Oaks

SPRING/SUMMER 2024 CALIFORNIA OAKS

Oaks underground: beneficial interconnections between oaks and soil fungi

by Angela Moskow, California Oaks

In October 2023, the *Washington Post* reported on an expedition in Kazakhstan to collect imperiled soil fungi. The Society for the Protection of Underground Networks (www.spun.earth/), a research organization dedicated to mapping and protecting underground fungi, collected from ecosystems in the Kazakh Steppe. This area, which is believed to sequester a great deal of carbon and host a diversity of soil fungi, is threatened by desertification.[1]

"Across much of the planet, thin, wildly interconnected filamentous—structures known as 'mycelium'—hold the earth together," the *Washington Post* reported.[2]

The Spun effort is part of the scientific community's burgeoning research to better understand the vital roles soil fungi play in supporting the Earth's ecosystems. Scientific study of mycorrhizae, which are mutually beneficial interactions between plants and fungi, began in the late 19th century.[3] New technologies have recently provided a clearer window into their diversity and importance in sustaining biodiversity, sequestering carbon, and tapping into water sources.

Closer to home, research has illuminated how California's native oak ecosystems are supported by a large diversity of fungi that have independently evolved multiple times, with many different structural and physiological characteristics. Mycorrhizae are a critical element of terrestrial ecosystems. Their basic structure, which differentiates them from other symbioses (mutually advantageous interactions between proximate organisms), can physically connect two plants in the same space and time. This connection is achieved by mycorrhizal hyphae—branching filaments that form the mycelium of a fungus—extending from one plant to another and effectively linking plants belowground (see photo on page 8).[4] A "mycorrhizal network" is the belowground system of interconnected hyphae of fungi and the roots of plants of the same or different species.[5]

Research has explored the vital interrelationship of mycorrhizal fungi and California's native oak communities, including carbon sequestration and mycorrhizal connections to water supplies, above- and belowground biodiversity, and Indigenous community practices in tending beneficial fungi in many areas of the state. This newsletter provides an overview of these relationships, including an article by Michael F. Allen, PhD, a distinguished emeritus professor whose research and writing over the past 50 years has made important contributions to our understanding of oaks underground (page 4).

Frank K. Lake, PhD, Research Ecologist/Tribal Liaison, U.S. Forest Service Pacific Southwest Research Station, holds hedgehog mushrooms (*Hydnum repandum*), which he gathers in the mixed evergreen forest of the western Klamath mountains where black oak, tanoak, and (less frequently) canyon live oak grow.

Imperiled biodiversity

California's native oak ecosystems began before the Quaternary ice ages, the most recent 2.588 million years of the Earth's history.[6] They coevolved with mycorrhizae, which play vital roles in sustaining oak communities and which are, in turn, supported by oaks. Large old growth oak stands are estimated to support up to 500 taxa of ectomycorrhizal fungi (those forming on deep roots).[7]

These interrelationships sustain much of the state's imperiled biodiversity. Oak ecosystems provide food, movement corridors, and vital habitat for California's native species, including 2,000 plants, 5,000 insects and arachnids, 80 amphibians and reptiles, 160 birds, and 80 mammals.[8] The Spring-Summer 2021 issue of *Oaks* reported on 34 federally and/or state listed (endangered or threatened), candidate, and/or state fully-protected vertebrates dependent upon oak (*Quercus*) and tanoak (*Notholithocarpus densiflorus*) habitat; as well as 134 plants and 26 listed and/or candidate invertebrates associated with *Quercus*.[9] [10]

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Inside

Protecting vital soil fungi

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The National Nature Monument Luční in the Czech Republic, a reserve for protection of diversity of mycorrhizal fungi, especially those associated with oaks, includes fungi such as *Boletus rhodopurpureus*, a rare mycorrhizal fungus, pictured above. (© Allen, M. *Mycorrhizal Dynamics in Ecological Systems*. Cambridge University Press. 2022). Reproduced with permission of The Licensor through PLSclear.

Soil is home to over half of the planet's species, including 90% of fungi, 85% of plants, and more than 50% of bacteria, according to estimates in a recent journal article.[1] Mycorrhizal fungi, mutually beneficial interactions between plants and fungi, are a vital part of ecosystems, yet these and other fungi are largely unknown. An estimated 92% to 95% of fungi have yet to be scientifically described.[2] Additionally, fungal protections are extremely limited.

