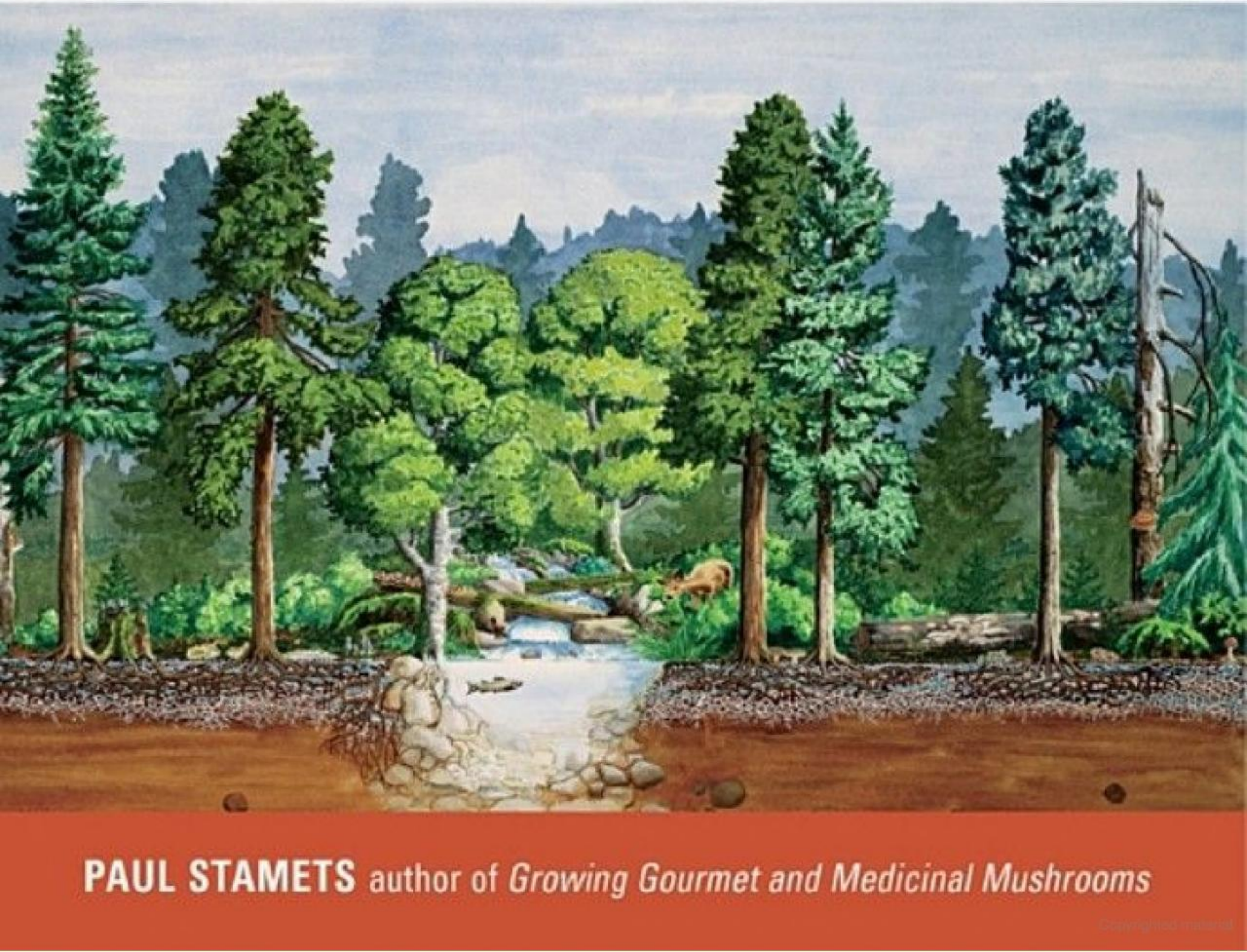
MYCELIUM RUNNING

How Mushrooms Can Help Save the World



PAUL STAMETS author of *Growing Gourmet and Medicinal Mushrooms*

Published in the United States by Ten Speed Press, an imprint of the Crown Publishing Group, a division of Random House, Inc., New York.
www.crownpublishing.com
www.tenspeed.com

Library of Congress Cataloging-in-Publication Data
Stamets, Paul.
Mycelium running : how mushrooms can help save the world / Paul Stamets.
p. cm.
Includes bibliographical references and index.
1. Mycelium. 2. Mushroom culture. 3. Fungi–Ecology. I. Title.
QK601.S73 2005
579.5163—dc22 2005015898

eISBN: 978-1-58008-579-3

Cover design by Betsy Stromberg and Andrew Lenzer
Text design by Betsy Stromberg

The information in this book is accurate to the best of the author's knowledge. However, neither the author nor the publisher can accept any responsibility for mistakes in identification or idiosyncratic reactions to mushrooms; people who eat mushrooms do so at their own risk. This material is intended for educational purposes only; it is advisable to seek the advice of a licensed, professional health-care provider for any condition that may require medical attention.

v3.1_r1

CONTENTS

Index

FOREWORD

Mushrooms—ignored by many, reviled by some—may turn out to be important keys to both human health and planetary health. Their indispensable role in recycling organic matter, especially in forests, has long been known. But how many people realize that trees and other green plants could not grow and reach maturity without symbiotic associations with mushrooms, at least with mycelium, the network of fungal threads in soil that act as interfaces between plant roots and nutrients?

A mushroom is the reproductive structure or fruiting body of mycelium. Mycelium runs through our world, performing many other feats as well, but it is hidden and inconspicuous-a strange life form that has not attracted the same scientific attention as micro-organisms or plants or animals. Even conventional mycologists hardly recognize its larger implications and possibilities.

Paul Stamets has never been a conventional thinker. I have known him for 25 years, and during that time, I have been repeatedly impressed by his insights into the interdependence of human beings and nature, his enthusiasm for harnessing and directing biological energies toward higher purposes, and his talent for thinking in novel and inventive ways. He has always looked at mushrooms from unique perspectives and as a result has made remarkable discoveries about them.

When we first met, I was questioning why Western medicine had never looked to mushrooms as sources of new therapeutic agents, given their prominence in the traditional pharmacopeias of China, Japan, and Korea. Paul took that question and ran with it, focusing on the natural competition that exists in soil between mycelium and bacteria. Fungi have evolved novel chemical defenses, a range of antibiotics that are often active against not only bacteria but also viruses and other infectious agents that cause disease in humans. One of the Big Ideas in this book is that fungi, especially fungi from old-growth forests, may be sources of new medicines that are active against a range of germs, including HIV/AIDS and the causative agents of smallpox and anthrax, potential bioterrorist threats.

Another of Paul's Big Ideas is that mycelium can be selected and trained to break down toxic waste, reducing it to harmless metabolites. He calls this strategy *mycoremediation* and has demonstrated its practicality in cleaning up oil spills. He suggests that our mushroom allies may even be able to detoxify chemical warfare agents.

This is one facet of a larger strategy that Paul calls *mycorestoration,* the use of fungi to improve the health of the environment: by filtering water, helping trees to grow in forests and plants to grow in gardens, and by controlling insect pests. The last possibility is especially noteworthy because it has the potential to neutralize pests like termites and fire ants by means that are completely nontoxic to human beings. Paul Stamets holds a number of patents in these areas, and I look forward to seeing his inventions put to use.

As a physician and practitioner of integrative medicine, I find this book exciting and optimistic because it suggests new, nonharmful possibilities for solving serious problems that affect our health and the health of our environment. Paul Stamets has come up with those possibilities by observing an area of the natural world most of us have ignored. He has directed his attention to mushrooms and mycelium and has used his unique intelligence and intuition to make discoveries of great practical import. I think you will find it hard not to share the enthusiasm and passion he brings to these pages.

Cortes Island, British Columbia
June 2005

ANDREW WEIL, MD

PREFACE

For 30 years, I have engaged fungi, or perhaps they have engaged me, in a mission to promote the benefits of mushrooms. My previous books *Growing Gourmet and Medicinal Mushrooms* (2000a) and *The Mushroom Cultivator,* coauthored with Jeff Chilton (1983), delve into the methods of cultivating mushrooms. This new book is designed to show readers how to grow mushrooms in gardens, yards, and woods for the purpose of reaping both personal and planetary rewards. As you will discover, mushrooms help us reconnect to nature in profound ways. Mushrooms, mysterious and once feared, can be powerful allies for protecting the planet from the ecological injury we inflict.

More specifically, this book focuses on healing the planet using mycelial membranes, also known as *mycelium,* a fungal network of threadlike cells; it is a mycological manual for rescuing ecosystems. Engaging mycelium for healing habitats is what I call “mycorestoration.” The umbrella concept of mycorestoration includes the selective use of fungi for mycofiltration, mycoforestry, mycoremediation, and mycopesticides. Mycofiltration uses mycelium to catch and reduce silt and catch upstream contaminants. Mycoforestry uses mycelium and mushrooms to enhance forest health. Mycoremediation neutralizes toxins. Mycopesticides refers to the use of fungi to help influence and control pest populations. This quartet of strategies can be used to improve soil health, support diverse food chains, and increase sustainability in the biosphere.

This book is written for a readership as diverse as the fungal community. For readers devoted to recycling, organic cultivation, habitat restoration, or applied mycology, I hope this book will be as useful as it is revolutionary. If you are a landscaper, bioremediator, ecoforester, sustainable-village planner, physician, scientist, futurist, or anyone who is passionately bemushroomed, I hope this book enriches your life and that you will pass on the love of mushrooms to future generations. And even if you have never walked through an old-growth forest, cultured fungus in a petri dish, relished a fresh-picked matsutake grilled over an open fire, or taken a mushroom-based medicine, I hope you will find this book—and my pragmatic environmental philosophy described herein—informative and inspiring. I contend that the planet’s health actually depends on our respect for fungi. This book will show how you can help save the world using mushrooms.

ACKNOWLEDGMENTS

Writing this book has been an adventure of a lifetime, for which I am indebted to many people. First, to my wife, Dusty, I thank you for your love, companionship, humor, heart, and honor. Many thanks to Azureus and La Dena for all your help with my field work and special projects. To my brother Bill, I thank you for your skill in editing and challenges to my ideas that helped focus my vision. I am also grateful to Meghan Keeffe, Karen O'Donnell Stein, Jasmine Star, Laura Tennen, and Betsy Stromberg for their helpful editorial comments and stewardship as we navigated through the production of this book. To my family, especially my mother and my father, I am grateful for how you supported me with your love and for nurturing my scientific curiosity. To Phil Wood and Jo Ann Deck, thank you for placing your faith in me. To David Sumerlin, Steve Cividanes, Jimmy Gouin, David Brigham, Andrew Lenzer, Noelle Machnicki, Damein Pack, Natalie Parks, Kevin Schoenacker, Bulmaro Solano, George Osgood, Alex Winstead, and the other employees at Fungi Perfecti, I thank you for helping me more times than I can recount. To my mentors, Dr. Alexander Smith, Dr. Daniel Stuntz, and Dr. Michael Beug, who first encouraged me on this path, and to my ally and friend Dr. Andrew Weil, you hold special places in my heart.

Battelle Laboratories, and their mycoremediation team, including Jack Word, Susan Thomas, Ann Drum, Meg Pinza, Pete Becker, and others are acknowledged for their contributions. Roger Gold and Grady Glenn of Texas A&M University are thanked for their work on my mycopesticide projects. David Arora, Kenny Ausubel, William Hyde, Omon Isik-huemhen, Taylor Lockwood, Tom Newmark, Bill Nicholson, John Norris, David Price, Ethan Schaffer, Nina Simons, Phil Stern, and Solomon Wasser also helped in their special ways.

I also want to thank my critics: you have made me stronger, and no doubt you will continue to do so. I thank the thousands of mycologists, from shamans to scientists, whose collective experiences created the body-intellect that has become the springboard for the mycorestoration revolution. Last, I am humbled by the psilocybes who have been my mushroom spirit teachers. May future generations continue to build upon this foundation of knowledge to help the health of people and our planet.

Part I

THE MYCELIAL MIND

There are more species of fungi, bacteria, and protozoa in a single scoop of soil than there are species of plants and vertebrate animals in all of North America. And of these, fungi are the grand recyclers of our planet, the mycomagicians disassembling large organic molecules into simpler forms, which in turn nourish other members of the ecological community. Fungi are the interface organisms between life and death.

Look under any log lying on the ground and you will see fuzzy, cobweblike growths called *mycelium,* a fine web of cells which, in one phase of its life cycle, fruits mushrooms. This fine web of cells courses through virtually all habitats—like mycelial tsunamis—unlocking nutrient sources stored in plants and other organisms, building soils. The activities of mycelium help heal and steer ecosystems on their evolutionary path, cycling nutrients through the food chain. As land masses and mountain ranges form, successive generations of plants and animals are born, live, and die. Fungi are keystone species that create ever-thickening layers of soil, which allow future plant and animal generations to flourish. Without fungi, all ecosystems would fail.

With each footstep on a lawn, field, or forest floor, we walk upon these vast sentient cellular membranes. Fine cottony tufts of mycelium channel nutrients from great distances to form fast-growing mushrooms. Mycelium, constantly on the move, can travel across landscapes up to several inches a day to weave a living network over the land. But mycelium benefits our environment far beyond simply producing mushrooms for our consumption.

Humans collaborate with these cellular networks, using fungi, specifically using mushroom mycelium as spawn, for both short- and long-term benefits. Mushroom spawn lets us recycle garden waste, wood, and yard debris, thereby creating mycological membranes that heal habitats suffering from poor nutrition, stress, and toxic waste. In this sense, mushrooms emerge as environmental guardians in a time critical to our mutual evolutionary survival.

I believe random selection is no longer the dominant force of human evolution. Our political, economic, and biotechnological policies may determine our future, for better or worse. Some forecasts claim that half of the current species could disappear in the next hundred years if current trends continue. A “what-if” Pentagon report issued in October 2003, *An Abrupt Climate Change Scenario and Its Implications for United States National Security* (Schwartz and Randall 2003), hypothesizes that a more dire and imminent collapse of our biosphere may occur as climates radically destabilize as a result of pollution and global warming.

I wonder what would happen if there were a United Organization of Organisms (UOO, pronounced “uh-oh”), where each species gets one vote. Would we be voted off the planet? The answer is pretty clear. When we irresponsibly exploit the Earth, disease, famine, and ecological collapse result. We face the possibility of being rejected by the biosphere as a virulent organism. But if we act as a responsible species, nature will not evict us. Our fungal friends equip us with tools to act responsibly and repair our shared environment, leading the way to habitat recovery. So knowing how to work with fungi—by custom pairing fungal species with plant communities—is critical for our survival. The twenty-first century may be remembered as the Biotech Age, when these kinds of mycotechnologies play a prominent and increasing role in strengthening habitat health.

CHAPTER 1

Mycelium as Nature's Internet

I believe that mycelium is the neurological network of nature. Interlacing mosaics of mycelium infuse habitats with information-sharing membranes. These membranes are aware, react to change, and collectively have the long-term health of the host environment in mind. The mycelium stays in constant molecular communication with its environment, devising diverse enzymatic and chemical responses to complex challenges. These networks not only survive, but sometimes expand to thousands of acres in size, achieving the greatest mass of any individual organism on this planet. That mycelia can spread enormous cellular mats across thousands of acres is a testimonial to a successful and versatile evolutionary strategy.

