ORIGINAL ARTICLE

Witnessing history: comparison of a century of sedimentary and written records in a California protected area

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Abstract

Weuse a combination of proxy records from a high-resolution analysis of sediments from Searsville Lake and adjacent Upper Lake Marsh and historical records to document over one and a half centuries of vegetation and socio-ecological change—relating to logging, agricultural land use change, dam construction, chemical applications, recreation, and other drivers—on the San Francisco Peninsula. A relatively open vegetation with minimal oak (*Quercus*) and coast redwood (*Sequoia sempervirens*) in the late 1850s reflects widespread logging and grazing during the nineteenth century. Forest and woodland expansion occurred in the early twentieth century, with forests composed of coast redwood and oak, among other taxa, as both logging and grazing declined. Invasive species include those associated with pasturage (*Rumex*, *Plantago*), landscape disturbance (*Urtica*, Amaranthaceae), planting for wood production and wind barriers (*Eucalyptus*), and agriculture. Agricultural species, including wheat, rye, and corn, were more common in the early twentieth century than subsequently. Wetland and aquatic pollen and fungal spores document a complex hydrological history, often associated with fluctuating water levels, application of algaecides, raising of Searsville Dam, and construction of a levee. By pairing the paleoecological and historical records of both lakes, we have been able to reconstruct the previously undocumented impacts of socio-ecological influences on this drainage, all of which overprinted known climate changes. Recognizing the ecological manifestations of these impacts puts into perspective the extent to which people have interacted with and transformed the environment in the transition into the Anthropocene.

Keywords Anthropocene · Coprophilous fungi · Historical records · Logging · Pollen · San Francisco Peninsula

Introduction

Our ability to reconstruct the vegetation of California prior to, and during, European colonization has been enhanced by analysis of fossil pollen and plant macrofossils, extracted from wetlands and lakes (e.g., Anderson et al. 2013; 2015; Ejarque et al. 2015; Broadman et al. 2022). However, because the number of low-elevation wetland and lake sites in California has declined since 1850 CE, our opportunity to examine the history of landscape change through time has

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been severely curtailed, just as our need for understanding landscape change has substantially increased. The decline in wetlands is primarily due to widespread human activities across the region, including the conversion of natural landscapes to agricultural land, draining of wetlands for protection from pests and disease, drying of landscapes by over-extraction of groundwater, expanding population growth and municipal water use, and channelization for flood control, among other factors (Dennis et al. 1984). Regionally, southern California coastal vegetated wetlands have declined by ~75% (Stein et al. 2014) since ~1850 CE; wetlands in California's Central Valley have declined by over 90% (Garone 2011); and in adjacent Santa Clara County, south of San Francisco, ~88% of freshwater marshes have been lost to development (Grossinger et al. 2007). The building of water storage reservoirs during the late nineteenth and early twentieth centuries has partially offset this trend, though many reservoirs are reaching the end of their useful

life because of sedimentation (Minear and Kondolf 2009) or dam failure. These same sediments offer an opportunity to examine environmental change at high resolution over decades to more than a century, to better understand the recent role of human impacts.

Here, we use sediment cores from two hydrologically connected lacustrine sites to reconstruct the detailed history of vegetation and environmental change around Jasper Ridge Biological Preserve (JRBP; San Mateo County, CA, USA), as well as changes in characteristics of the lakes themselves. We analyze pollen and non-pollen palynomorph (NPP) assemblages taken from sediment cores extracted from Searsville Lake and Upper Lake Marsh (informally named). Because Searsville Lake has very high sedimentation rates—around 16 m of sediment have accumulated during its ~ 130-year lifespan—our high temporal resolution analysis of pollen and NPPs allows us to detect not only broad patterns of vegetation and wetland change since the construction of Searsville Dam, but also changes at a finer scale that can be compared against the known history of human activities and landscape modification over the past ~ 130 years.

Historical records can be extremely helpful in clarifying many aspects of environmental change through time, and the historical record from the nineteenth and twentieth centuries is rich (Supplemental 1). Searsville Lake and Upper Lake Marsh sediments are ideal for studying recent vegetation change not only because of their high resolution, but because historical records for the Jasper Ridge region go back to the Spanish Mission Period in the late eighteenth century, prior to the construction of the dam. Thus, we are able to pair paleoecological with historical data to provide an integrated picture of landscape change (sensu Ejarque et al. 2015; Reynolds et al. 2018; Broadman et al. 2022; others). Sites like Searsville Lake, where we can link cause and effect, are critical for the interpretation of proxy environmental data and are increasingly valuable for efforts to mitigate and manage impacts on our natural environment in the Anthropocene.