A few taxa, such as *Boletus rhodopurpureus*, a species existing only in older oak and beech stands primarily in Eastern Europe, are well enough described to have legal protection. They are also afforded protection by preserves such as the National Nature Monument Luční in the Czech Republic, where a rare mushroom, the fruiting structure of the fungus, is shown in the photo above. The Global Fungal Red List Initiative describes the threats to this species: "Being confined mainly to older *Quercus* stands, it is highly endangered by intense forestry practices such as clear cutting, which do not enable the persistence of the species' mycelia."[3]

Fungal protections are limited in the United States. The only federal Endangered Species Act protections that affect fungi are for two lichen species (*Gymnoderma lineare* and *Cladonia perforata*).[4] Likewise, Record of Decision amendments to the Northwest Forest Plan for federal land in Washington, Oregon, and Northern California include protections for fungal species associated with habitat for Northern Spotted Owl (*Strix occidentalis caurina*), a tanoak-dependent subspecies that is state and federally listed as threatened. These fungi are presumed rare, associated with late-successional old-growth forests, and in need of protection not afforded by the plan's major elements.[5 6 7]

As readers of *Oaks* are well aware, California's native oak ecosystems, the state's primary old growth resource, are inadequately protected. This issue's overview of the diverse and complex underground world of oaks provides yet another window into what is at stake as the state fails to protect the imperiled biodiversity of oak ecosystems.

Sincerely,

Janet

Janet S. Cobb, Executive Officer
California Wildlife Foundation/California Oaks

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[1] Anthony MA, et al. 2023. Enumerating soil biodiversity. *Proceedings of the National Academy of Sciences* 120(33) DOI: 10.1073/pnas.2304663120

[2] Antonelli A, et al., *State of the World's Plants and Fungi 2023* (5th ed.) Royal Botanic Gardens, Kew.

[3] See: Global Red Fungal Red List Initiative, *Boletus rhodopurpureus* Smotl. https://redlist.info/iucn/species_view/102959/

[4] Allen JL, et al. 2015. Fungal conservation in the USA., *Endangered Species Research*. 28: 33-42.

[5] Casellano MA, et al. 1999. *Handbook to Strategy 1 Fungal Taxa from the Northwest Forest Plan*. Portland, OR: USDA Forest Service, Pacific Northwest Research Station, General Technical Report PNW-GTR-46.

[6] Casellano, MA, et al. 2003. *Handbook to Additional Fungal Species of Special Concern in the Northwest Forest Plan*: USDA Forest Service, Pacific Northwest Research Station, General Technical Report PNW-GTR-46.

[7] Molina R. 2008. Protecting rare, little known, old-growth forest-associated fungi in the Pacific Northwest USA: A case study in fungal conservation. *Mycological Research* 112 (Pt 6):613-38.

California Oaks Coalition

California Oaks Coalition brings together international, national, Tribal, state, regional, and local organizations to conserve and perpetuate the state's primary old-growth resource. Members of California Oaks Coalition are united by the vital role of oaks in sequestering carbon, maintaining healthy watersheds, providing habitat, and sustaining cultural values.

- Amah Mutsun Land Trust
- American River Conservancy
- American River Watershed Institute
- AquAlliance
- Banning Ranch Conservancy
- Butte Environmental Council
- California Institute for Biodiversity (CIB)
- California Invasive Plant Council (Cal-IPC)
- California Native Plant Society (CNPS), including Dorothy King Young, El Dorado, Sanhedrin, and Yerba Buena chapters and the San Diego Restoration Committee
- California Rangeland Trust
- California State University Chico Ecological Reserves
- California Water Impact Network (C-WIN)
- California Wilderness Coalition (CalWild)
- Californians for Western Wilderness (CalUWild)
- Canopy
- Carrizo Plain Conservancy
- Center for Biological Diversity
- Central Coast Heritage Tree Foundation
- Chimineas Ranch Foundation
- Clover Valley Foundation
- Conejo Oak Tree Advocates
- Confluence West
- Dumbarton Oaks Park Conservancy
- Earth Discovery Institute
- El Cerrito Trail Trekkers
- Endangered Habitats Conservancy
- Endangered Habitats League
- Environmental Defense Center
- Environmental Protection Information Center (EPIC)
- Environmental Water Caucus
- Foothill Conservancy
- Forests Forever
- Friends of Harbors, Beaches and Parks
- Friends of Olompali
- Friends of the Richmond Hills
- Friends of Spenceville
- Global Conservation Consortium for Oak (GCCO)
- Hills For Everyone
- Laguna de Santa Rosa Foundation
- LandPaths
- Loma Prieta Resource Conservation District
- Lomakatsi Restoration Project
- Los Padres ForestWatch

Lower Kings River Association
Mountains Recreation and Conservation Authority
Northern California Regional Land Trust
Ojai Trees
Placer Land Trust
Planning and Conservation League
Point Blue Conservation Science
Redbud Audubon Society–Lake County
Redlands Conservancy
Regrounding
ReLeaf Petaluma
Resource Conservation District of Santa Monica Mountains
River Partners
River Ridge Institute
Rural Communities United
Sacramento Tree Foundation
Sacramento Valley Conservancy
Santa Barbara Botanic Garden
Santa Clarita Organization for Planning and the Environment (SCOPE)
Save Lafayette Trees
Save Napa Valley
Sequoia Riverlands Trust
Shasta Environmental Alliance
Sierra Club Northern California Forest Committee–Oak Woodland Subcommittee
Sierra Club Placer Group
Sierra Foothill Conservancy
Smith River Alliance
Stewards of the Arroyo Seco
Tejon Ranch Conservancy
Tending the Ancient Shoreline Hill
Tuleyome
Tuolumne River Trust
Universidade de Trás-os-Montes e Alto Douro, Department of Forest and Landscape Architecture (Vila Real, Portugal)
University of California, Los Angeles, Mildred E. Mathias Botanical Garden
Ventura Land Trust
Woodland Tree Foundation

California Oaks provides the following support for coalition members:

1) Research and advocacy updates.
2) Collaboration in protecting oaks.
3) Information to educate and engage the public.
4) Tools for participating in planning processes and educating opinion leaders.
5) Materials to inform local, regional, and state governmental agencies of the opportunities for and benefits of protecting oak woodlands.
6) Sharing stories from coalition efforts to keep oaks standing.