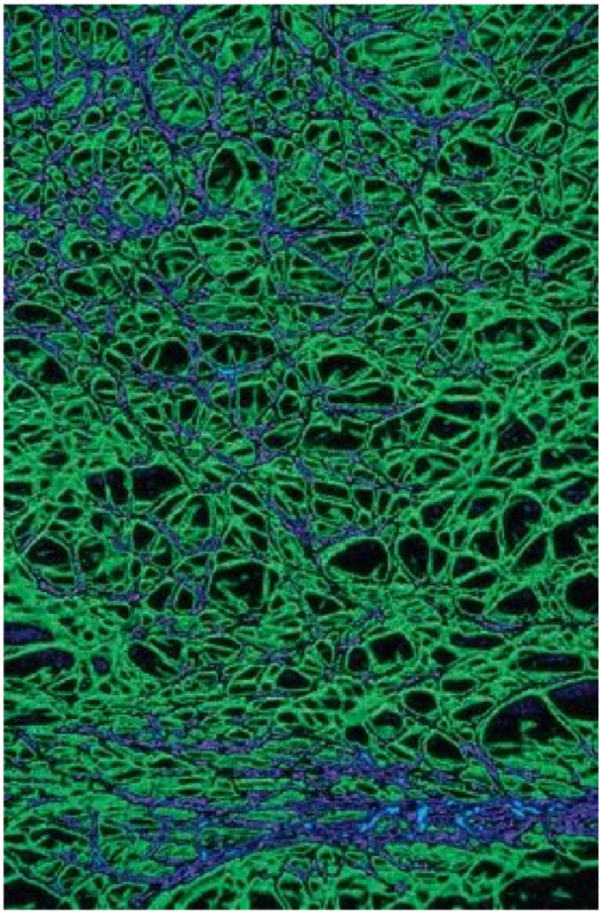


FIGURE 1 The mycelial network is composed of a membrane of interweaving, continuously branching cell chains, only one cell wall thick.

The History of Fungal Networks

Animals are more closely related to fungi than to any other kingdom. More than 600 million years ago we shared a common ancestry. Fungi evolved a means of externally digesting food by secreting acids and enzymes into their immediate environs and then absorbing nutrients using netlike cell chains. Fungi marched onto land more than a billion years ago. Many fungi partnered with plants, which largely lacked these digestive juices. Mycologists believe that this alliance allowed plants to inhabit land around 700 million years ago. Many millions of years later, one evolutionary branch of fungi led to the development of animals. The branch of fungi leading to animals evolved to capture nutrients by surrounding their food with cellular sacs, essentially primitive stomachs. As species emerged from aquatic habitats, organisms adapted means to prevent moisture loss. In terrestrial creatures, skin composed of many layers of cells emerged as a barrier against infection. Taking a different evolutionary path, the mycelium retained its netlike form of interweaving chains of cells and went underground, forming a vast food web upon which life flourished.

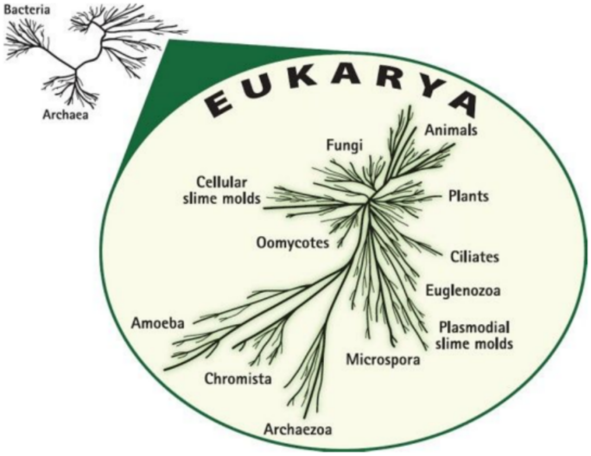


FIGURE A Evolutionary Branches of Life. Animals have a more common ancestry with fungi than with any other kingdom, diverging about 650 million years ago. A new super-kingdom, Opisthokonta, has been erected to encompass the kingdoms Fungi and Animalia under this one taxonomic concept (Sina et al. 2005).

FIGURE 2 The journal *Mycologia* featured this 15- to 20-million-year old amber with a mushroom embedded, now called *Aureofungus yaniguaensis,* dating from Miocene time and collected in the Dominican Republic. The oldest mushrooms in amber are estimated at 90 to 94 million years old.

About 250 million years ago, at the boundary of the Permian and Triassic periods, a catastrophe wiped out 90 percent of the Earth's species when, according to some scientists, a meteorite struck. Tidal waves, lava flows, hot gases, and winds of more than a thousand miles per hour scourged the planet. The Earth darkened under a dust cloud of airborne debris, causing massive extinctions of plants and animals. Fungi inherited the Earth, surging to recycle the postcataclysmic debris fields. The era of dinosaurs began and then ended 185 million years later when another meteorite hit, causing a second massive extinction. Once again, fungi surged and many symbiotically partnered with plants for survival. The classic cap and stem mushrooms, so common today, are the descendants of varieties that predated this second catastrophic event. (The oldest known mushroom—encased in amber and collected in New Jersey—dates from Cretaceous time, 92 to 94 million years ago. Mushrooms evolved their basic forms well before the most distant mammal ancestors of humans.) Mycelium steers the course of ecosystems by favoring successions of species. Ultimately, mycelium prepares its immediate environment for its benefit by growing ecosystems that fuel its food chains.

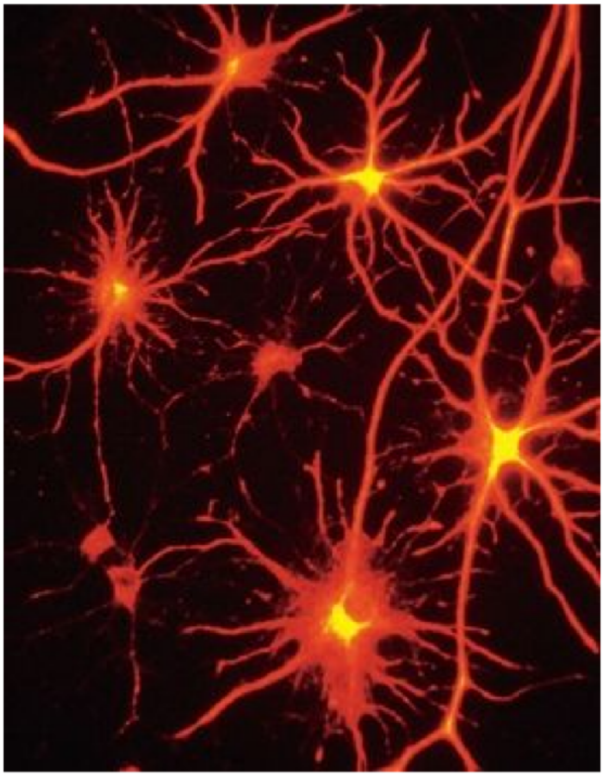


FIGURE 3 Micrograph of astrocytic brain cells. Networking of neurons creates pathways for distributing information. Mycelial nets share this same architecture.

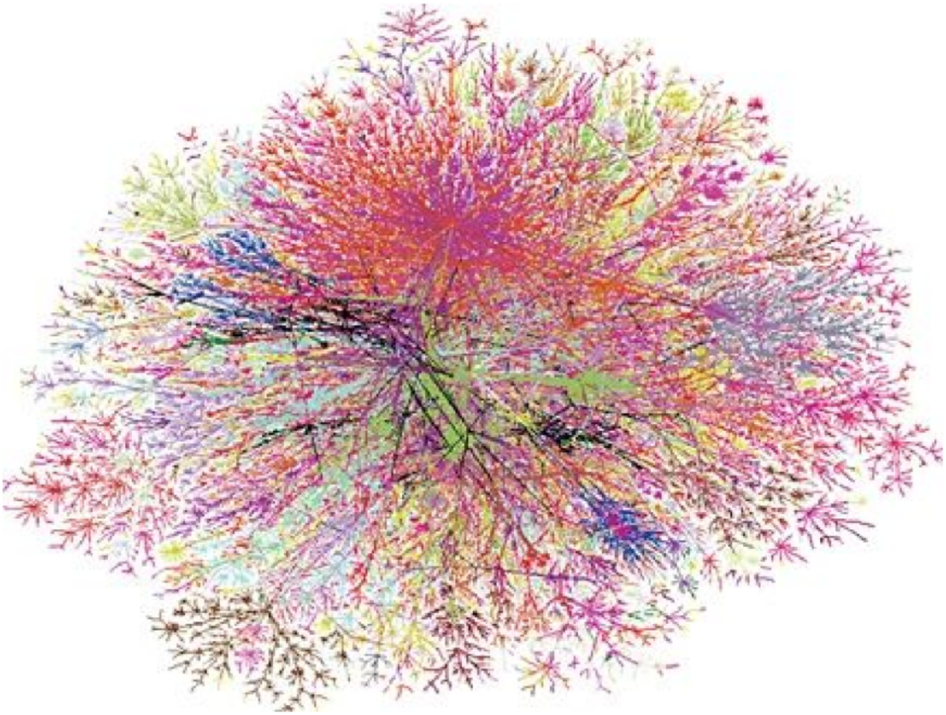
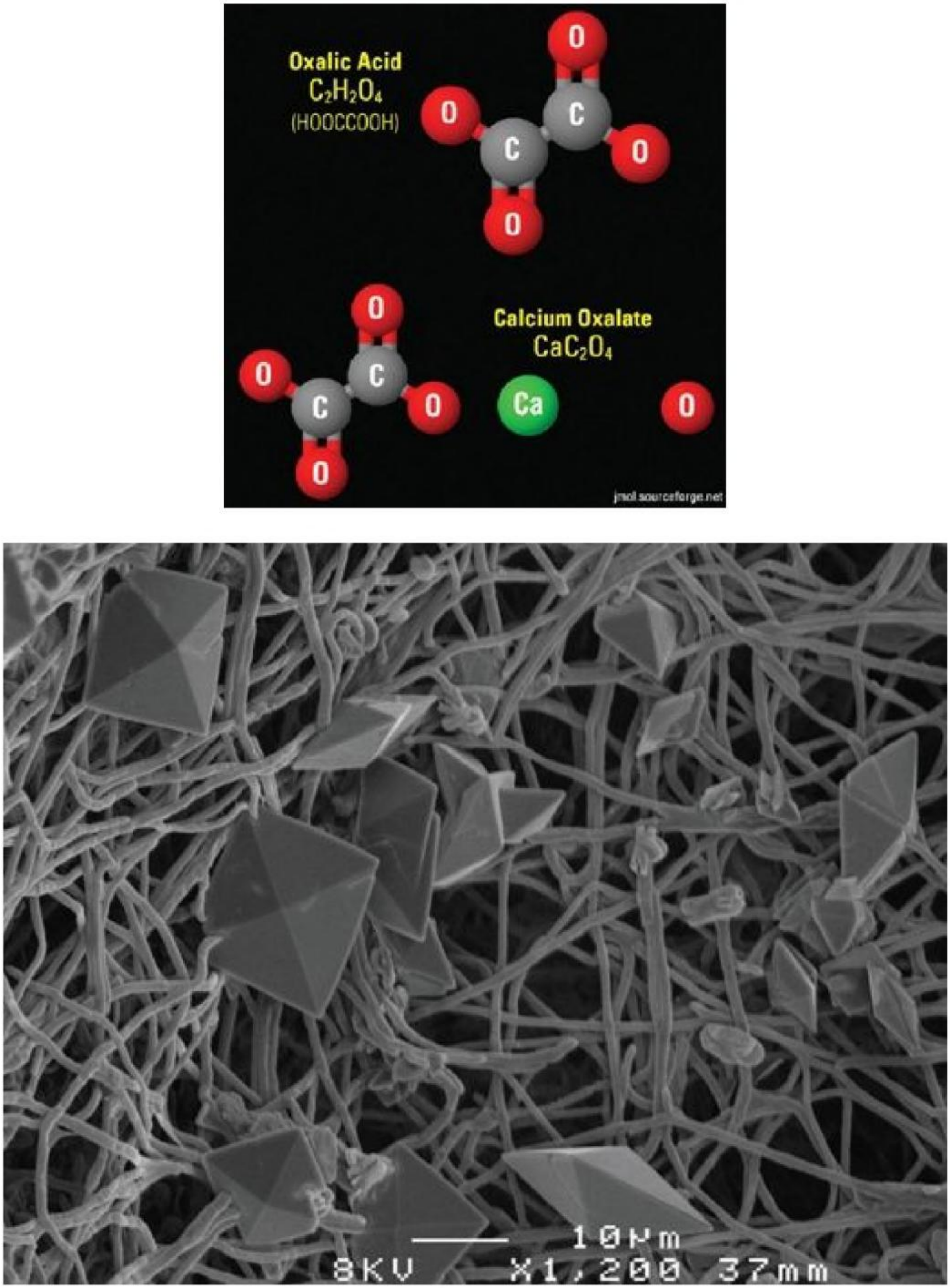


FIGURE 4 A diagram of the overlapping information-sharing systems that comprise the Internet.

Ecotheorist James Lovelock, together with Lynn Margulis, came up with the Gaia hypothesis, which postulated that the planet's biosphere intelligently piloted its course to sustain and breed new life. I see mycelium as the living network that manifests the natural intelligence imagined by Gaia theorists. The mycelium is an exposed sentient membrane, aware and responsive to changes in its environment. As hikers, deer, or insects walk across these sensitive filamentous nets, they leave impressions, and mycelia sense and respond to these movements. A complex and resourceful structure for sharing information, mycelium can adapt and evolve through the ever-changing forces of nature. I especially feel that this is true upon entering a forest after a rainfall when, I believe, interlacing mycelial membranes awaken. These sensitive mycelial membranes act as a collective fungal consciousness. As mycelia's metabolisms surge, they emit attractants, imparting sweet fragrances to the forest and connecting ecosystems and their species with scent trails. Like a matrix, a biomolecular superhighway, the mycelium is in constant dialogue with its environment, reacting to and governing the flow of essential nutrients cycling through the food chain.



FIGURES B AND C Oxalic acid and calcium oxalate. Oxalic acid crystals are formed by the mycelia of many fungi.

Oxalic acid mineralizes rock by combining with calcium and many other minerals to form oxalates, in this case calcium oxalate. Calcium oxalate sequesters two carbon dioxide molecules. Carbon-rich mushroom mycelia unfold into complex food webs, crumbling rocks as they grow, creating dynamic soils that support diverse populations of organisms. Below: Scanning electron micrograph of calcium oxalate crystals forming upon mycelium.

FIGURE D Prototaxites was the name given to this fossil—a remnant of a life form approximately 420 million years old, existing at the end of the late Silurian and through the beginning of the Devonian periods. Found in Canada and Saudi Arabia, this organism was widespread across the landscapes of the Paleozoic era. First described in 1859, this fossil remained a mystery until C. Kevin Boyce and others proved that it was a giant fungus in 2007.

FIGURE E Artist depiction of Prototaxites, which was the tallest known organism on land in its time, laying down or standing upright. The tallest plants, featured next to Prototaxites, were less than a meter high.