Study area

Stanford University's Jasper Ridge Biological Preserve (JRBP; Woodside, San Mateo County, California) is a 483-ha protected area located on the San Francisco Peninsula in the eastern foothills of the Santa Cruz Mountains (Coast Range; Fig. 1). Today, JRBP is embedded in a land use matrix including cattle and horse farms, suburban/rural development, and, in the upper reaches of the watershed, relatively undeveloped forested environments. Immediately to the east of JRBP is the main Stanford campus and "Silicon Valley," a highly urbanized global center for technology innovation. On the western side of JRBP are Searsville Lake (104 m elevation; Fig. 1a,

c), a ~ 130-year-old reservoir, and Upper Lake Marsh (104 m elevation; Fig. 1a, d), a natural sag pond on the San Andreas Fault, which is hydrologically connected to Searsville Lake.

Searsville Dam was constructed in 1892 and impounded water in the steep-sided ravine of San Francisquito Creek. When first constructed, the spillway elevation was 101.52 m (333.07 ft). The spillway level was raised in 1894 by 2.90 m (9.5 ft) and again in 1920 by 1.79 m (5.87 ft), bringing it to the current elevation of 104.17 m (341.76 ft) (Kittleson et al. 1996) See Supplemental 1 for further details of the history of human occupation at JRBP. Since its construction, Searsville Lake has filled > 90% with sediment (Freyberg 2001). As the reservoir has filled over the years, parts of the original inundated area have been transformed into a riparian forest, which now separates three distinct but hydrologically connected lakes—Searsville, Middle, and Upper Lakes—the last of which is now further separated from the others by berms along Portola Road (Fig. 1a). Five creeks flow into these lakes: Alambique, Dennis Martin, Sausal, Westridge, and Corte Madera. San Francisquito Creek flows out of the reservoir for ~ 18 km before entering south San Francisco Bay (Fig. 1b).

Modern climate and vegetation

The Mediterranean climate of the area features cool, moist (rainy) winters and warm, dry summers (Supplemental 2). Los Gatos, ~ 30 km SE of JRBP at ~ 120 m elevation, is the closest station with long-term weather data (1893–2016 CE) and shows an average monthly low-temperature range of 3.7–11.8 °C, and high of 13.8–29.4 °C in January and July, respectively. Ninety-two percent of moisture comes during the November–April rainy season, with average monthly precipitation varying from a high of 154.2 mm in January to 0.5 mm in July, and an annual average of 683.5 mm of precipitation (WRCC 2009).