For more information, please contact Oak Project Director Angela Moskow, amoskow@californiaoaks.org.

RESOURCES

Beauty, bounty, and biodiversity: The story of California Indians' relationship with edible native geophytes, by M. K. Anderson, et al., in December 2016 issue of *Fremontia* (Vol. 44, No. 3), www.fs.usda.gov/psw/publications/lake/psw_2017_lake002_anderson.pdf

Global Fungal Red List Initiative: redlist.info/en/iucn/welcome

Global Fungi (globalfungi.com/), an initiative of the Institute of Microbiology of the Czech Academy of Sciences in Prague, which provides worldwide fungal sequencing data and information on the composition of soil fungal communities in terrestrial environments.

Global Soil Mycobiome Consortium (gsmc-fungi.github.io), led by researchers at the Mycology and Microbiology Center of University of Tartu (Estonia), was initiated in 2015 to provide mapping of fungal distribution and education about the role of fungi in ecosystem services.

Inoculant-Supported Restoration: A Technical Report, by K. Dybala, et al., published by Point Blue Conservation Science: pointblue.org/wp-content/uploads/2022/01/ISR-Technical-Report_FINAL.pdf

Mushroom Observer (mushroomobserver.org) is a platform to identify and record mushroom observations and expand the community for the scientific exploration of mushrooms (mycology).

Society for the Protection of Underground Networks is a scientific research organization dedicated to mapping and protecting underground fungi: spun.earth

State of the World's Plants and Fungi 2023—Tackling the Nature Emergency: Evidence, gaps, and priorities (5th ed.), by A. Antonelli, et al, published by Royal Botanic Gardens, Kew: kew.org/science/state-of-the-worlds-plants-and-fungi

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Summer truffle (*Tuber aestivum*)

Fungal inoculum

"Fungal inoculum is a blend of viable spores that take up residence in and around a plant's roots. It is being used to revitalize areas where mycorrhizal communities have diminished due to land disturbances. In exchange for carbon, fungi provide water and nutrients to plants and support their growth and long-term health. These age-old underground networks are responsible for most plants we see aboveground. Their adaptations help landscapes tolerate drought and extreme heat. Ecosystem restoration begins and continually cycles via the habitat of the soil and the microbes within it." *—Lukas Martinelli, soil biogeochemist, Lawrence Berkeley National Laboratory*

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Joe Ree, PhD, of the San Diego Wildlife Alliance holds a bolete mushroom (genus *Xerocomellus*), the fruiting body of a mycorrhizal fungus closely associated with the imperiled coastal sage scrub oak (*Quercus dumosa*). Ree and colleague Ruby Iacuaniello collected mushrooms of this and other mycorrhizal species to cultivate them *in vitro*. Though the methodology is still in development, their goal is to inoculate lab-grown oaks with their natural mycorrhizal symbiotes before transferring them from agar to soil. The results will hopefully improve our ability to use tissue culture as a powerful tool for the conservation of imperiled oak species.

The Red List of US Oaks *designates 5 California oak species, including* Quercus dumosa, *as* Threatened *(either Critically Endangered, Endangered, or Vulnerable), utilizing International Union for Conservation of Nature criteria (see: mortonarb.org/app/uploads/2021/05/Red-List-of-Oaks-2017.pdf). No California native oak species are protected by the California or federal Endangered Species Act.*

Oak mycorrhizal soil carbon storage and hydrology

by Michael F. Allen, PhD, Professor Emeritus, Department of Microbiology and Plant Pathology, University of California, Riverside

Characterizing and understanding the biology of keystone organisms such as oaks and their mycorrhizal communities is of central importance to managing landscapes in the face of climate change. Native plant sequestration can play a critical role in mitigating impacts of elevated atmospheric carbon dioxide (CO_2) to ecosystems. Rising atmospheric CO_2 can drive increasing photosynthesis directly and also via increased water-use efficiency. But other factors, including higher temperatures, drought, and nutrient uptake, constrain carbon fixation.

Oaks are among the plants that may be well adapted to weathering projected change and sequestering carbon. Adaptations include thick bark and sclerophyllous leaves, which are able to withstand dryness and heat. Oaks grow in riparian zones but also across dry hillsides, stony deserts, and savannas. Two interactive strategies facilitate their ability to survive drought and sequester carbon: deep roots and mycorrhizae, which are mutually beneficial interactions between plants and fungi.[1 2 3] Oak roots have been measured as deep as 25 meters to access water, and mycorrhizal fungi track roots through the bedrock along rock fractures down at least 3 meters.[4 5] The interaction of these two strategies is key to their incredible adaptability, which plays a large role in carbon sequestration.