I believe that the mycelium operates at a level of complexity that exceeds the computational powers of our most advanced supercomputers. I see the myce-lium as the Earth's natural Internet, a consciousness with which we might be able to communicate. Through cross-species interfacing, we may one day exchange information with these sentient cellular networks. Because these externalized neurological nets sense any impression upon them, from footsteps to falling tree branches, they could relay enormous amounts of data regarding the movements of all organisms through the landscape. A new bioneering science could be born, dedicated to programming myconeurological networks to monitor and respond to threats to environments. Mycelial webs could be used as information platforms for mycoengineered ecosystems.

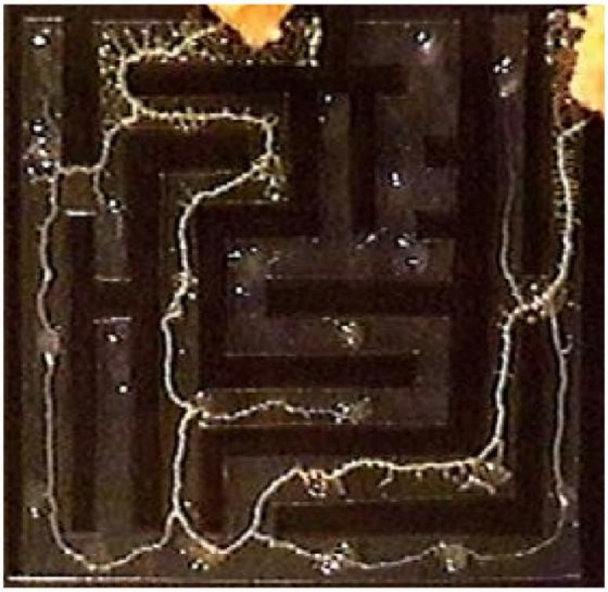


FIGURE 5 A slime mold, *Physarum polycephalum,* chooses the shortest route between 2 food sources in a maze, disregarding dead ends. In a controversial article, Toshuyiki Nakagaki proposes that this represents a form of cellular intelligence.

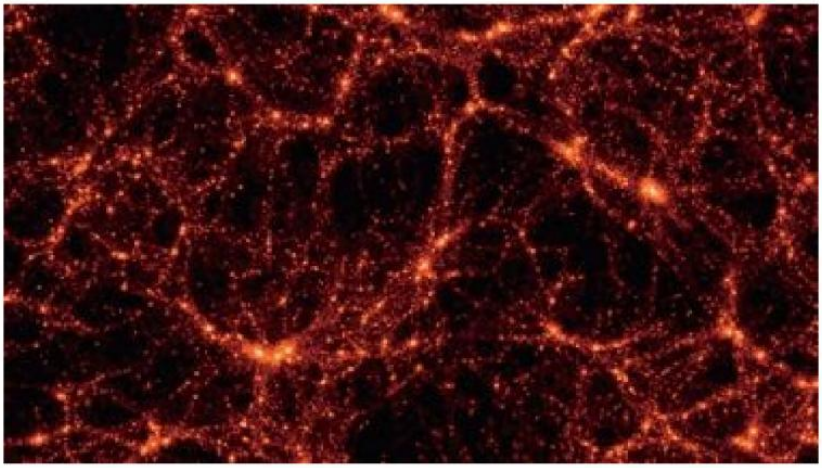


FIGURE 6 Computer model of the early universe. These primeval filaments in space resemble the mycelial archetype.

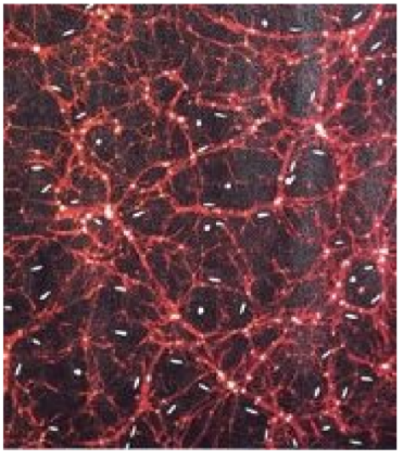


FIGURE 7 Computer model of dark matter in universe. In a conjunct of string theory, more than 96 percent of the mass of the universe is theorized to be composed of these molecular threads. Note the galaxies interspersed throughout the myceliumlike matrix.

The idea that a cellular organism can demonstrate intelligence might seem radical if not for work by researchers like Toshuyiki Nakagaki (2000). He placed a maze over a petri dish filled with the nutrient agar and introduced nutritious oat flakes at an entrance and exit. He then inoculated the entrance with a culture of the slime mold *Physarum polycephalum* under sterile conditions. As it grew through the maze it consistently chose the shortest route to the oat flakes at the end, rejecting dead ends and empty exits, demonstrating a form of intelligence, according to Nakagami and his fellow researchers. If this is true, then the neural nets of microbes and mycelia may be deeply intelligent.

A few recent studies support this novel perspective—that fungi can be intelligent and may have potential as our allies, perhaps being programmed to collect environmental data, as suggested above, or to communicate with silicon chips in a computer interface. Envisioning fungi as nanoconductors in mycocomputers, Gorman (2003) and his fellow researchers at Northwestern University have manipulated mycelia of *Aspergillus niger* to organize gold into its DNA, in effect creating mycelial conductors of electrical potentials. NASA reports that microbiologists at the University of Tennessee, led by Gary Sayler, have developed a rugged biological computer chip housing bacteria that glow upon sensing pollutants, from heavy metals to PCBs (Miller 2004). Such innovations hint at new microbiotechnologies on the near horizon. Working together, fungal networks and environmentally responsive bacteria could provide us with data about pH, detect nutrients and toxic waste, and even measure biological populations.

FIGURE 8 Cultures of this yet-to-be-named Californian *Psilocybe* mushroom swirl like a cyclone as they grow outward; the rate of growth increases with time.

FIGURE 9 Several mycelial mats of the root-rot *Armillaria* mushroom spiral outward, killing a forest in Montana. Once these trees die, they become highly flammable. (See also figure 60 for a larger patch of *Armillaria*, the largest organism in the world.)

Fungi in Outer Space?

Fungi may not be unique to Earth. Scientists theorize that life is spread throughout the cosmos, and that it is likely to exist wherever water is found in a liquid state. Recently, scientists detected a distant planet 5,600 light-years away, which formed 13 billion years ago, old enough that life could have evolved there and become extinct several times over (Savage et al. 2003). (It took 4 billion years for life to evolve on Earth.) Thus far 120 planets outside our solar system have been discovered, and more are being discovered every few months. Astrobiologists believe that the precursors of DNA, prenucleic acids, are forming throughout the cosmos as an inevitable consequence of matter as it organizes, and I have little doubt that we will eventually survey planets for mycological communities. The fact that NASA has established the Astrobiology Institute and that Cambridge University Press has established *The International Journal for Astrobiology* is strong support for the theory that life springs from matter and is likely widely distributed throughout the galaxies. I predict an *Interplanetary Journal of Astromycology* will emerge as fungi are discovered on other planets. It is possible that proto-germplasm could travel throughout the galactic expanses riding upon comets or carried by stellar winds. This form of interstellar protobiological migration, known as *panspermia,* does not sound as farfetched today as it did when first proposed by Sir Fred Doyle and Chandra Wickramasinghe in the early 1970s. NASA considered the possibility of using fungi for interplanetary colonization. Now that we have landed rovers on Mars, NASA takes seriously the unknown consequences that our microbes will have on seeding other planets. Spores have no borders.

FIGURE 10 Hurricane Isabella approaches North America in October 2003.

FIGURE 11 Spiral galaxies conform to the same archetypal pattern as hurricanes and mycelium.

The Mycelial Archetype

Nature tends to build upon its successes. The mycelial archetype can be seen throughout the universe: in the patterns of hurricanes, dark matter, and the Internet. The similarity in form to mycelium may not be merely a coincidence. Biological systems are influenced by the laws of physics, and it may be that mycelium exploits the natural momentum of matter, just like salmon take advantage of the tides. The architecture of mycelium resembles patterns predicted in string theory, and astrophysicists theorize that the most energy-conserving forms in the universe will be organized as threads of matterenergy. The arrangement of these strings resembles the architecture of mycelium. When the Internet was designed, its weblike structure maximized the pooling of data and computational power while minimizing critical points upon which the system is dependent. I believe that the structure of the Internet is simply an archetypal form, the inevitable consequence of a previously proven evolutionary model, which is also seen in the human brain; diagrams of computer networks bear resemblance to both mycelium and neurological arrays in the mammalian brain (see figures 3 and 4). Our understanding of information networks in their many forms will lead to a quantum leap in human computational power (Bebber et al. 2007).

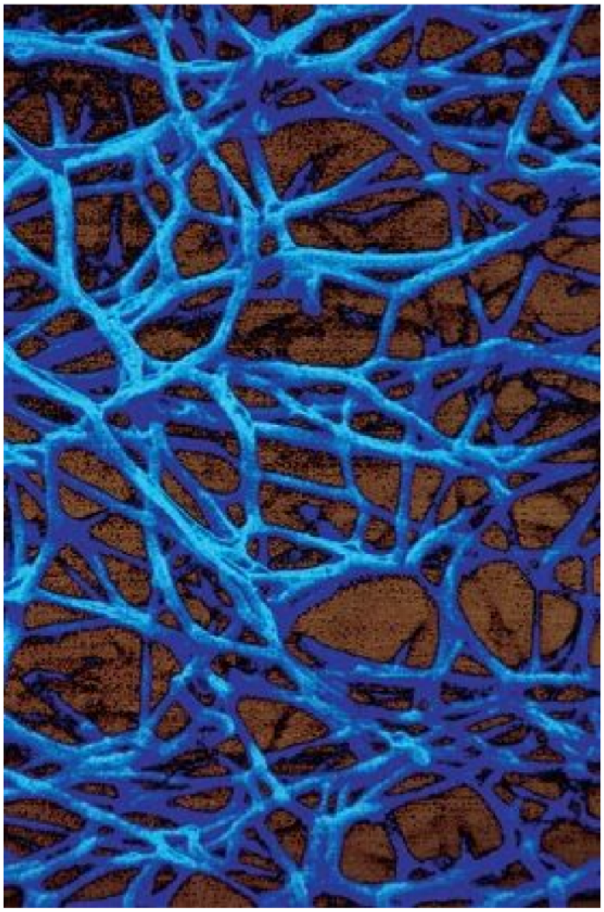


FIGURE 12 Close-up of mycelium.

Mycelium in the Web of Life

As an evolutionary strategy, mycelial architecture is amazing: one cell wall thick, in direct contact with myriad hostile organisms, and yet so pervasive that a single cubic inch of topsoil contains enough fungal cells to stretch more than 8 miles if placed end to end. I calculate that every footstep I take impacts more than 300 miles of mycelium. These fungal fabrics run through the top few inches of virtually all landmasses that support life, sharing the soil with legions of other organisms. If you were a tiny organism in a forest's soil, you would be enmeshed in a carnival of activity, with mycelium constantly moving through subterranean landscapes like cellular waves, through dancing bacteria and swimming protozoa with nematodes racing like whales through a microcosmic sea of life.

Year-round, fungi decompose and recycle plant debris, filter microbes and sediments from runoff, and restore soil. In the end, life-sustaining soil is created from debris, particularly dead wood. We are now entering a time when mycofilters of select mushroom species can be constructed to destroy toxic waste and prevent disease, such as infection from coliform or staph bacteria and protozoa and plagues caused by disease-carrying organisms. In the near future, we can orchestrate selected mushroom species to manage species successions. While mycelium nourishes plants, mushrooms themselves are nourishment for worms, insects, mammals, bacteria, and other, parasitic fungi. I believe that the occurrence and decomposition of a mushroom pre-determines the nature and composition of down-stream populations in its habitat niche.

Wherever a catastrophe creates a field of debris—whether from downed trees or an oil spill—many fungi respond with waves of mycelium. This adaptive ability reflects the deep-rooted ancestry and diversity of fungi—resulting in the evolution of a whole kingdom populated with between 1 and 2 million species. Fungi outnumber plants at a ratio of at least 6 to 1. About 10 percent of fungi are what we call mushrooms (Hawksworth 2001), and only about 10 percent of the mushroom species have been identified, meaning that our taxonomic knowledge of mushrooms is exceeded by our ignorance by at least one order of magnitude. The surprising diversity of fungi speaks to the complexity needed for a healthy environment. What has been become increasingly clear to mycologists is that protecting the health of the environment is directly related to our understanding of the roles of its complex fungal populations. Our bodies and our environs are habitats with immune systems; fungi are a common bridge between the two.

All habitats depend directly on these fungal allies, without which the life-support system of the Earth would soon collapse. Mycelial networks hold soils together and aerate them. Fungal enzymes, acids, and antibiotics dramatically affect the condition and structure of soils (see figure 25). In the wake of catastrophes, fungal diversity helps restore devastated habitats. Evolutionary trends generally lead to increased bio-diversity. However, due to human activities we are losing many species before we can even identify them. In effect, as we lose species, we are experiencing devolution—turning back the clock on biodiversity, which is a slippery slope toward massive ecological collapse. The interconnectedness of life is an obvious truth that we ignore at our peril.

In the 1960s, the concept of “better living through chemistry” became the ideal as plastics, alloys, pesticides, fungicides, and petrochemicals were born in the laboratory. When these synthetics were released into nature, they often had a dramatic and initially desirable effect on their targets. However, events in the past few decades have shown that many of these inventions were in fact bitter fruits of science, levying a heavy toll on the biosphere. We have now learned that we must tread softly on the web of life, or else it will unravel beneath us.

Toxic fungicides like methyl bromide, once touted, not only harm targeted species but also nontargeted organisms and their food chains and threaten the ozone layer. Toxic insecticides often confer a temporary solution until tolerance is achieved. When the natural benefits of fungi have been repressed, the perceived need for artificial fertilizers increases, creating a cycle of chemical dependence, ultimately eroding sustainability. However, we can create mycologically sustainable environments by introducing plantpartnering fungi (mycorrhizal and endophytic) in combination with mulching with saprophytic mushroom mycelia. The results of these fungal activities include healthy soil, biodynamic communities, and endless cycles of renewal. With every cycle, soil depth increases and the capacity for biodiversity is enhanced.

Living in harmony with our natural environment is key to our health as individuals and as a species. We are a reflection of the environment that has given us birth. Wantonly destroying our life-support ecosystems is tantamount to suicide. Enlisting fungi as allies, we can offset the environmental damage inflicted by humans by accelerating organic decomposition of the massive fields of debris we create—through everything from clear-cutting forests to constructing cities. Our relatively sudden rise as a destructive species is stressing the fungal recycling systems of nature. The cascade of toxins and debris generated by humans destabilizes nutrient return cycles, causing crop failure, global warming, climate change and, in a worst-case scenario, quickening the pace towards ecocatastrophes of our own making. As ecological disrupters, humans challenge the immune systems of our environment beyond their limits. The rule of nature is that when a species exceeds the carrying capacity of its host environment, its food chains collapse and diseases emerge to devastate the population of the threatening organism. I believe we can come into balance with nature using mycelium to regulate the flow of nutrients. The age of mycological medicine is upon us. Now is the time to ensure the future of our planet and our species by partnering, or running, with mycelium.

