, Large Toothed Aspen), **Salicylic acid** $C_7H_6O_3$ a glycoside (willow, meadowsweet, quaking aspen, big toothed aspen, balsam poplar), **Tannin** $C_{76}H_{52}O_{46}$ a glycoside (basswood / linden, beaked hazelnut, black cherry, elm, hemlock, Labrador tea, northern red oak, burr oak, staghorn sumac, willow, and lots more).

Antifungal (This list needs to be expanded as global research expands and discoveries are put out to the general public.): **Betulinic acid** $C_{30}H_{48}O_3$, pentacyclic triterpenoid (white ash, speckled alder, gray birch, white birch, black birch, yellow birch, dogwood, selfheal, ber tree, tropical carnivorous plants, flowering quince, and rosemary)**;** **Populin** $C_{20}H_{22}O_8$ glucoside (trembling aspen, large toothed aspen, poplar); **Sabinene** $C_{10}H_{16}$ natural bicyclic monoterpene (beech, oak, spruce, Juniper bushes, clove plants, spices like black pepper and nutmeg); **Salicylic acid** $C_7H_6O_3$ a glycoside (Willow, Meadowsweet, Quaking Aspen, Big Toothed Aspen, Balsam Poplar); **Tannin** $C_{76}H_{52}O_{46}$ a glycoside (basswood / linden, beaked hazelnut, black cherry, elm, hemlock, Labrador Tea, Northern Red Oak, Burr Oak, staghorn sumac, willow, and lots more).

Antioxidant **Anthocyanin** $C_{15}H_{11}O_6Cl$ flavonoid Antioxidant against reactive oxygen species caused by abiotic stresses, such as overexposure to ultraviolet light and extreme temperatures. Being red it attracts pollinators and attracts those eating its fruits to spread the seeds. (Visibly red. All higher plants, particularly red berries,) **Atranorin** $C_{19}H_{18}O_8$ a depside colorless. Absorbs UV rays & re-emits them as fluorescence to be used for photosynthesis (hence causes photocontact dermatitis), antibacterial, anticarcinogenic, strong antimicrobial, antioxidant, cytoprotective, and pro-oxidant. (Many Lichens); **Digallates** $C_{43}H_{32}O_{20}$ antioxidant, antiviral (Red Maple. Needs more research for other maples); **Quercetin** $C_{15}H_{10}O_7$ flavonoid Antioxidant, immunostimulant (Northern Red Oak, White Oak, Beech); **Sabinene** $C_{10}H_{16}$ natural bicyclic monoterpene, with scents, antioxidant, antifungal, antimicrobial (Oak, beech, spruce, Juniper bushes, clove plants, spices like black pepper and nutmeg)

Sun tolerant / Sunscreen: Betulinic acid Betulinic acid $C_{30}H_{48}O_3$, pentacyclic triterpenoid (speckled alder, gray birch, white birch, black birch, yellow birch, white ash, dogwood, selfheal, ber tree, tropical carnivorous plants, flowering quince, and rosemary); **Old bark becomes a powder** after green bark has photosynthesized (trembling aspen, large toothed aspen). **Parietin** $C_{16}H_{12}O_5$ (Orange colored lichens): Xanthomendoza and Xanthoria – Sunburst Lichens); **Calycin acid** $C_{18}H_{10}O_5$ (Bright yellow lichens: candleflame, goldspeck, yellow specklebelly lichens)**. Usnic Acid** $C_{18}H_{16}O_7$ **(**light blue green lichen)**:** ON ROCKS: concentric ring lichen, rock shield, pixie cups, greenshield, rock shield, reindeer lichen ON SOIl: horsehair, reindeer lichen, boreal pixie cup, British soldier, ON TREES: eastern candlewax, horsehair lichen, witch's hair, greenshield, Maple Dust, Lobaria textured lichen, starburst lichen, frayed ramalina, beard lichen, old man's beard, powdered sunshine ON WOOD: pixie cup, bristly beard lichenhttps://www.colorado.edu/ebio/2015/10/20/mystery-aspen-powder

Early Succession / Pioneer These tend to be plants whose seeds are carried by light winds and whose bark is sun tolerant. See above. For their community, many have nitrogen fixing bacteria within their roots, many have fine roots or deep roots that go searching for water and nutrients, making them hard to dig up. Many have constituents that protect themselves but also their community, and many have thorns and bristles to protect their early life. They prevent erosion. The following is not a complete list. Watch for what grows in severe cracks in cement, close to roadways or along highways. Go to sidewalk cracks, roadsides, clearcuts or an old pasture before they have had humans "manage" them. (Purslane, certain mosses, grasses, sedges, legumes, alder, willow, meadowsweet, elderberry, birch, trembling aspen, large toothed aspen +.)

Inhibits Seed Germination: **Parasorbic Acid** (mountain ash)

Drought Tolerant, **Hibernates in drought:** (lichen and dry land mosses), **minimizes water loss by adjusting stomata numbers and opening times:** (Douglas fir, Ponderosa pine) , **Acetic acid** (black locust); **Hardwood trees** with deep roots.

Salt Tolerant (author has limited to local varieties) **Deciduous Trees**: Serviceberry, Witchhazel, Red Oak, White Oak, Eastern Redcedar, Horsechestnut, and Maidenhair Tree. **Shrubs and Groundcovers** Bearberry, Chokeberry, St. Johnswort, Winterberry, Saltspray Rose (Rosa rugosa), Sumac, Snowberry or Coralberry, Lilacs, Blueberry/Cranberry Vaccinium spp. Bayberry (Nitrogen fixing), Scotch Broom (Nitrogen fixing), Arrowwood (Viburnum dentatum); **Conifers**: Larch, White Spruce, Jack Pine, Ponderosa Pine, **Perennials**: Blue Fescue Grass, Hosta, Candytuft, Sea Lavender, Fountain Grass, Sedum 'Autumn Joy'.

Resists pollution Serviceberry, London Plane (Also note which trees shrubs and lichen are most likely to live in Cities.)

Antibiotic
Anti-viral

End