Oaks form surface as well as deep roots.[6] Fungi radiate out from the roots, accessing soil moisture and nutrients in forms and spatial locations that are inaccessible to the roots.[7] As they develop and respond to changing environmental conditions, oaks form two mycorrhizal types—arbuscular, on surface roots, and ectomycorrhizal on deep roots. They have an important ability to switch between these two types of mycorrhizae, likely affecting their carbon sequestration (an area in need of more research). Oaks in riparian zones preferentially form ectomycorrhizae and tap groundwater, while those on slopes also form arbuscular mycorrhizae, tapping water stored in rock pockets.[8]

Deep roots allow deciduous oaks to grow well into the dry season of Mediterranean climates, and evergreen oaks to photosynthesize through the dry season.[9] In a mixed oak—pine forest, deep roots, which reach to groundwater, obtain nutrients and sustain neighboring trees through hydraulic lift. During the day, water is pulled up through the vascular system and transpired into the air. But at night, water in dry surface soil moves back out roots and into surface mycorrhizal fungi.[10] Fungal hyphae—branching filaments that form the mycelium of a fungus—near the root are hydrophobic, retaining the water within the fungal walls. Water travels out the fungal hyphae into the surrounding soil, where the hyphal tips are hydrophilic. That water leaks into soil as small droplets, dissolving nitrogen and other nutrients. The next day, as light opens stomata (pores on leaves that control gas exchange) for photosynthesis, the water and dissolved nutrients are reabsorbed, facilitating more carbon fixation.[11] During 2008, a dry year, access to deep water by black oak extended the photosynthetic period for nearly 60 days, compared with sugar pine and its shallow roots.[12]

The amount of carbon sequestered by oaks and their mycorrhizal fungi is variable and site specific. In a mixed black oak-pine forest, up to 34% of the net primary production—the amount of biomass or carbon produced by primary producers per unit area and time—goes to mycorrhizal fungi.[13] Under coast live oak, carbon was found even 3 meters deep along earthquake fractures, derived from roots and mycorrhizal fungi, with hyphae extending into older granite matrix.[14]

Fine roots less than 1 millimeter lived 7 years in a mixed oak-pine forest, and 17 years for roots of 1 millimeter in diameter.[15] In a New Mexico stand of pine, juniper, and oak, mycorrhizal root tips lived from 2 to 6 years.[16] Based on direct root observations, intact fine roots decompose rapidly upon death, but there are many compounds added by the mycorrhizae in surface soils and deep into the strata above bedrock (regolith) that contribute to carbon sequestration. Plant tissue and fungi also contribute organic compounds. Further, mycorrhizal fungi mobilize and bind calcium, and some of the root plus fungal CO_2 respired creates calcium carbonates; deep in soils these can remain a long-lived (millennia) form of sequestered inorganic carbon-caliche (mineral deposits).[17]

Altogether, oaks make a patchy and dynamic component of California's ecosystems. While not precisely measured, oaks plus their mycorrhizal associates are responsible for a large fraction of carbon sequestration.

To understand dynamics of black oak interacting with surrounding forest, a thermal-protected sap-flow sensor measures transpiration; a belowground sensor network measures temperature, CO2, and soil moisture; and minirhizotrons take images of roots, fungal hyphae, and soil organisms, at the University of California James San Jacinto Mountains Reserve. Hidden nearby is a tower with an eddy flux system measuring CO2 and water flux between the atmosphere and the canopy, a camera placed on another tower to observe the soil surface, and an eddy flux system to measure flux between the soil surface and the canopy.

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1 Baldocchi DS, et al, 2021. On the inter- and intra-annual variability of ecosystem evapotranspiration and water use efficiency of an oak savanna and annual grassland subjected to booms and busts in rainfall. *Global Change Biology* 27:359-375.

2 Allen MF, 2015. How oaks respond to water limitation. In: Standiford RB, et al. (tech. coords). *Proceedings of the seventh California oak symposium: Managing oak woodlands in a dynamic world*. Gen. Tech. Rep. Berkeley, CA: USDA, Forest Service, Pacific Southwest Research Station: PSW-GTR-251. 13-22.

3 Allen MF. *Mycorrhizal Dynamics in Ecological Systems*. Cambridge University Press. UK, 2022.

4 Jackson RB, et al. 1999. Ecosystem rooting depth determined with caves and DNA. *Proceedings of the National Academy of Sciences* 96:11387-11392.

5 Bornyasz MA, et al. 2005. Ectomycorrhizae in a soil-weathered granitic bedrock regolith: Linking matrix resources to plants. *Geoderma* 126:141-160.