CHAPTER 2

The Mushroom Life Cycle

For you to use mycelia as healing membranes, a basic understanding of the mushroom life cycle is helpful. Although we notice mushrooms when they pop up, their sudden appearance is the completion of cellular events largely hidden from view—until the inquisitive mycophile digs deeper. Although mycologists have a basic understanding of the mushroom life cycle, we are clueless how mushroom species interact with most other organisms coexisting in the same habitat. With each nuance revealed, the body-intellect of mycology expands, and our knowledge slowly inches forward. What is so exciting about mycology is that the depth of undiscovered knowledge laying before us is more vast than our minds can imagine.

Mushrooms reproduce through microscopic spores, visible as dust when they collect en masse. When the moisture, temperature, and nutrients are right, spores freed from a mushroom (essentially mushroom seeds) germinate into threads of cells called *hyphae.* As each hypha grows and branches, it forms connections with other hyphae from compatible spores to create a mycelial mat, which matures, gathering nutrients and moisture. From mycelium, cells aggregate to form a primordium—called "pinheads" or baby mushrooms by growers. Under optimal conditions, the transformation from spores to mycelium to mushroom can take just a few days.

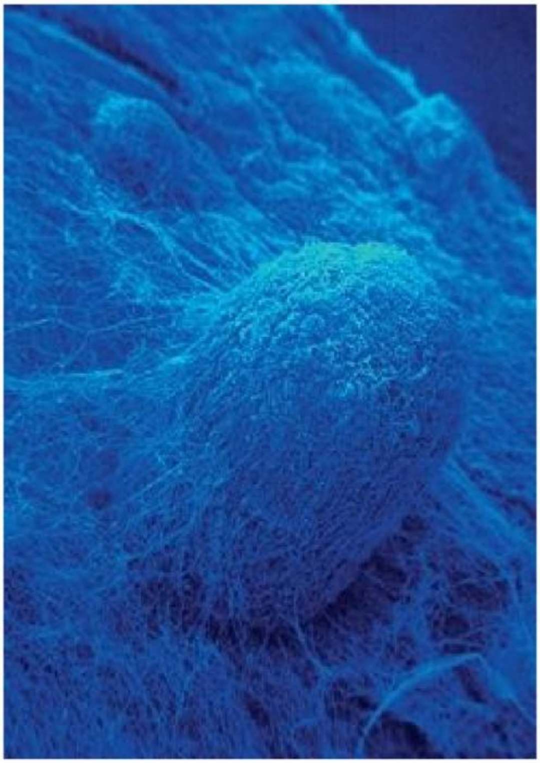


FIGURE 13 Depiction of the mushroom life cycle.

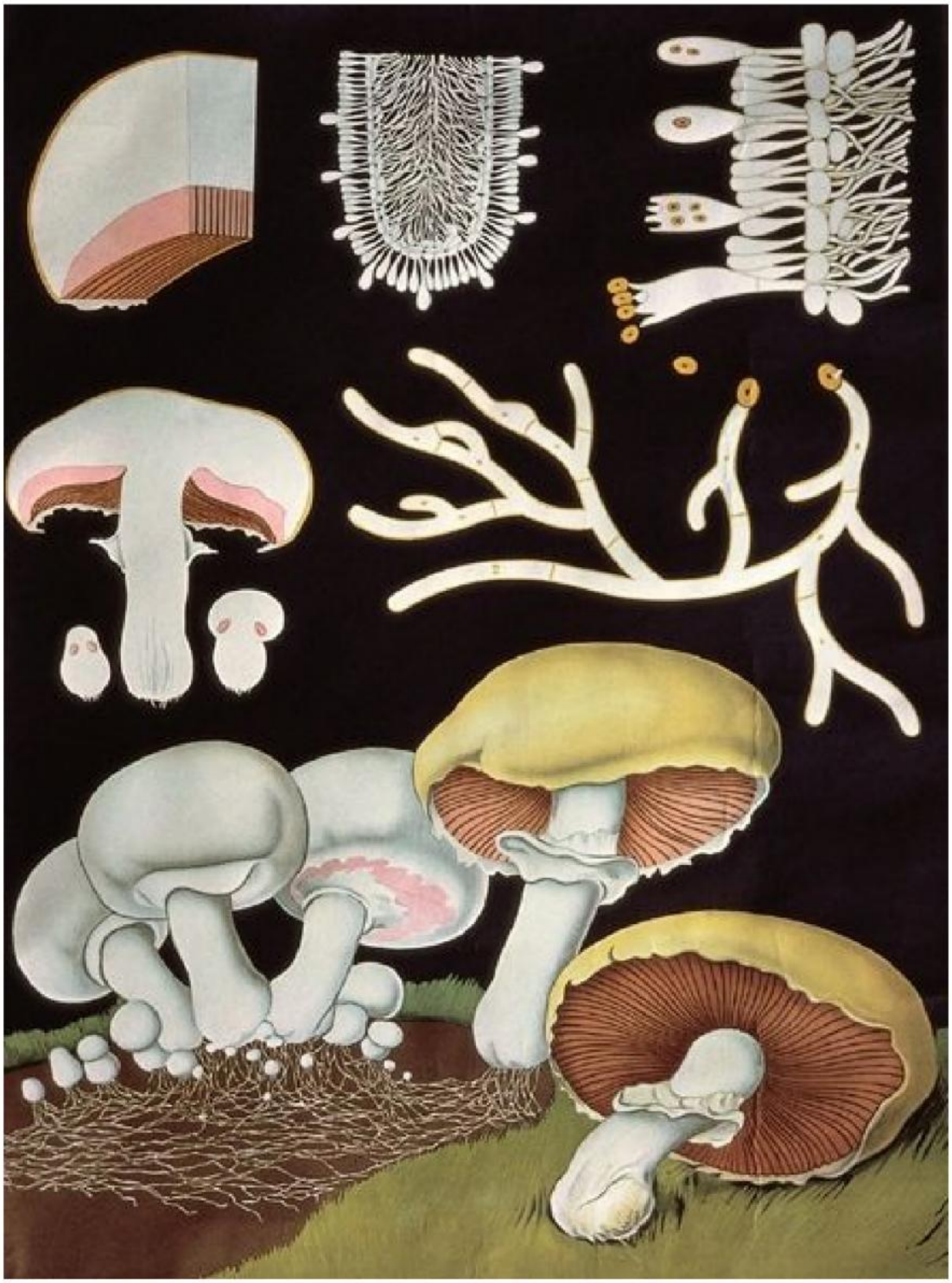


FIGURE 14 Scanning electron micrograph of primordium forming from a mycelial mat.

Mushrooms can be divided into 2 basic categories depending upon how they form: predeterminant or indeterminant. Most mushrooms are predeterminant, meaning the stem, cap, and gills preform in the primordial state. If the young primordia are damaged, deformities appear in adulthood.

FIGURE 15 A baby mushroom is called a *primordium,* a stage between mycelium and mature mushroom.

FIGURE 16 An example of an indeterminant mushroom species, a *Ganoderma,* perhaps *Ganoderma curtisii,* a sister species to reishi *(Ganoderma lucidum)*. The mushrooms formed and grew around twigs and grass—the latter of which remains green, vibrant, and healthy, despite being surrounded by fungal tissue, a phenomenom I find peculiar, and biologically interesting.

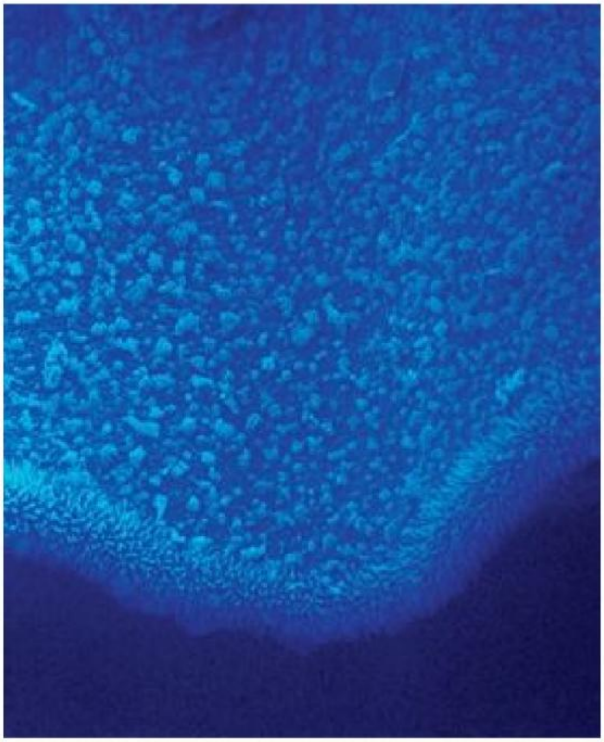


FIGURE 17 Low magnification of a mushroom gill plate showing the gill edge and surface plane populated with spore-producing basidia.

Less common are the indeterminant mushrooms, including many *Ganodermas, Phaeolus schweinitzii,* and the rare *Bridgeoporus nobilissimus.* Their mycelia form primordia that envelop sticks and twigs as they grow. If these young mushrooms are damaged at this stage and go on to recover, they mature with little trace of wounds.

Mushrooms display many artful forms, adapted for the purpose of dispersing spores: classic button mushroom, hoof-shaped conk (which has many pores, and hence is called a *polypore*), ridge-forming chanterelle, toothed *Hericium,* coral-like *Ramaria,* leafy *Sparassis,* and cup-forming *Auricularia.* These mushrooms, so diverse in shape, produce spores from similar clublike structures called *basidia,* which arise from a specialized layer of cells called the *hymenium.* In oyster and button mushrooms, the hymenial layer covers the surfaces of the gills. Despite their anatomical differences, these mushrooms produce microscopic spores in a similar way.

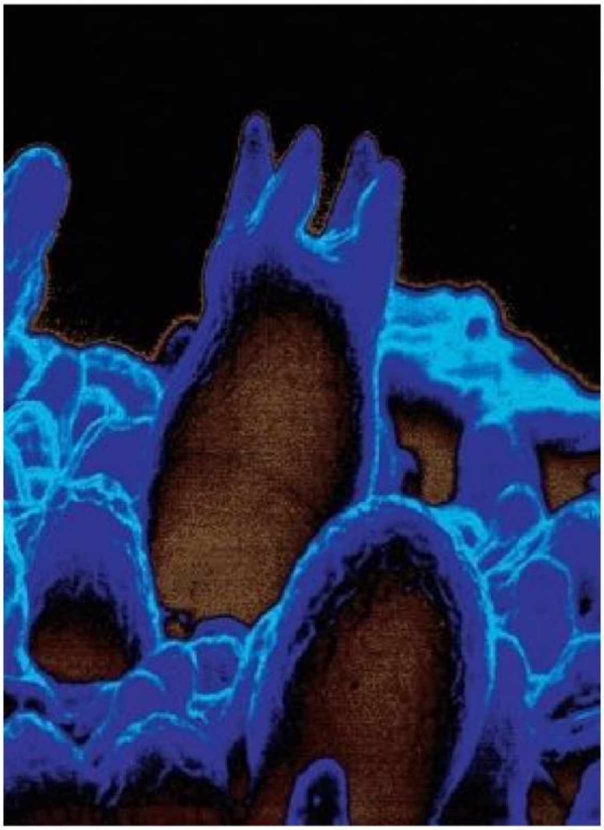


FIGURE 18 Emerging young basidium.

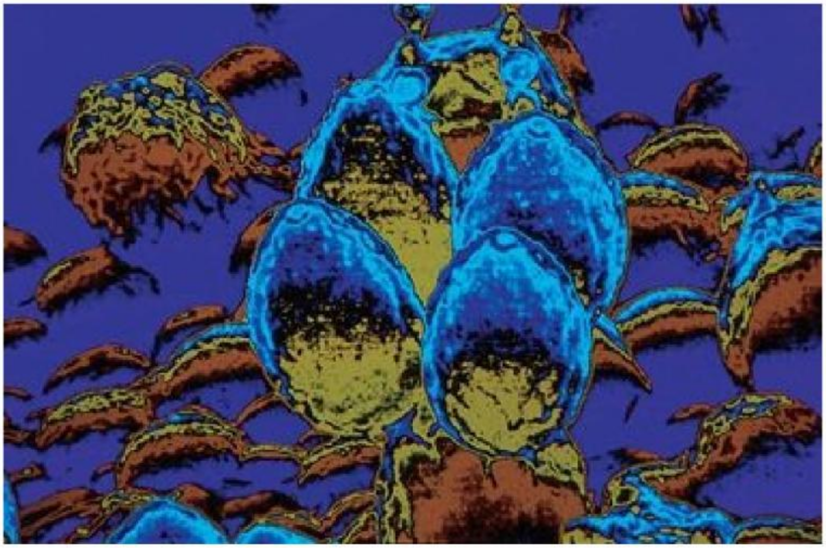


FIGURE 19 Mature basidium just before spore release.

Many mushrooms launch spores from basidia, which populate the gills on oyster mushrooms, for instance, and emerge in increasing quantities as the mushroom body matures. The vast majority of species produce 4-spored basidia, which are jettisoned in pairs with enough force to throw them inches away from the mushroom (see figures 18 and 19). Nicholas Money (1998) measured this force as 25,000 g's, approximately 10,000 times the forces experienced by the space shuttle astronauts escaping the gravitational pull of the Earth to obtain orbit.

Although spores tend to fall near their parent mushroom, trails of spores can sometimes be seen wafting in the air. Correspondingly, spores tend to be most concentrated closest to the ripening mushroom, with the concentration decreasing exponentially with distance. However, many insects and mammals also participate in distribution. Drawn by the mushrooms' scent, insects use them as a home for their larvae, which then grow up and carry spores with them when they leave the nest. Mammals eat mushrooms for nourishment, and many spores survive digestion and are dispersed through the animals' waste. Mycologist James Trappe of Oregon State University showed that voles and flying squirrels ate subterranean truffles in old-growth forests, and in turn, spotted owls ate the flying squirrels and voles. (However, scientists do not yet know whether the scat from these spotted owls harbors viable truffle spores.) He discovered that these mammals' diets are dependent on truffle mushrooms, and that from the animals' fertile fecal droppings, the subterranean truffle mushroom is assured wider dispersal of its spores through the forest. This interdependency between animals and fungi is only one example of many in nature. That so many mushrooms compete for distribution and safe harbors for their spores may be one reason why so many spores are necessary.

David Arora reports in *Mushrooms Demystified* (1986) that a large *Ganoderma applanatum* is estimated to liberate up to 30 billion spores a day, and more than 5 trillion a year! (See figure 20.) This prodigious output of spores is necessary for fungi to find new habitats in which to thrive. Species like chanterelles are slow to release spores, typically producing mushrooms that persist and continue to release spores for many weeks, in contrast to fast-collapsing inky caps, which sporulate and liquefy within hours. Species vary in the timing and duration of spore release, depending on temperature, moisture, habitat, their animal partners, and their own constitution.

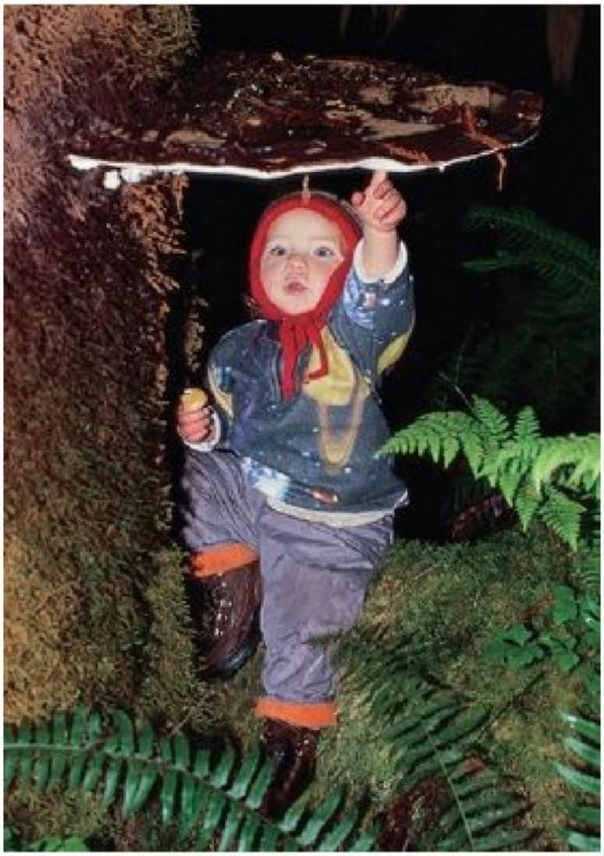


FIGURE 20 Cedar Cividanes reaches upward to touch the underside of a large specimen of the artist conk *(Ganoderma applanatum)* in the old-growth forest of the Duckabush River basin. In the Pacific Northwest, this mushroom produces prodigious quantities of spores from late spring through early fall.

FIGURE 21 From the artist conk featured in the previous image, we took a thumbnail-size slice of tissue back to the laboratory, where we broke it in half, cut out a tiny fragment, and transferred it to a nutrient-filled petri dish to start a culture. The resulting mushroom that grew is genetically identical to the wild artist conk from which it came. The original mushroom, whose small wound soon healed over, still survives in the old-growth forest. I encourage such low-

impact practices for collecting cultures without removing the mushrooms from their ecosystem.

Within a species, younger, thicker-fleshed mushrooms are typically more succulent than older ones and correspondingly have fewer spores. With oysters and buttons, for instance, the flesh above the gills, thick when young, thins as each wave of spores is released by successions of basidia. Generally, when a mature mushroom stops producing spores, it becomes an essential food source for people, deer, bears, squirrels, voles, and insects from gnats to arthropods, and no doubt influences legions of other organisms in the food chain.

Once spores are produced, most are quick to germinate. The spores of some mushrooms, like oysters, can germinate as soon as they leave the basidia and find a hospitable niche, whereas others, like shiitake, germinate more readily after drying out and then rehydrating. With many mushroom species, germination begins in the dimpled depression on the spore. In the first minutes, this process looks like that of a seed sprouting. The sproutlike hypha mitotically divides. Next comes the mating of hyphae from 2 compatible spores, each of which is mononucleate, having half of the code necessary for producing fertile offspring. After their mating, when the hyphae fuse to form one mycelium, the resulting cellular network, called a *dikaryon,* is invigorated, binucleate, and capable of producing descendant fertile mushrooms with spore-bearing ability. In the laboratory and in nature, cultures from mated spores grow far faster than mycelium originating from a single spore.

FIGURES 22, 23, AND 24 After a *Russula* mushroom climaxes and disintegrates, its spores germinate into a mycelial matrix. Days later, the mycelium spreads from the disintegrated parent mushroom's corpse, forming a mycelial network. Such surface mycelia soon submerge into the duff or soil, disappearing from view. Mycelia can be found under practically any log, stick, bale of straw, cardboard, or other organic material on the ground. In a gram of this myceliated soil, more than 1 mile of cells form; in a cubic inch more than 8 miles. In this photo, my hiking boot covers approximately 300 miles of mycelium. Hence from a mycelium's point of reference, a journey of 10,000 miles is only 33 plus footsteps!

You can grow mushrooms from spores or tissue. If you are creating your own cultures, it is essential that you use mushrooms that are fresh. If fresh mushrooms are not available, you can purchase cultures (spawn) or spores from commercial sources. What are the differences between cultures created from spores and those created from tissue? Each mating of 2 spores expresses but one of several possible phenotypes from the genome of the contributing mushrooms. In contrast, using a piece of living tissue from the mushroom—cloning—captures the exact genetic composition of the contributing mushroom. Cloning usually requires knowledge of sterile tissue culture technique and a clean room laboratory. (For more information on these techniques, refer to the books listed in the paragraph below.) Many mushrooms can also be propagated naturally from broken stem butts, which is another, although low-tech, form of cloning (see chapter 9). When stem butts regrow, or if you clone a mushroom by taking a piece of internal flesh and placing it on a petri dish filled with sterilized media, you are capturing the exact individual mushroom in hand. This book reveals easy-to-use techniques using spores, spawn, and stem butts for getting mushrooms into culture without needing a laboratory.

FIGURES 25, 26, AND 27 The path of decomposition: wood chips; wood chips colonized by mycelium; myceliated wood chips after digestion by worms and other organisms.

For more detailed descriptions of mushroom life cycles, see my book *Growing Gourmet and Medicinal Mushrooms* (2000a). I also highly recommend *The Fungi* by Carlile, Watkinson, and Gooday (2001), and *Fungal Morphogenesis* by David Moore (1998), both of which are available through www.fungi.com.

CHAPTER 3

Mushrooms in Their Natural Habitats

Mushrooms can be placed in 4 basic categories: *saprophytic, parasitic, mycorrhizal,* and *endophytic,* depending upon how they nourish themselves. However, exceptions abound, since some species employ more than one strategy, making them difficult to categorize. Approximately 8,000 macrofungi (visible to the naked eye) are saprophytic, around 2,000 to 3,000 are mycorrhizal, and the remaining are either endophytic or parasitic, although more species are constantly being discovered and categorized. The balance of populations can vary drastically with environmental change, however: deforestation causes a rise in saprophytes and a decline in mycorrhizal mushrooms, for example. Now let's take a short tour through the 4 major categories of mushrooms.

FIGURE 28 Turkey tail *(Trametes versicolor)* fruiting on a conifer log deep in old-growth forest in Olympic National Park.

Saprophytic Mushrooms: The Decomposers

Saprophytic mushrooms, the decomposers, steer the course for proliferating biological communities, shaping and forming the first menus in the food web from dead plants, insects, and other animals. Most gourmet and medicinal mushrooms are wood decomposers, the premier recyclers on the planet; building soils is the primary outcome of the activities of these saprophytic fungi, whose filamentous mycelial networks weave through and between the cell walls of plants. When organic matter falls from the canopy of trees and plants overhead onto the forest floor, the decomposers residing in the soil process this newly available food. (Competition is intense: on the forest floor, a single “habitat” can actually be matrices of fungal networks sharing one space.) These fungi secrete enzymes and acids that degrade large molecules of dead plants into simpler molecules, which the fungi can reassemble into building blocks, such as polysaccharides, for cell walls. From dead plants, fungi recycle carbon, hydrogen, nitrogen, phosporus, and minerals into nutrients for living plants, insects, and other organisms sharing that habitat.

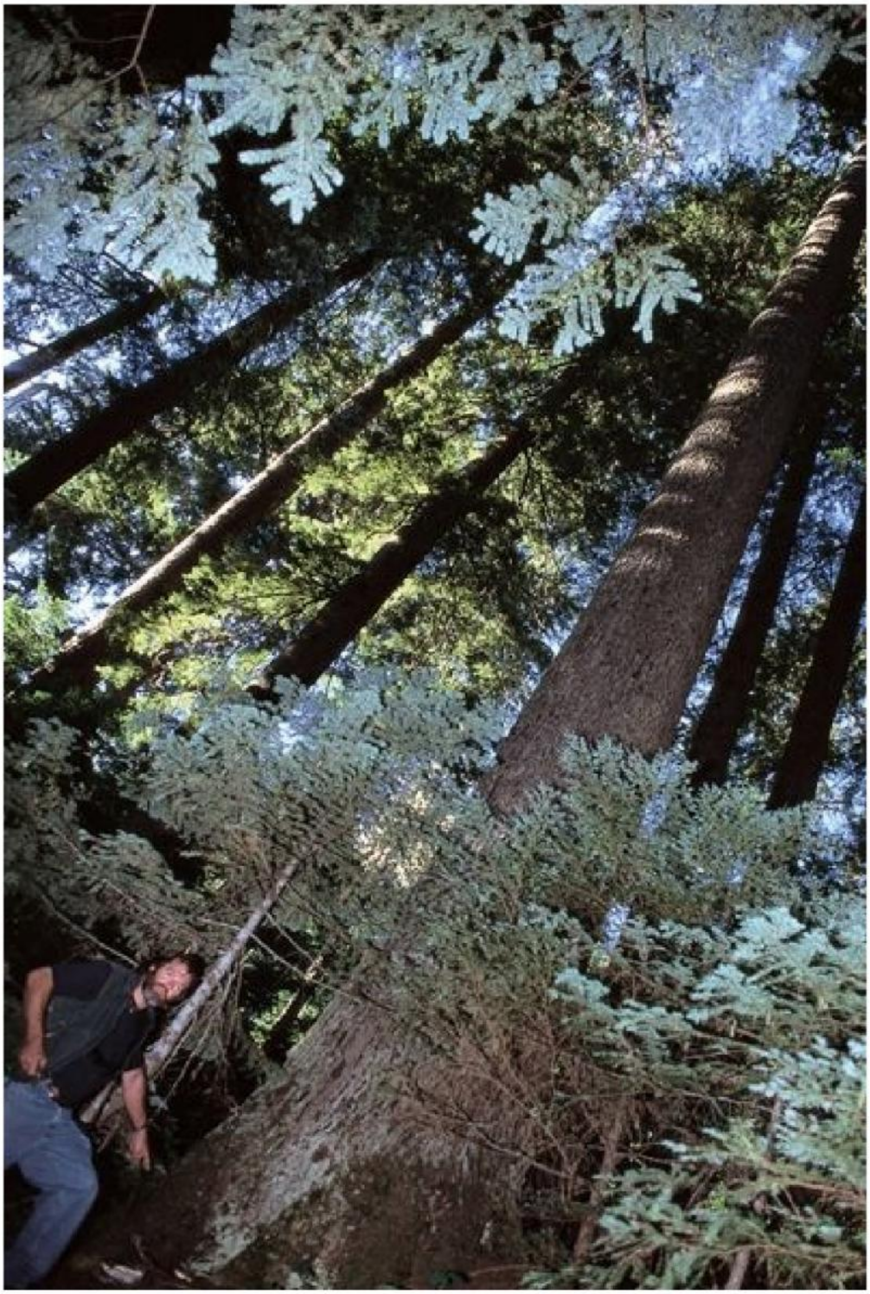


FIGURE 29 These towering old-growth trees near Mount Rainier, grow out of thin soil but gather nutrients from afar from their mycelium-supported roots. In fact, most plants are supported by vast and complex colonies of fungi working in concert. Here I point to *Bridgeoporus nobilissimus* (for a closer view see figure 50), a mushroom exclusive to old-growth habitat and the first fungus to be listed as an endangered species.

As decomposers, saprophytic mushrooms can be separated into 3 key groups: primary, secondary, and tertiary, although some mushroom species can cross over from one category to another, depending upon circumstances. Primary, secondary, and tertiary decomposers can all coexist in one location. Primary and secondary decomposers such as oyster and meadow mushrooms are the easiest to cultivate.

Primary Decomposers

These saprophytes are typically the first to grow on a twig, a blade of grass, a chip of wood, a log, a stump, or a dead insect or other animal. Primary decomposers are typically fast growing, sending out rapidly extending strands of mycelium that quickly attach to and decompose plant tissue. These woodland species include oyster mushrooms (*Pleurotus* species), shiitake *(Lentinula edodes),* and maitake *(Grifola frondosa)*. However, species employ different sets of enzymes to break down plant matter into varying stages of decomposition.

Secondary Decomposers

Secondary decomposers rely on the activity of primary fungi that initially, although partially, break down plant and animal tissues. Secondary decomposers all work in concert with actinomycetes, other bacteria, and fungi, including yeasts, in soil in the forest floor or in compost piles. Heat, water, carbon dioxide, ammonia, and other gases are emitted as by-products of the composting process. Once the microorganisms (especially actinomycetes) in the compost piles complete their life cycles, the temperature drops, encouraging a new wave of secondary decomposers.

FIGURE 30 David Arora, author of *Mushrooms Demystified* and *All That the Rain Promises and More* is positioned to take a photograph of a family of ambiguous Stropharias, *Stropharia ambigua,* near my home.

Cultivators exploit this sequence to grow the white button mushroom *(Agaricus bisporus),* the most widely cultivated mushroom in the world. Other secondary saprophytes that compete with compost-grown mushrooms are inky caps (belonging to the family Coprinaceae, which includes the choice, edible shaggy mane *[Coprinus comatus]* and others including the hallucinogenic *Panaeolus subbalteatus* and *Panaeolus cyanescens*); and, in outdoor wood chip beds, the ambiguous Stropharia *(Stropharia ambigua).* Industrial growers try to thwart these undesired invaders by heat steaming their composts to temperatures inhospitable to their spores.

that grow both parasitically and saprophytically.

Parasitic Mushrooms: Blights of the Forest or Agents for Habitat Restoration?

Parasites are predators that endanger the host's health. In the past, foresters saw all parasitic fungi as hostile to the long-term health of forests. Although they do parasitize trees, they nourish other organisms. Parasitic fungi such as the honey mushroom, which can destroy thousands of acres of forest, are stigmatized as blights. However, more foresters are realizing that a rotting tree in the midst of a canopied forest is, in fact, more supportive of biodiversity than a living tree. Parasitic mushrooms may be nature's way of selecting the strongest plants and repairing damaged habitats. Ultimately, parasitic mushrooms set the stage for the revival of weakened habitats that are too stressed to thrive.

Of all the parasitic blight mushrooms that are edible by humans, the assorted honey mushrooms such as *Armillaria mellea* and *Armillaria ostoyae* are the best known. One mycelial mat from a honey mushroom *(Armillaria bulbosa)* made national headlines when a specimen was found in a Michigan forest that covered 37 acres, weighed at least 50 tons, and was estimated to be 1,500 years old. In Oregon, a far larger honey mushroom *(Armillaria ostoyae)* mycelial mat found on a mountaintop covers more than 2,400 acres and is possibly more than 2,200 years old (see figure 60). Each time this fungus blight sweeps through, nurse logs are created, soil depth increases, and centimeters of soil accumulate to create ever-richer habitats where once only barren rock stood. (For further discussion of *Armillaria* blights, see figure 59.) What makes mushroom mycelia different from the mycelia from mold fungi is that some mushroom species can grow into massive membranes, thousands of acres in size, hundreds of tons in mass, and thousands of years old.