6 See *Supra* note 2. 14.

7 See *Supra* note 2. 15.

8 Querejeta JI, et al. 2009. Topographic position modulates the mycorrhizal response of oak trees to interannual rainfall variability. *Ecology* 90:649-662.

9 Kitajima K, et al. 2013. Contribution of hydraulically lifted deep moisture to the water budget in a Southern California mixed forest. *Journal of Geophysical Research-Biogeosciences* 118:1561-1572.

10 Querejeta JI, et al. 2003. Direct nocturnal water transfer from oaks to their mycorrhizal symbionts during severe soil drying. *Oecologia* 134:55-64.

11 Egerton-Warburton LM, et al. 2008. Efflux of hydraulically lifted water from mycorrhizal fungal hyphae during imposed drought. *Plant Signaling & Behavior* 3:68-71.

12 See *Supra* note 9.

13 Allen MF, et al. 2014. Net primary production of ectomycorrhizas in a California forest. *Fungal Ecology* 10:81-90.

14 See *Supra* note 5.

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[15] Vargas R, et al. 2008. Dynamics of fine root, fungal rhizomorphs, and soil respiration in a mixed temperate forest: Integrating sensors and observations. *Vadose Zone Journal* 7:1055-1064.

[16] Treseder KK, et al. 2004. Species-specific measurements of ectomycorrhizal turnover under N-fertilization: Combining isotopic and genetic approaches. *Oecologia* 138:419-425.

[17] Allen MF, et al. 1996. Differential production of oxalate by mycorrhizal fungi in arid ecosystems. *Biology and Fertility of Soils* 22:287-292.

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Transport of water and nutrients from soil to root cells via hyphae is the primary mycorrhizal function that supports oak ecosystems. There are, however, many other facets to this story. For example, the relationship between dependent species and oaks is, in some cases, one in which fungi play important above as well as belowground roles that directly and indirectly support these species. The federally and state-threatened Northern Spotted Owl (*Strix occidentalis caurina*), a tanoak-dependent subspecies, relies on northern flying squirrels and red tree voles as primary sources of prey. Ectomycorrhizal truffle fungi, fruiting structures commonly found in old growth forests, are important food sources for both of these mammals.[11] These animals, in turn, help to distribute fungal spores (such as via fecal pellets), perpetuating the ecosytem.[12]

Similarly, the California Spotted Owl (*Strix occidentalis occidentalis*), an oak-dependent subspecies and candidate for federal Endangered Species Act listing, preys upon the San Bernardino flying squirrel, a subspecies of northern flying squirrel. (Both the owl and squirrel are listed as taxa of concern in the Western Riverside County Multiple Species Habitat Conservation Plan.) A large portion of the squirrel's diet is comprised of truffle fungi. These fungi, as well as mushroom-producing fungi that are food sources for other small mammals that the owls consume, are sensitive to drought and nitrogen deposition (a pollutant produced by fossil fuel consumption and food production), further imperiling the squirrels and owls.[13]

Disturbances can also alter mycorrhizal communities and the plant communities they support. For example, the Southern California Coastal Range has a Mediterranean-type climate with winter precipitation, where water in soil above the bedrock is available only from April until early June. Coast live oaks actively photosynthesize all year, with virtually all summer moisture derived from the deep bedrock delivered by roots supported by ectomycorrhizae, which also extend moisture to nearby seedlings.[14] However, the invasion of many of California's coast live oak woodlands by non-native grasses and forbs may inhibit the formation of ectomycorrhizal fungi.[15]

Indigenous tending of fungal ecosystems

While anthropogenic disturbances to mycorrhizal communities are threating oak ecosystems, the story of human interaction with fungi

LaVerne Glaze, Karuk/Yurok, with American matsutake mushrooms (*Tricholoma magnivelare*). This image originally appeared in, "California Indian ethnomycology and associated forest management" (*Journal of Ethnobiology*, 2013) and is the property of the U.S. Forest Service and Karuk Tribe.

also includes examples of beneficial interactions. In their research, M. Kat Anderson, PhD, and Frank K. Lake, PhD, estimate that Tribes gathered mushrooms in an area greater than two-thirds of California at the time of European contact, with fungi serving as important sources of food, medicine, tinder, and dye.[16]

Their 2013 *Journal of Ethnobiology* article includes species harvested, uses, harvest strategies, and habitat management practices. A table summarizes uses of fungi (including those that grow in soil and those on wood) by California Tribal groups, which includes the Tribe, the Tribal or common name, scientific name or possible taxon, associated plants or plant communities, uses, and references. Many of the mushrooms, truffles, and other fungi described are associated with oak communities.[17]

Native consultants identified mushrooms in the forest, with collection followed by DNA analysis of some of the mushrooms. The authors also present two case studies, conducted in lower montane mixed conifer forests of the central and southern Sierra Nevada and mixed evergreen forests of Northern California, which provide ethnographic evidence that Tribes actively managed mushrooms and habitats in these two forest types. "Indigenous knowledge of mushroom gathering was an intricate system that took into account weather patterns, elevation, environmental site criteria, habitats, substrates, soil types, plant associations, wildlife and ecological relationships," Anderson and Lake wrote.[18] "Native Americans were an essential part of the ecology of oak woodlands and forests."[19]

Oral interviews identified the beneficial effects of burning, which included improved growth and diversity of mushrooms, fewer plant diseases, opened-up underbrush, reduced leaf litter that could block mushroom emergence, reduction of risk of crown fires, and the creation of better habitats for useful plants and animals. Further, the authors hypothesize that Native American management practices promoted the growth of larger, healthier trees, which also fostered mycorrhizal communities. They describe spore dispersal activities, such as scattering rotten caps of American matsutake mushrooms downhill to "lengthen the fruiting line."[20]

Today's overgrown forests with closed canopies prevent water from penetrating the soil to be taken up by mycorrhizae to provide vital moisture to oaks and other trees. Overly thick layers of duff and litter also prevent the emergence of fruiting bodies of mushrooms to maintain genetic diversity and provide food for wildlife and humans.[21]

Finally, the article suggests avenues of research for reintroducing Indigenous fungi harvesting and management practices within an adaptive management framework—one that honors place-based forms of knowledge and combines ecological field experimentation and modeling.[22]

Supporting fungi and ecosystems

Originally this newsletter was envisioned to include a comprehensive list of oak-associated mycorrhizae, but molecular investigations are showing that many European names used for North American taxa that look similar are in fact quite different.[23] Further, a great diversity of fungi exist within taxa. In *Mycorrhizal Dynamics in Ecological Systems*, Michael F. Allen notes: "In every sequence analysis I have undertaken, no individual taxon that I sequenced matched exactly that of the type specimen or other

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Shifting the paradigm in how climate action is envisioned, led, and implemented

Participants of a Stewardship Pathways training event held on Kumeyaay land in 2023 focused on technical skills in plant propagation and enhancing soil fertility.

by Diane Terry and Amber Pairis, PhD, Climate Science Alliance

On the southern slopes of Palomar Mountain in northern San Diego County, prescribed fire and cultural burn activities led by the La Jolla Band of Luiseño Indians are supporting soil health and native plant biodiversity, while advancing workforce development and fire certification for Tribal participants.[1] On another part of the mountain, nature trails created by the Pauma Band of Luiseño Indians are being established to connect Tribal community members to spaces where forest health and fire resilience improvements have been implemented by the Pauma Mountain Crew for years. Along the Orange County coastline, rematriation and restoration of a 6-acre village site by the Acjachemen Tongva Land Conservancy aims to provide access for community members to reclaim stewardship of this space. Across desert landscapes, intergenerational environmental and cultural education are being provided within nearly 3,000 acres of land stewarded by the Native American Landscape Conservancy.

These four projects are a small snapshot of activities under the umbrella of the Collaborative of Native Nations for Climate Transformation and Stewardship (CNNCTS, www.cnncts.org), which consists of over 20 Indigenous-led land stewardship projects being coordinated in tandem across Southern California. The weaving together of multiple projects under one umbrella is an intentional effort to shift the paradigm in how climate action is envisioned, led, and implemented.

CNNCTS (pronounced "connects") represents the strategic integration of collaborative efforts that have been in practice on lands and in communities for years. San Diego State University and the Climate Science Alliance (Climate ScienceAlliance.org), a community-led organization fiscally sponsored by the California Wildlife Foundation, co-lead CNNCTS with the guidance of the Alliance's Tribal Working Group (climatesciencealliance.org/tribal-working-group) and involvement of the CNNCTS network of partners. The Tribal Working Group, a network of over 20 Tribal governments and organizations in Southern California, focuses on community priorities and holistic stewardship approaches to collaboratively safeguard the lands and cultures of Southern California Tribes while honoring Tribal sovereignty. Over the past 7 years, the group has focused on advancing the integration of academic and traditional knowledge systems, identifying regionally specific adaptation strategies that enhance ecological, cultural, and community resilience to climate change—resulting in the creation of CNNCTS, which officially launched in August 2023.

CNNCTS is composed of a close-knit network of four Tribal governments (La Jolla Band of Luiseño Indians, Pala Band of Mission Indians, Pauma Band of Luiseño Indians, and Viejas Band of Kumeyaay Indians), four universities (California State University, Long Beach; San Diego State University; University of California, Riverside, and Santa Barbara), and seven Tribal-serving nonprofit organizations (Acjachemen Tongva Land Conservancy, Climate Science Alliance, Inter Tribal Long Term Recovery Foundation, Native American Land Conservancy, Native Coast Action Network, Sacred Places Institute for Indigenous Peoples, and Tipey Joa Native Warriors). The addition of partnerships with three federal agencies (National Park Service, U.S. Fish and Wildlife Service, and U.S. Forest Service), advances co-stewardship opportunities on public lands.