Many saprophytic fungi can be weakly parasitic, especially if a host tree is dying from other causes, such as environmental stress or parasite infestation. Saprophytes that can take advantage of a dying tree are termed *facultative* parasites. For example, oyster mushrooms *(Pleurotus ostreatus)* are classic saprophytes, although they are frequently found on dying cottonwood, oak, poplar, birch, maple, and alder trees. And although reishi *(Ganoderma lucidum)* is considered a true saprophyte by most mycologists, the Australian Quarantine Inspection Service has classified this medicinal species as a parasite and has banned its importation. Authorities on other islands including New Zealand and Hawaii also consider this mushroom a threat to their native trees. Some parasitic fungi behave like saprophytes, such as honey mushrooms *(Armillaria mellea* and *Armillaria ostoyae),* which may be found thriving on the corpse of their tree host.

Most parasitic fungi, however, are microfungi, barely visible to the naked eye, but en masse they inflict cankers and lesions on the shoots and leaves of trees. Often their prominence in a middle-aged forest is symptomatic of other imbalances in the ecosystem, such as acid rain, groundwater pollution, and insect damage. After a tree dies, parasitic fungi may inhabit the tree, competing with saprophytes for dominance. Since the hosts for some parasites can be short-lived, natural selection sometimes favors fast growers. Foresters have observed this with *Phytophthora ramorum,* the cause of sudden oak disease; this downy mildew pathogen can kill an ancient oak tree in days and an ancestral forest in a few weeks, and remain viable on the dead carcasses of its victims, allowing a new staging platform for infection further into the forest.

FIGURE 34 Matsutake, which are mycorrhizal mushrooms known to mycologists as *Tricholoma magnivelare,* growing deep in the old-growth forest of Washington State.

Mycorrhizal Mushrooms: Fungus and Plant Partnerships

Mycorrhizal mushrooms (*myco* means "mushroom"; *rhizal* means "related to roots"), such as matsutake, boletus, and chanterelles, form mutually beneficial relationships with pines and other plants. In fact, most plants from grasses to Douglas firs have mycorrhizal partners. The mycelia of fungal species that form exterior sheaths around the roots of partner plants are termed *ecto*mycorrhizal. The mycorrhizal fungi that invade the interior root cells of host plants are labeled *endo*mycorrhizal, although currently the preferred term for these fungi is *vesicular arbuscular mycorrhizae* (VAM). Both plant and mycorrhizae benefit from this association. Because ectomycorrhizal mycelium grows beyond the plant's roots, it brings distant nutrients and moisture to the host plant, extending the absorption zone well beyond the root structure. The mycelium dramatically increases the plant's ingestion of nutrients, nitrogenous compounds, and essential elements (phosphorus, copper, and zinc) as it decomposes surrounding debris. David Perry (1994) postulates that the surface area—hence its absorption capability—of mycorrhizal fungi may be 10 to 100 times greater than the surface area of leaves in a forest. As a result, the growth of plant partners is accelerated. Plants with mycorrhizal fungal partners can also resist diseases far better than those without. Fungi benefit from the relationship because it gives them access to plant-secreted sugars, mostly hexoses that the fungi convert to mannitols, arabitols, and erythritols.

One of the most exciting discoveries in the field of mycology is that the mycorrhizae can transport nutrients to trees of different species. One mushroom species can connect many acres of a forest in a continuous network of cells. In one experiment, researchers compared the flow of nutrients via the mycelium between 3 trees: a Douglas fir *(Pseudotsuga menziesii),* a paper birch *(Betula papyrifera),* and a western red cedar *(Thuja plicata)*. The Douglas fir and paper birch shared the same ectomycorrhiza, while the cedar had an endomycorrhiza (VAM). The researchers covered the Douglas fir to simulate deep shade, thus lowering the tree's ability to photosynthesize sugars. In response, the mycorrhizae channeled sugars, tracked by radioactive carbon, from the root zone of the birch to the root zone of the fir. More than 9 percent of the net carbon compounds transferred to the fir originated from the birch's roots, while the cedar received only a small fraction. The amount of sugar transferred was directly proportional to the amount of shading (Simard et al. 1997). An earlier study by Kristina Arnebrant and others (1993) showed a similar bidirectional transfer of nitrogen-based nutrients from alder *(Alnus glutinosa)* to pine *(Pinus contorta)* through a shared ectomycorrhizal mycelium.

FIGURE 35 Dusty Yao happily holds her harvest of wild porcinis, the mycorrhizal *Boletus edulis,* collected in the mountains above Telluride, Colorado.

FIGURE 36 Jim Gouin is pleased to find these delicious matsutakes *(Tricholoma magnivelare),* a mycorrhizal mushroom, in the mountains somewhere within 200 miles of Seattle, Washington.

FIGURE 37 Eureka! My basket awaits a bountiful collection of these apricot-smelling chanterelles, probably *Cantharellus formosus,* a mycorrhizal mushroom species growing in a 40-year-old Douglas fir forest near Olympia, Washington. My practice is to pick no more than 25 percent of the mushrooms of a wild patch, leaving young ones, and when encountering pairs of mushrooms, only pick one of them. Chanterelles tend to form as twins, so cutting one mushroom near to the ground saves the other twin, allowing it to mature, sporulate, and spread.

The Simard experiment showed that a common mycelial net could unite 3 species of trees and underscored a remarkable ability of mycorrhizal fungi: mycorrhizae can keep diverse species of trees in forests fed, particularly younger trees struggling for sunlight. Now we have a better understanding of how saplings survive in the shadows of elder trees that tower overhead and block out essential light. The fact that a single mycorrhizal mushroom nutritionally supported 2 different trees—one a conifer and the other deciduous—shows that the mycelium guards the forest's overall health, budgeting and multidirectionally allocating nutrients.

Another example of a fungus and plant partner-ship is the matsutake, which has a unique relationship with the non-chlorophyll-producing candystick plant *(Allotropa virgata)*. The candystick gains virtually all its sugars from the matsutake mycelium and the western hemlock and/or Sitka spruce with which it associates (Hosford et al. 1997; Trudell et al. 2003). One mycologist I know speculates that the spot fruitings of matsutake *(Tricholoma magnivelare)* on a slope of Oregon's Mount Hood may, in fact, be from a vast interconnected mycelial colony extending over thousands of acres. A further example is the bigleaf maple *(Acer macrophyllum),* which projects vinelike aerial roots that ascend to the canopy of Pacific Northwest

FIGURE 40 The Perigord truffle *(Tuber melanosporum)*, is one of the most sought-after and highly regarded gourmet mushrooms in the world. This mushroom is mycorrhizal, growing in association with filberts and oak trees.

Many American growers hope for huge profits when they try to grow European truffles, mycorrhizal mushrooms that sell at very high prices. In an attempt to duplicate the well-established truffle orchards in France, Spain, and Italy, where the renowned Perigord black truffle *(Tuber melanosporum)* fetches up to $500 per pound, dozens of growers have tried to cultivate nonnative European truffles around the American oaks or filberts on their land. Capitalizing on this desire, several companies now market truffle-inoculated trees for commercial use, and calcareous (high in calcium) soils in Texas, Washington, and Oregon have been suggested as ideal sites for these. One company (www.truffletree.com) that seems on top of its game confirms that the tree, inoculated with truffle mycorrhizae, is absent of competitor fungi before shipment (although it makes no promises about yield). However, I know of only a few successes—one from North Carolina and one from Northern California—that have produced European truffles, and only after more than a decade of effort. In the past 30 years tissue culture techniques have increasingly replaced the tradition of transplanting truffle-supporting trees. Despite this development, most plantings or inoculations of European truffles beyond their native habitat still fail to produce mushrooms. Showing that growing native species is far more successful than growing nonnative ones, a trufflateur in Washington recently produced the Oregon white truffle *(Tuber gibbosum)*, after patiently waiting for 20 years until the first truffles could be harvested. Nevertheless, commercialization of mycorrhizal gourmet mushrooms has seen little success outside of the European truffle orchards, particularly those in France and Italy.

The reality is, though, that our native species of mycorrhizae quickly outcompete the foreign European truffles. Since European truffles like basic (high pH) soil, the addition of calcium diminishes competition from native mushrooms, but this alone will not assure success. In New Zealand, where the repertoire of competing mycorrhizae is limited to just a few species, inoculated trees are likely to do better than in regions of North America that are resplendent with hundreds of competing mycorrhizal varieties.

FIGURE 41 Truffle "brule" surrounds this filbert tree. As the mycelium of *Tuber melanosporum* consolidates its domain, the surrounding vegetation dies, creating a noticeable zone in the calcareous soils, a telltale sign that truffle mycelium has taken root.

One method of inoculating mycorrhizae calls for planting young seedlings near the root zones of proven truffle trees. The new seedlings acquire mycorrhizae from a neighboring tree, and a second generation of trees carrying the mycorrhizal fungus is produced. After a few years, the new trees are dug up and replanted in new locations. This method has had the longest history of success in European sites where the soils, trees, and fungi are compatible.

Another approach, simple and elegant but not guaranteed, is to dip the exposed roots of seedlings into water enriched with the spore mass of a mycorrhizal candidate. First, mushrooms are gathered from the wild, and the spore-bearing surfaces are removed from the fruiting bodies, crushed, and immersed in water. Thousands of spores are washed off, resulting in an enriched broth of inoculum. A spore-mass slurry from a single mushroom, diluted in a 5-gallon bucket of water, can inoculate a hundred or more seedlings. Mycorrhized seedlings are healthier and grow faster than nonmycorrhized ones (see figure 42). Even if you are not successful in growing truffle mushrooms, the trees benefit from this pairing with the introduced mycelium.

Tossing spores using water as a carrier on the ground above the root zones of likely tree candidates is another method that takes little time and effort. Habitats should be selected on the basis of their parallels in the wild. For instance, chanterelles can be found in oak forests in the Midwest and in Douglas fir forests in the Northwest. Casting a spore mass of chanterelles into a forest similar to one where chanterelles naturally proliferate is obviously the best choice. However, the success rate is not high: even tree roots confirmed to be mycorrhized with gourmet mycelia will not necessarily yield harvestable mushrooms. Fungi and their host trees may have beneficial associations for long periods of time with no edible fruiting bodies appearing. Inoculations of mycorrhizae by one generation of mycologists may not see fruition until the next generation.

Chanterelles are one of the most popular collected mushrooms. In the Pacific Northwest, harvesting chanterelles is a controversial, multimillion-dollar business. Unfortunately, the gourmet mycorrhizal mushroom species are not readily cultured. Chanterelles demonstrate an unusual interdependence on soil yeasts, making tissue culture difficult. At least 4 organisms must be cultured simultaneously: the host tree, the mushroom, pseudomonas bacteria, and soil yeasts (red soil yeast, *Rhodotorula glutinis,* is needed for stimulating spore germination and healthy mycelial development). Not only do other microorganisms play essential roles, but the timing of their introduction is also critical to success in the fungal theater. Many experts believe that decades will pass before the plantations growing mycorrhizal species like chanterelles mature to a productive state.

No one has yet grown chanterelles to the fruiting body stage under sterile laboratory conditions, although greenhouse-grown pines have produced chanterelles after inoculation. In 1997 Eric Danell (accompanied by F. Camacho) was the first to successfully cultivate a chanterelle, fruiting mushrooms with a potted 16-month-old pine seedling in a greenhouse. Soon thereafter, Danell patented this particularly vigorous strain, which showed commercial potential. Field tests in 24 locations revealed chanterelle mycelium in the seedlings' root zones 2 years after inoculation. Unfortunately, he could not stop grazing animals, such as deer, squirrels, and beetles, from foraging and disturbing his crops. More recently, Danell started a Swedish company called Cantharellus AB to commercialize this breakthrough mycotechnology in the creation of chanterelle orchards. His group has planted thousands of trees with the chanterelle mycelium in an attempt to create mushroom plantations that produce mushrooms within a decade of planting. For the time being, only the patient might want to invest in mycorrhizal plantations.

FIGURE 42 Comparison of big leaf maples *(Acer macrophyllum)* without (smaller) and with (larger) mycorrhizae.

Given the long time involved in honing laboratory techniques, I favor the low-tech approach and traditional method of planting seedlings adjacent to known producers of chanterelles, matsutake, truffles, and boletus and then replanting the seedlings several years later. In this way, we can value the forest not for its quantity of harvestable lumber but for its potential to harbor mushroom colonies.

Mutualistic Species: Fungal Partnerships

Mutualism occurs when 2 or more organisms work directly together for their mutual benefit, usually to prevent infestation by parasites and gather

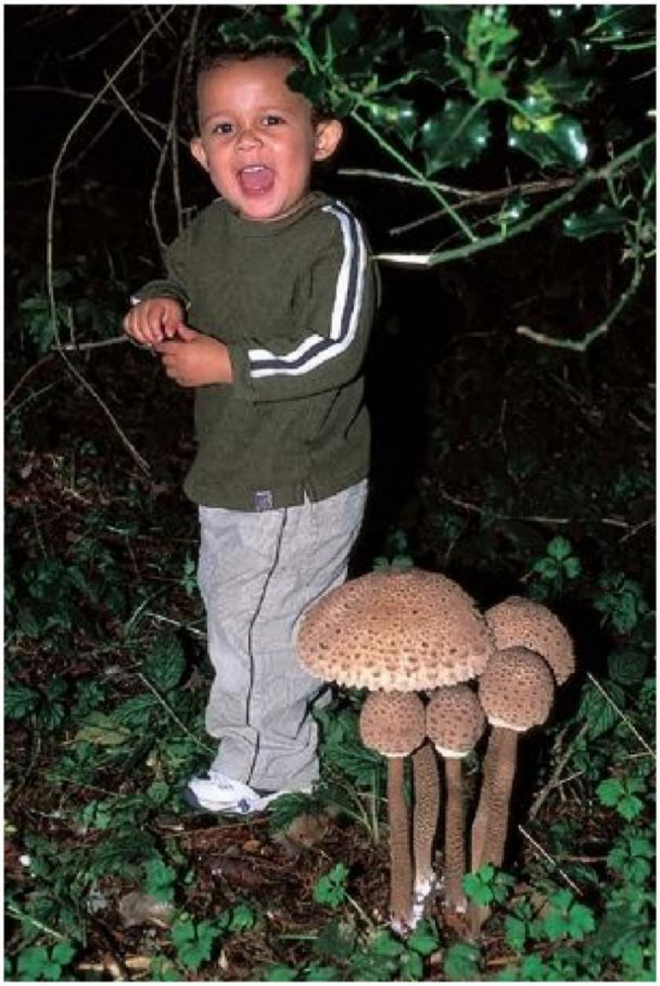


FIGURE 45 Trevon Stamets is excited to have his picture taken with the parasol mushroom *(Lepiota procera)* which is cultivated by ants to help them stave off infections. Many ants and termites farm fungi.

Snails as Fungus Farmers

Snails and slugs love mushrooms—an unfortunate situation for many of us mushroom lovers. Some snails enlist fungi to help them digest plants. Silliman and Newell (2003) found that a seaside snail, the marsh periwinkle *(Littoraria irrorata),* damages and then defecates on certain grass *(Spartina alternifolia),* where a particular fungus soon grows. Days later, the snails return to the grass, now overgrowing with fungus, and consume both fungus and plant. Grasses without the snail-enabled fungus grew 50 percent faster but were less appealing to feeding snails, whereas the plants covered with fungus were more palatable and nutritious for the snails. As you can see, the snail and fungus relationship affects other species in the marsh environment, such as grasses.