Working collaboratively, the network brings together five focus areas—each created with capacity-building in mind:

1. **Advance science-informed climate action** through research collaborations, knowledge co-production and exchange, and interdisciplinary curriculum development.
2. **Translate knowledge systems to practice** with a virtual community space—the *Tribal Hub of Knowledges*—and hands-on experiential learning at Stewardship Living Labs.
3. **Put adaptation into action** by supporting community-led stewardship demonstration projects and seeding pilot projects.
4. **Expand landscape stewardship pathways** to build capacity with economic and workforce development.
5. **Promote social entrepreneurship** to help build a climate-resilient economy through support for development of Indigenous-led businesses.

These focus areas support Tribal communities as well as students and researchers at CSU, UC, and community colleges to get involved in and learn from Indigenous-led coastal resilience, cultural and prescribed fire, climate-informed restoration, and land rematriation efforts.

The policies and land management practices of today were not envisioned with climate change in mind and have historically and intentionally excluded Indigenous peoples from lands they have stewarded since time immemorial. CNNCTS is our commitment to accelerating a new model for community-centered adaptation, where activities are led by our community partners in a space that upholds the equal valuation of knowledge systems and is embedded in a process that requires respect, reciprocity, and relationships.

Join the CNNCTS mailing list (cnncts.org/newsletter), and follow us on Instagram (@cnncts_ca). Questions? Get in touch at info@cnncts.org. To learn about and get involved in more projects like CNNCTS join the Climate Science Alliance mailing list (climatesciencealliance.org/newsletters), and follow along on Instagram (@ClimateScienceAlliance), Facebook, and LinkedIn.

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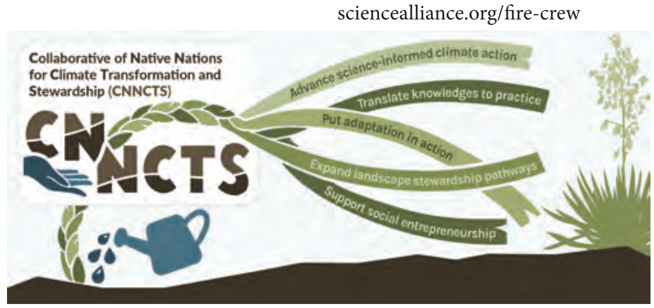
[1] Indigenous Fire, Forestry, and Fuels Crew: climatesciencealliance.org/fire-crew



The five focus areas of CNNCTS are represented by woven strands of a yucca plant.

Major habitat restoration project completed at Ravenswood

© Charles Anderson, Epicycle Media

Tidal action being reestablished at Ravenswood.

by Dave Halsing, Executive Project Manager, South Bay Salt Pond Restoration Project

On a crystal-clear day in December 2023, 150 people watched from a hilltop in Bedwell Bayfront Park as an excavator removed a portion of levee around a former salt pond to return tidal flows to 295 acres for the first time in over 100 years. The breach event marked the South Bay Salt Pond Restoration Project's (southbayrestoration.org) completion of Phase 2 construction at the Ravenswood Pond Complex in the Don Edwards San Francisco Bay National Wildlife Refuge, following years of important collaboration with California Wildlife Foundation.

The restored tidal flows are depositing sediment in the pond bottom and in coming months and years will reestablish tidal marsh vegetation, providing a large increase in tidal wetland habitat in this part of San Francisco Bay. This completed work marks a major milestone in the restoration project, the largest of its kind on the West Coast.

In 2003, 15,100 acres of former salt-production ponds were acquired from Cargill Salt for the South Bay Salt Pond Restoration Project (restoration project). About one-third of that area was added to the State of California's Eden Landing Ecological Reserve, and the rest became part of the U.S. Fish and Wildlife Service's Don Edwards wildlife refuge. In the 20 years since, the restoration project has worked with its partner agencies, local governments, and a wide range of stakeholders and other partners, including the California Wildlife Foundation, to pursue its three main goals of habitat restoration, flood protection, and public access and recreation.

The Phase 2 project at Ravenswood included a suite of habitat restoration types in four former salt ponds. The largest of those ponds is 295 acres, where the tidal flows were reintroduced on December 13, 2023. Tidal marshes are critical to the federal- and state-endangered salt marsh harvest mouse (*Reithrodontomys raviventris*) and Ridgway's Rail (*Rallus obsoletus obsoletus*), and are excellent habitats for native fish and many birds and mammals. They also buffer human communities from coastal flooding and are a good early step to adapt to rising sea levels. Work in the three other Ravenswood ponds (jointly about 330 acres), completed in 2023, enhance them for use by shorebirds, ducks, and other waterbirds that prefer pond habitat.

Completing this work necessitated the import and placement of almost 500,000 cubic yards of clean earthen fill to raise and improve internal berms to avoid unintentional coastal flooding and to build habitat transition zones, which benefit wildlife and protect against erosion. To meet the project's public access goals, trail development, benches, and interpretive signage will be completed in the spring of 2024.

Multi-objective projects like this one are complicated, and each phase takes about a decade to plan, design, permit, fundraise, and build. Major milestones are few and far between, which is why a celebratory event to mark an occasion such as the completion of Phase 2 at Ravenswood is so meaningful. The Ravenswood breach event acknowledged the moment, and also thanked the many entities and individuals who contributed to the decade of work, including funders, partners, neighbors, technical experts, elected officials, and other stakeholders.

Event participants watched from the hill in Menlo Park's Bedwell Bayfront Park as the last few feet of levee dirt were cleared from a narrow section, allowing waters from a king tide in San Francisco Bay to pour in through the breach and begin slowly spreading out across the pond bottom. Within hours, the formerly dry pond bottom—frequently described as a "moonscape"—was underwater. The pond now fills and drains with each tidal cycle and is on its way to becoming a healthy wetland.

California Wildlife Foundation plays a vital role as non-profit partner to the U.S. Fish and Wildlife Service in working with the "dirt brokers"—construction and/or trucking companies that provide clean fill material from nearby excavation projects at no cost to the restoration project. In the case of the Ravenswood Ponds, for example, the foundation collaborated with Pacific States Environmental to find, test, get approval for, and deliver all of the "clean dirt." Without material to make improvements in some pond levees, the project could not have safely breached levees in other places.

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Thanks to the generosity of Pacific States Environmental, in partnership with California Wildlife Foundation, millions of cubic yards of clean, tested soil have been delivered to this and other South Bay restoration sites, saving state and federal partners millions of dollars.

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deposited sequences for the fungus identified."[24]

The research underway to identify and better understand mycorrhizae has generated many publications, some of which focus on oak ecosystems, exploring topics beyond those discussed here, such as the role of mycorrhizae in plant interactions with pathogens.[25] Additionally, numerous popular books investigate fungi, such as *Finding the Mother Tree: Discovering the Wisdom of the Forest,* by Suzanne Simard; *Entangled Life: How Fungi Make our Worlds*, by Merlin Sheldrake; and *Let's Become Fungal!: Mycelium Teachings and the Arts*, by Yasmine Ostendorf-Rodríguez.

While wildlands are increasingly becoming islands within human-developed landscapes, emerging knowledge about mycorrhizae is building recognition of the need to better protect fungi and the ecosystems they support.[26] From Kazakhstan to California, there is a great deal of work in front of us if we are to sustain and perpetuate the Earth's vital ecosystems.

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1 Moens J. 2023. How a few bags of dirt could help make the planet more resilient to climate change. *Washington Post*, Oct. 8.

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6 Prof. David William Stahle, University of Arkansas, March 19, 2019, via email.

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8 Meadows R. 2007. Oaks: Research and outreach to prevent oak woodland loss. *California Agriculture* 61(1):7–10.

9 Humboldt marten (*Martes caurina* subsp. *humboldtensis*) was not in the original report.

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17 *Ibid.*

18 *Ibid.*

19 M. Kat Anderson, PhD, University of California, Davis, February 22, 2024, via email.

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21 See *Supra* note 19.

22 See *Supra* note 16.

23 Prof. Michael F. Allen, University of California, Riverside, Dec. 2, 2023, via e-mail

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25 Tarkka MT, et al. 2021. Ectomycorrhizal fungus supports endogenous rhythmic growth and corresponding resource allocation in oak during various below- and aboveground biotic interactions. *Nature Portfolio Scientific Reports* 11:23680.

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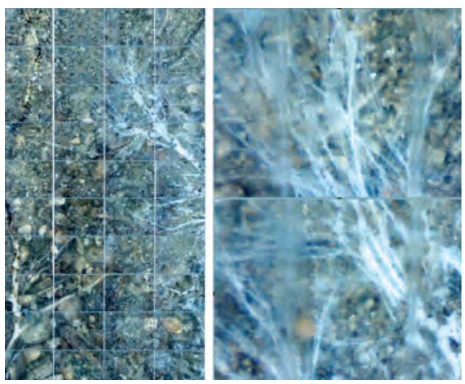

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Rhizomorphs and hyphae emanating from an oak root, imaged using an automated minirhizotron. This network emerged early in 2011 and lasted through the growing season, supported by hydraulic redistribution from deep soil moisture. This image was taken during the peak drought period in July 2011.[27 28] *Photo was originally published in Allen and Kitajima (footnote 27).*

How you can help:

- Donate to California Wildlife Foundation/California Oaks. A secure donation can be made from our website: californiaoaks.org.
- Spend time in an oak woodland or forest. Click on californiaoaks.org/resources for a partial listing of oak landscapes around the state that have public access.
- Please consider including oak conservation in your financial and estate planning efforts. Information can be found at: californiaoaks.org/donate.
- Be vigilant about threats to oak woodlands and oak-forested lands in your community and consult californiaoaks.org for guidance.
- Restore oaks to areas where they historically grew.
- Sign up for the *Oaks* e-newsletter at californiaoaks.org.
- Support local and statewide measures to protect natural resources.
- Hold decision-makers accountable for protecting green infrastructure.
- Learn about and support Indigenous stewardship of oak ecosystems.
- Learn about mycorrhizae.

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Latin names are used for species with designated state or federal conservation status. They are also used by some of the newsletter authors for oak species.

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