Endophytes: Mutualistic Symbionts

Endophytes are primarily benevolent, nonmycorrhizal fungi that partner with many plants, from grasses to trees. Their mycelia thread between cell walls but don't enter them, enhancing a plant's growth and ability to absorb nutrients, while staving off parasites, infections, and predation from insects, other fungi, and herbivores. Generally, endophytes are not true saprophytes or parasites but are in a class of their own. In contrast to mycorrhizal fungi, many endophytes grow well under laboratory conditions, so we can make spawn by using methods like those used for saprophytic mushrooms (Stamets 2000a).

The vast majority of endophytes are undescribed, and some appear to have lost the ability to produce spores, living vegetatively in a continuous mycelial state. Most endophytes described thus far are ascomycetes. One example is *Pezicula aurantiaca,* a small cuplike mushroom that lives on healthy alder trees. Like many endophytes, this fungus is dimorphic, expressing itself in two forms, with one being an asexual mold.

Endophytic fungi are especially skilled at producing specialized mycotoxins (often alkaloids), a class of compounds that includes toxic cyclopeptides and serotonin-like tryptamines such as psilocybin. Endophytes hosted by grasses are similar to the ergot fungi whose alkaloids prevent their hosts from insect attack. Endophytes in large crabgrass, for example, appear to produce toxins that kill fire ants, and those in grasses such as the darnel weed *(Lolium temulentum)* cause sleepiness in cattle and horses, a fact long known to ranchers in Central America. However, Stanley Faeth (2002) suggests that varying levels of alkaloids in plants may not yet afford consistent protection against herbivores. Because some grasses produce more mycotoxins than others in the same habitat, cattle may sometimes get a chemical cocktail but other times not, making it more difficult for them to learn which grasses to avoid.

Nevertheless, endophytes, which were once thought to be pathogens, are increasingly viewed as engaging the plant in a mutually beneficial relationship. In a 2003 experiment in Panama, researchers found that when endophyte-free leaves from the chocolate-producing cocoa tree *(Theobroma cacao)* were inoculated with endophytes, leaf necrosis and mortality declined threefold, suggesting a biodefensive effect is possible against other pathogens such as *Phytophthora,* the genus responsible for sudden oak death —a disease devastating California's native oak population. (Arnold et al.

2003).

Spores from endophytes compete with many other free-flying fungal spores. According to one estimate, more than 10,000 spores of fungi land on each leaf per day. Amidst such competition, friendly fungi taking up residence is actually an asset to plants otherwise subject to pathogenic assault. Increasingly, mycologists believe that endophytic fungi may have coevolved with hospitable plants (Arnold and Herre 2003).

Wheat farmers benefit from the endophyte *Piriformospora indica*. The basidiomycete of this species has yet to be identified, so it's referred to as *imperfect* (in the mycological world, this means that the fungus has no sexual phase or the sexual phase has not yet been discovered). This species is a root-based endophyte that promotes the growth of wheat shoots and roots and is capable of increasing leaf and seed production by more than 30 percent while shielding roots from infection by pathogenic microbes. Furthermore, seedlings paired with this mutualist successfully germinated 95 percent of the time, compared to only 57 percent for seedlings without this species. Root and shoot mass also doubled (Varma et al. 1999). This species has also demonstrated growth-enhancing properties when paired with maize *(Zea mays),* tobacco *(Nicotiana tobaccum),* and parsley *(Petroselinum crispum)*. This fungus is easy to cultivate in the laboratory and widely coexists with many grasses. Clearly, pairing this and other endophytes with agricultural crops can increase yield, decrease disease, and reduce the need for fertilizers and insecticides.

Endophytic fungi may have other practical applications in agriculture. Joan Henson and other researchers (2004) filed a patent application using a *Curvularia* species isolated from grasses in the geothermal zones of Yellowstone and Lassen Volcanic national parks. This fungus qualifies as an *extremophile*—a thermally tolerant species that grows at the far fringe of temperatures where life can be found—and confers some tolerance to drought and heat to the host plant. Henson's research showed that grasses inoculated with this endophyte survived temporary exposure to extraordinarily high temperatures—158°F or 70°C—while those without shriveled and died. Although wheat did not survive in their experiment, it did demonstrate increased drought resistance. When watermelon seedlings and mustard seedlings were dusted with *Curvularia* spores, the spores germinated and inhabited the young plants. After the endophytic fungi became established on their hosts, researchers exposed the seedlings to extremely high temperatures (122°F or 50°C). The seedlings with the endophytic spores survived prolonged exposures, but the same types of seedlings without endophytic spores died. The discovery of the *Curvularia* spores' effects on plants may expand the biological tool set for mycorestoration, possibly even drastically expanding oasis environments and countering desertification.

FIGURE 46 The tinder or amadou mushroom *(Fomes fomentarius)*, a species found predominantly on birch, is distributed throughout the boreal forests of the world.

Some wood conks once seen as parasites on trees may in fact be symbiotic endophytes. Baum and others (2003) report that the basidiomycetous polypore *Fomes fomentarius,* the tinder polypore or ice man mushroom, can operate as a nonsaprophytic endophyte in beech trees *(Fagus sylvatica).* This well-known polypore (see figure 46 and figure 252) is commonly found on beech, birch *(Betula),* poplar *(Populus),* alder *(Alnus),* maple *(Acer),* cherry *(Prunus),* and hickory *(Carya)*—trees that thrive in the boreal regions of the world. In the Baum experiment, healthy beech wood was cut into sections and incubated in culture dishes for 8 weeks, whereupon fungal cultures of this conk emerged. A number of isolates of *Fomes fomentarius* were identified from the wood sections, and some proved to be genetically different strains.

The fact that one species can perform separate but complementary functions in the forest suggests that the species may play a larger role in the forest than is presently understood. How many other perennial wood conks do the same? I once received a call from a manager of a chestnut orchard in Quebec, who told me that trees sporting chaga (see figure 47), the aerial sclerotium of *Inonotus obliquus,* were resistant to chestnut blight. (*Sclerotium* is a compact mass of hardened mycelium, with stored food, that can sometimes become a detached entity.) When he made a poultice of ground chaga and packed it into the lesions of infected chestnut trees, the wounds healed over and the trees recovered free of the blight. This leads me to wonder whether *Inonotus obliquus* can operate as an endophyte, as does *Fomes fomentarius,* and whether these species, or others like them, could defend host trees against invading parasites.

FIGURE 47 Mycologist Jim Gouin in Quebec, Canada, with chaga, the aerial sclerotium of *Inonotus obliquus.*

Many other mushrooms may be endophytes, including gilled species. For decades mycologists have been mystified how *Psilocybe cyanescens,* a psilocybin mushroom, can suddenly appear when trees are chipped into landscape mulch. A mycologist friend of mine had a truckload of fresh, mostly alder chips delivered to his house in the spring. Soon thereafter, his mostly conservative friends took some home for mulching. That fall most of their mulched beds were fruiting with hundreds of potent *Psilocybes*. Where could they have come from, my mycologist friend wondered? The only plausible explanation is that the mycelia were already in the wood,

CHAPTER 4

The Medicinal Mushroom Forest

Forest dwellers long ago discovered the value of medicinal mushrooms for the healing of both the body and the forest. Sadly, most of our ancestors' empirical knowledge is lost, but what little survives hints at a rich, albeit vulnerable, resource. The science of soils—mapping the matrix of plant, animal, and microbial communities in a habitat—remains in its infancy. Researchers have shown, however, that the forest is thoroughly interlaced with fungal nets of mycorrhizal, saprophytic, parasitic, and endophytic species. Mushrooms are forest guardians. A forest ecosystem cannot be defined without its fungi because they govern the transition between life and death and the building of soils, all the while fueling numerous life cycles. Primary saprophytes initiate the decomposition process, and what the saprophytes don't break down, the mycorrhizal fungi do. I suspect that the overlying saprophytic fungi on the forest floor also influence the diversity of mycorrhizal fungi through their selection of trees to associate with, and that they stream nutrients to the root zones. Other groups of fungi (including endophytes and parasites) also work in concert. With a complex interplay of partnerships, mutualism, and parasitism, fungi build the soils beneath our feet.

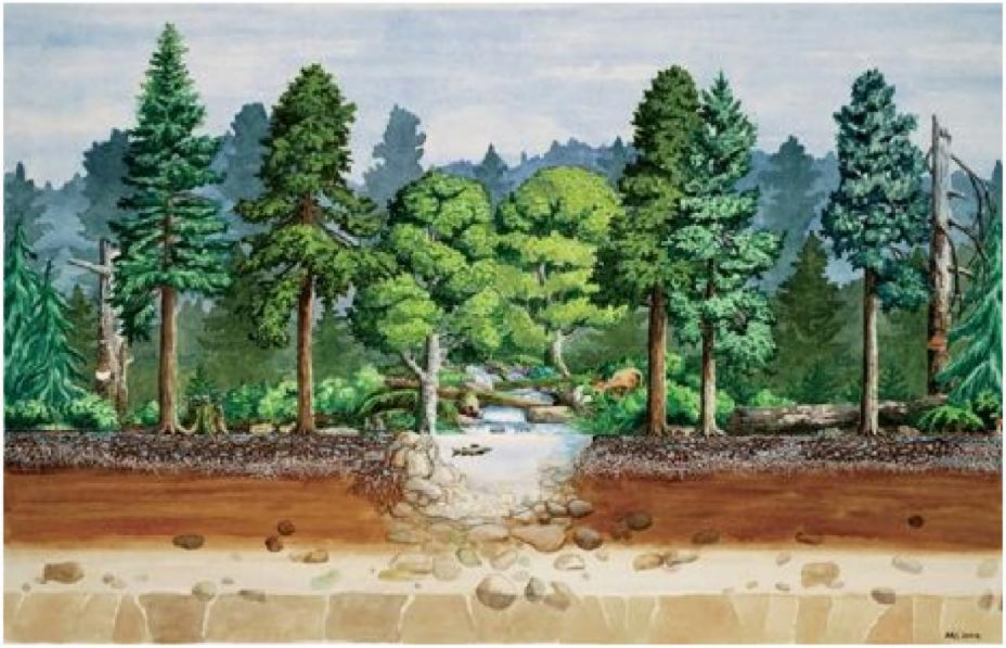


FIGURE 48 The health of a forest eco-system's foundation is an interplay of mycelial networks from saprophytic, mycorrhizal, endophytic, and parasitic fungi.

As loggers cut down the old-growth forests, many fungi lose their foothold in the ecosystem. Whether these fungi remain as mycelia, not resurfacing in fruiting for decades or centuries, is a matter of debate. When the forest returns to its previous majestic state, do the same mushroom strains also return, having lain latent in the landscape?

Fungi as Allies of People and the Planet

Let's look at the environment I know best: the rainforests of Washington State where I once worked as a logger. The dominant trees in the Olympics and the Cascades of the Pacific Northwest are Douglas firs, western and mountain hemlocks, red cedars, maples, alders, and various true firs—western, Pacific silver, noble, grand, white, red, and subalpine. More than 2,000 species of mushrooms live symbiotically with Douglas firs. Randy Molina and others (1997) estimate that 250 species of mycorrhizal fungi associate with hemlocks. Of the more than 527 mushroom species growing in old-growth forests, at least 109 of them are native to the Pacific Northwest (USDA 1993).

FIGURE 49 Dusty Yao hunts medicinal mushrooms in the Olympics.

One of the rarest old-growth-forest mushroom species is *Bridgeoporus nobilissimus* (formerly known as *Oxyporus nobilissimus*) the noble polypore (Stamets 2002a; Redberg et al. 2003). This mushroom once held the record for the largest in the world but was bumped by a more massive individual of the species, *Rigidoporus ulmarius,* estimated to weigh more than 660 pounds (about 300 kg). Other rare species are likely to thrive in old-growth forests, but they may go undiscovered for decades to come.

Most of the mushrooms collected in the forest are gathered for food. And most of these varieties are mycorrhizal, dependent on trees. The most recent data I have seen on the harvesting of wild mushrooms comes from a species survey in which the British Columbia Ministry of Forests tabulated 40 mushroom species of commercial interest (Berch and Cocksedge 2003). The most commonly collected mushrooms are chanterelles, matsutake, and hedgehogs.

Some Commonly Collected Wild Edible Mushrooms from Northwestern North America*

Mushroom	Common Name
Boletus edulis**	King bolete
Cantharellus cibarius**	Chanterelle
Cantharellus formosus**	Chanterelle
Cantharellus subalbidus**	White chanterelle
Coprinus comatus*	Shaggy mane
Cortinarius caperatus**	Gypsy mushroom
Craterellus cornucopiodes**	Horn of plenty
Hydnum repandum**	Hedgehog
Hypomyces lactifluorum***	Lobster
Leccinum insigne**	Aspen bolete
Leccinum seabrum	Birch bolete
Morchella elata*	Black morel
Morchella esculenta*	Yellow or white morel
Pleurotus ostreatus*	Oyster
Polyozellus multiplex**	Blue chanterelle
Sparassis crispa***	Cauliflower
Tricholoma matsutake**	Pine mushroom
Tuber gibbosum**	Oregon white truffle

* Species are saprophytes unless otherwise indicated.

** Mycorrhizal species, difficult to cultivate.

*** Nonmycorrhizal species, parasitic.

We face escalating challenges to our health from pollution and disease. Even in this era of high-tech genomics, natural compounds still provide a baseline for synthesizing drugs. Estimates are that two-thirds of our pharmaceuticals still originate from nature. For example, natural medicines such as taxol, discovered in the bark of Pacific yew trees *(Taxus brevifolia),* give chemists clues to manufacturing similar potent compounds for treating deadly diseases, including ovarian and other cancers. Andrea Stierle, Gary Strobel, and Donald Stierle (1995) discovered that an endophytic fungus, *Taxomyces andreanae,* inhabiting the yew tree synthesized taxol, and for this discovery they were awarded several patents. Synthesizing taxol requires numerous steps, and despite advances, it's still more economical to derive taxols from natural sources, such as the English yew *(Taxus baccata)* or North American ground hemlock *(Taxus canadensis)*.

FIGURE 50 The author squats beside a massive noble polypore *(Bridgeoporus nobilissimus)* growing on a stump in the Oregon Cascades. This mushroom, 53 inches in diameter and estimated to weigh more than 300 pounds, is perhaps the largest of its kind in North America.

FIGURE 51 An unusual mushroom, the noble polypore *(Bridgeoporus nobilissimus)* hosts other plants and fungi. This young specimen, weighing several hundred pounds, is covered with a luxuriant coat of moss.

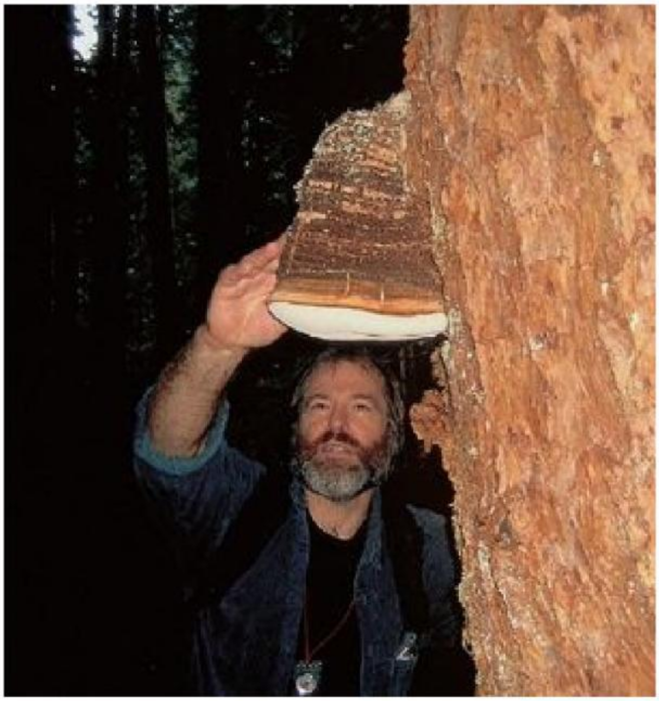


FIGURE 54 Agarikon *(Fomitopsis officinalis)* a mushroom found in the old-growth forests of the Olympic Peninsula in the Pacific Northwest. Extracts from the culture I generated from cloning this conk produced compounds very active against two pox viruses when screened through the Biodefense BioShield program administered jointly through the U.S. National Institutes of Health (NIH) and the U.S. Army Medical Research Institute of Infectious Diseases (USAMRIID), a coordinated effort to combat potentially weaponized viruses. The genome of this species may give rise to novel antivirals and hence should be protected. Although the mushrooms were not active when boiled in water, specially prepared extracts from living mycelium showed potent activity against vaccinia pox and cowpox viruses.

A moldy cantaloupe, sent to an army research lab in 1941 by a housewife from Peoria, Illinois, gave rise to the strains of *Penicillium chrysogenum* that allowed for the commercial production of penicillin. This discovery saved millions of lives and billions of dollars, and helped us win WWII, since the Germans and Japanese did not have effective antibiotics. In contrast, agarikon *(Fomitopsis officinalis)* does not enjoy the luxury of this *Penicillium* mold's widespread cosmopolitan habits. Agarikon is restricted to an endangered habitat in rapid decline. Less than 5 percent of our northwestern old-growth forests survive today, in the aftermath of 150 years of logging. No doubt strains of agarikon living in these ancestral forests will prove to be more potent against pox viruses than what I have recently discovered. The old-growth mycoforests suddenly become more valuable not as a timber source but as a remedy against natural or weaponized diseases.

FIGURE 55 Another agarikon *(Fomitopsis officinalis)* collected in the central Cascades of Washington State. A specially prepared extract from this strain was very active against pox viruses. Strains appear to differ in their antipox activities.

What other mycomedical remedies await discovery in our ancient forests? I have little doubt that many other mushrooms will provide us with antiviral or anticancer drugs—provided our forests survive the effects of short-sighted political and corporate agendas. With the increasing threat of bioterrorism—especially from viruses like smallpox and bacteria like anthrax—protecting our fungal genetic diversity, especially in old-growth forests, is a matter of national defense. Most importantly, the survival of future generations may be at stake. (For a further discussion, see Mushrooms That Prevent and Heal Viral Disease here.)

Wild Medicinal Mushrooms of North America

Preliminary studies on mushrooms have revealed novel antibiotics, anticancer chemotheuropeutic agents, immunomodulators, and a slew of active constituents. The following charts list a few of them. For more information on the medicinal properties of mushrooms, please consult *MycoMedicinals: An Informational Treatise on Medicinal Mushrooms,* by Paul Stamets and C. Dusty Yao (2002), and *Medicinal Mushrooms,* by Christopher Hobbs (2003).

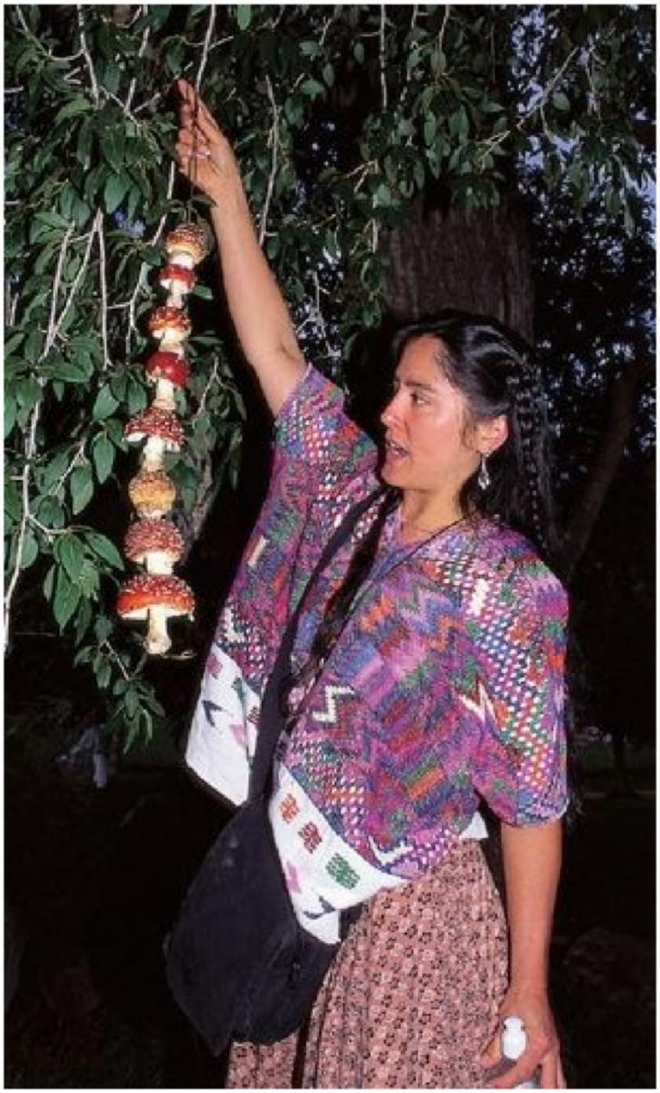


FIGURE 56 Dusty Yao with necklace of soma *(Amanita muscaria)*.

Cross-Index of Mushrooms and Targeted Therapeutic Effects

Each mushroom species has a unique chemistry and molecular architecture. Many species are now known to have medicinal properties useful for improving human health. Here is a short list of some of those properties.

	Antibacterial	Anti-Candida	Anti-inflammatory	Antioxidant	Antitumor	Antiviral	Blood Pressure	Blood Sugar Moderator	Cardiovascular	Cholesterol Reducer	Immune Enhancer	Kidney Tonic	Liver Tonic	Lungs/Respiratory	Nerve Tonic	Sexual Potentiator	Stress Reducer
Agaricus brasiliensis (Himematsutake)					X	X		X		X	X						
Cordyceps sinensis (Cordyceps)	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X
Flammulina velutipes (Enokitake)					X						X						
Fomes fomentarius (Ice Man Polypore)	X					X											
Ganoderma applanatum (Artist Conk)	X		X		X									X			
Ganoderma lucidum (Reishi/Ling Chi)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X
Ganoderma oregonense (Oregon Polypore)	X				X				X		X			X	X		
Grifola frondosa (Maitake/Hen of the Woods)	X	X			X	X	X	X			X			X	X		X
Hericium erinaceus (Yamabushitake/Lion's Mane)	X	X	X		X										X		
Inonotus obliquus (Chaga)	X		X		X	X		X			X		X				
Lentinula edodes (Shiitake)	X	X			X	X	X	X		X	X	X	X			X	X
Phellinus linteus (Mesima)	X		X			X											
Piptoporus betulinus (Birch Polypore)	X		X			X					X						
Pleurotus ostreatus (Hiratake/Pearl Oyster)	X					X	X		X	X					X		
Polyporus sulphureus (Chicken of the Woods)	X																
Polyporus umbellatus (Zhu Ling)	X		X		X	X					X		X	X			
Schizophyllum commune (Suehirotake/Split-Gill)		X			X	X											
Trametes versicolor (Yun Zhi/Turkey Tail)	X			X	X	X					X	X	X				

Mushrooms with Activity Against Specific Cancers

For the past 30 years, researchers have studied mushrooms' effectiveness against cancer. Some of their findings are summarized below.

	Breast	Cervical / Uterine	Colorectal	Gastric / Stomach	Leukemia	Liver	Lung	Lymphoma	Melanoma	Ovarian	Pancreatic	Prostate	Sarcoma
Agaricus brasiliensis		X	X										X
*Clitocybe illudens** *(Omphalotus olearius)*	X						X			X	X		X
Cordyceps sinensis					X		X	X					
Flammulina velutipes								X				X	
Ganoderma lucidum					X	X	X					X	X
Grifola frondosa	X		X		X	X	X					X	
Hericium erinaceus				X		X							
Inonotus obliquus		X											
Lentinula edodes	X					X			X			X	
Phellinus linteus		X	X	X		X			X				
Piptoporus betulinus									X				
Pleurotus ostreatus													X
Polyporus umbellatus					X	X	X						
Schizophyllum commune		X		X									
Trametes versicolor	X	X		X	X	X	X					X	

* Poisonous species, not edible.

Antimicrobial Properties of Mushrooms

Despite recent medical advances, microbes, especially viruses, continue to kill millions of people, stimulating the search for new antimicrobial agents that are safe for human use. Mushrooms, which naturally produce a surprising array of antibiotics, may provide the answer. Mushrooms share a deeper evolutionary history with animals than with any other kingdom, so humans and mushrooms share risks of infection from some of the same microbes, for instance the bacteria *Staphylococcus aureus* and *Pseudomonas fluorescens.* Although mycelium has just a single cell wall protecting it from

Mushrooms That Prevent and Heal Viral Disease

That medicinal mushrooms have been ingested for hundreds and, in some cases, thousands of years, strongly suggests most are not toxic, and research supports them as likely candidates in our search for natural antiviral agents. Suzuki and others (1990) discovered an anti-viral water-soluble lignin in an extract of the mycelium of shiitake mushrooms *(Lentinula edodes)* isolated from cultures grown on rice bran and sugarcane bagasse. Another mushroom recognized for its antiviral activity is *Fomes fomentarius,* a hoof-shaped wood conk growing on trees, which inhibited the tobacco mosaic virus in a study (M. Aoki et al. 1993). Collins and Ng (1997) identified a polysaccharopeptide from turkey tail *(Trametes versicolor)* mushrooms inhibiting HIV type 1 infection, while Sarkar and others (1993) identified an antiviral substance extracted from shiitake *(Lentinula edodes)* mushrooms.

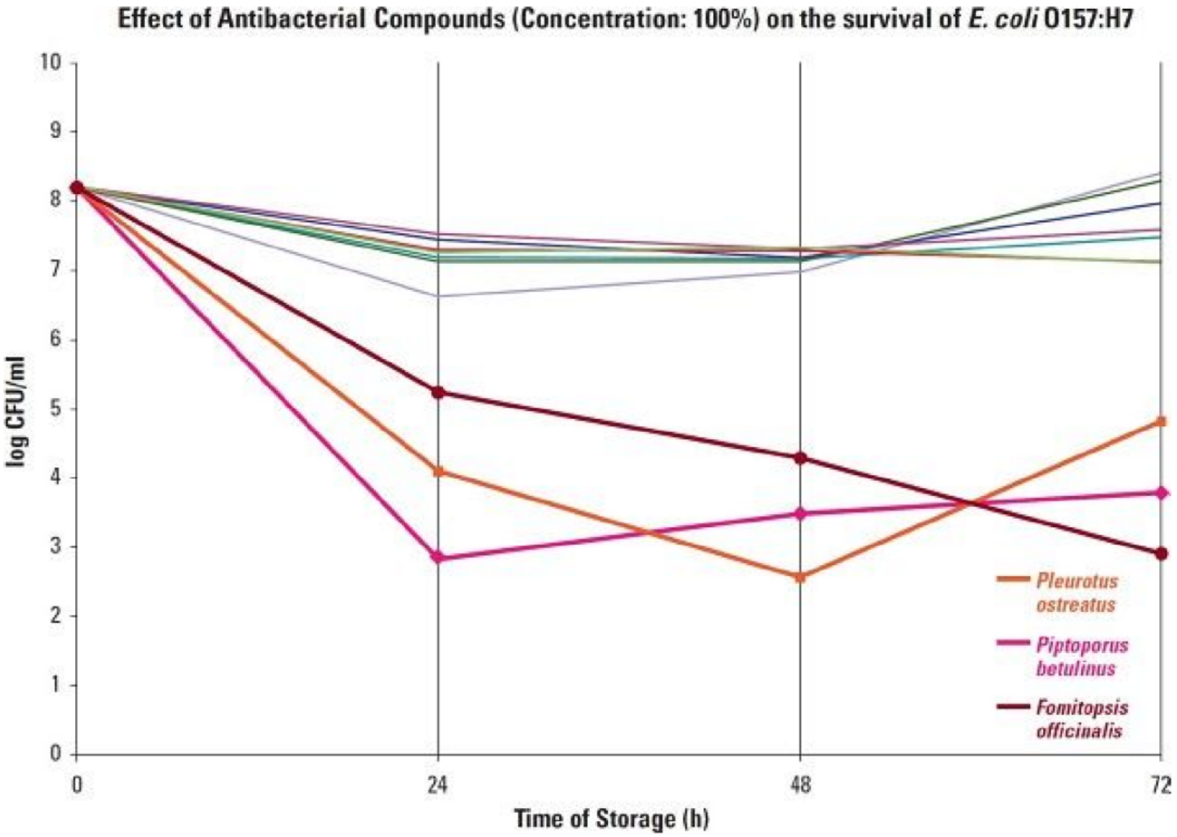


FIGURE G This chart and figure H show the antimicrobial activity of cold-water extracts created from washing exudates secreted from living mycelia from ten mushroom species. Vertical scale is log 10. With both *Escherichia coli* and *Staphylococcus aureus*, the number of colonies forming units (CFUs) per gram of water plummeted from more than 100,000,000 to the 1,000–10,000 CFU range in 48–72 hours, equivalent to more than 99.99% inhibition. The most antibacterially active species were an oyster mushroom (*Pleurotus ostreatus*), the birch polypore (*Piptoporus betulinus*), and agarikon (*Fomitopsis officinalis*).

More recently, derivatives of the gypsy mushroom *(Cortinarius caperatus)* were discovered by Piraino and Brandt (1999) to inhibit the replication and spread of varicella zoster (the shingles virus), influenza A, and the respiratory syncytial virus (RSV) that causes colds. Eo and others (1999, 2000) found antiviral activity in the methanol-soluble fractions of reishi mushrooms *(Ganoderma lucidum)* that selectively inhibited herpes simplex 1 and 2, and the vesicular stomatitus virus (VSV). Wang and Ng (2000) isolated a novel ubiquitin-like glycoprotein from oyster mushrooms *(Pleurotus ostreatus)* that inhibited HIV. Mushroom derivatives also activate natural immune response in mammalian cells, in effect boosting an organism's resistance to microbial infection (Stamets 2003b). Summaries on the antiviral properties of mushrooms were published by Brandt and Piraino (2000) and Stamets (2001c), and reports on antimicrobial properties were published by Suay and others (2000) and Stamets (2002b).