Present-day vegetation in the upper elevations of the Searsville Lake watershed (San Mateo Fine Scale Vegetation Map 2022) includes redwood (*Sequoia sempervirens*)/Douglas fir (*Pseudotsuga menziesii*) forests and evergreen hardwood forests (oak [*Quercus* spp.], tanoak [*Notholithocarpus densiflorus*], and madrone [*Arbutus menziesii*] (San Mateo County Enhanced Lifeform Map 2022)). California chaparral—(coyotebrush [*Baccharis pilularis*], chamise [*Adenostoma fasciculatum*], toyon [*Heteromeles arbutifolia*], poison oak [*Toxicodendron diversilobum*]), California lilac [*Ceanothus* spp.], and hollyleaf cherry [*Prunus ilicifolia*])—is found mainly on west-facing slopes to the east of Searsville Lake, along with patches of California buckeye (*Aesculus californica*) woodlands and California bay (*Umbellularia californica*) (JRBP 2017, San Mateo Fine Scale Vegetation Map 2022). Serpentine grassland and patches of blue oak (*Quercus douglassi*) are found on the high ridge to the east of Searsville Lake (JRBP 2017; San
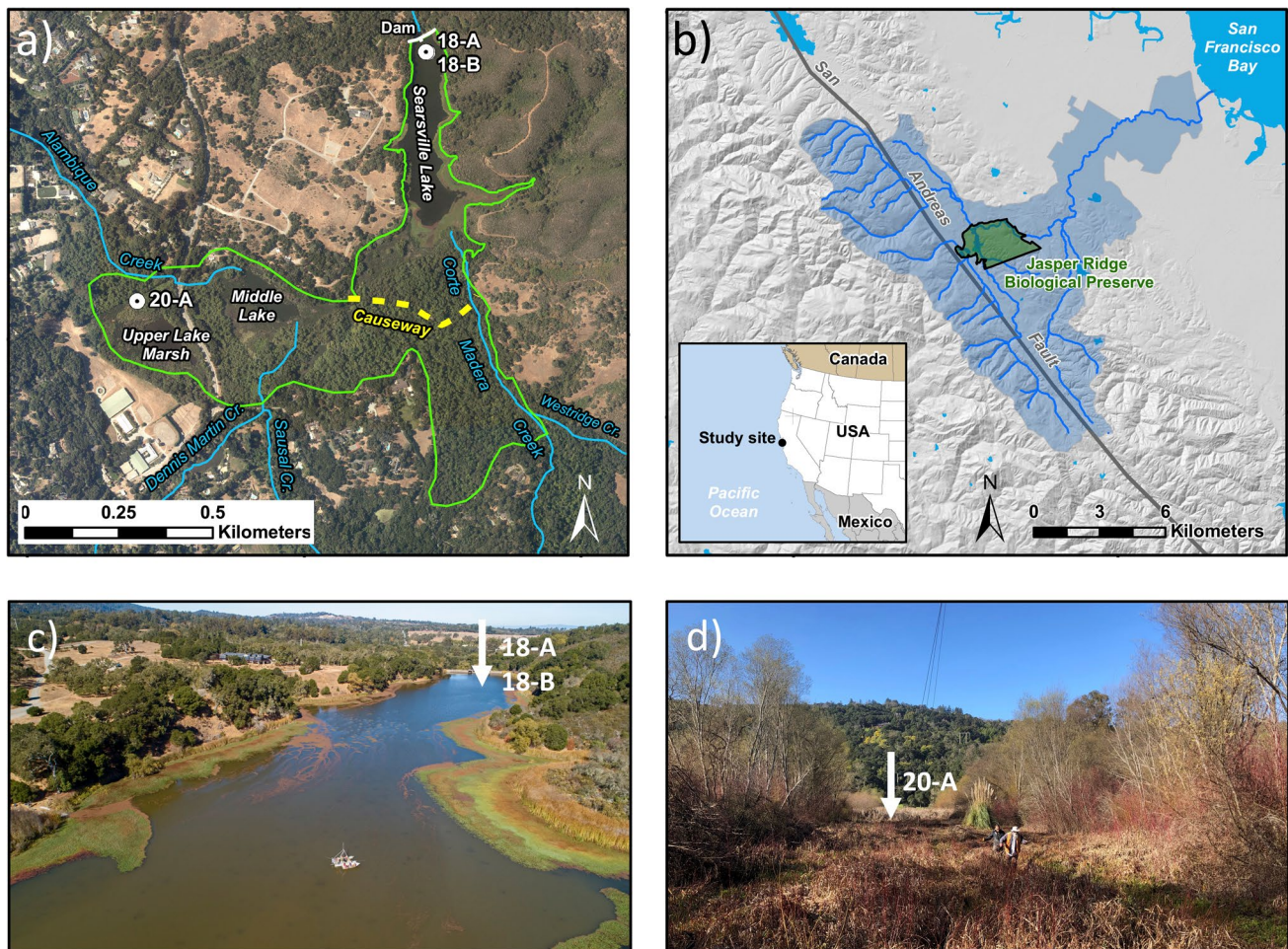
Fig. 1 Searsville Lake and Upper Lake Marsh map and core setting.
a Location map of Searsville Lake and informally named Middle
Lake and Upper Lake Marsh, within Jasper Ridge Biological Preserve
(JRBP), California, including coring locations for JRBP2018-VC01A
(18-A), JRBP2018-VC01B (18-B), and JRUL2020-VC01A (20-A),
and original extent of Searsville Lake (green border); **b** regional per-
spective of JRBP (green polygon) and the San Francisquito Creek
watershed (blue polygon with creeks as blue lines), south of San

Francisco, California, and along the San Andreas Fault (gray line);
c Searsville Lake, 2018, looking northeast with coring locations for
JRBP2018-VC01A (18-A) (photo by Nona Chiariello) and JRBP2018-
VC01B (18-B); **d** Upper Lake Marsh, 2018, looking east-southeast
with coring location for JRUL2020-VC01A (20-A) (photo by Anthony
D. Barnosky). Maps (**a**, **b**) prepared by Trevor Hébert, Jasper Ridge
Biological Preserve. Data sources: 2018 San Mateo County Airphoto,
ESRI maps, Jasper Ridge Biological Preserve

Mateo Fine Scale Vegetation Map 2022). Oak woodland and
California annual/perennial grasslands are present in patches
throughout JRBP and regionally. Riparian forest (willows [*Salix*
spp.], white alder [*Alnus rhombifolia*], dogwood [*Cornus* spp.]),
is found south and west of Searsville Lake and surrounding
Upper Lake Marsh. Freshwater marsh environments, with
cattails (*Typha* spp.), sedges (*Carex* spp. and *Scirpus* spp.),
tules (*Schoenoplectus acutus*), rushes (*Juncus* spp.), and bur-
reeds (*Sparganium eurycarpum*), are present around both sites,
and, in slightly deeper water, parrot's feather (*Myriophyllum
aquaticum*), knotweed (*Polygonum* spp.), pondweed
(*Potamogeton* spp.), and water fern (*Azolla filiculoides*) are
common (JRBP 2012; terminology after Hickman 1993).

Methods

Core collection

Searsville Lake cores JRBP2018-VC01A and JRBP2018-
VC01B (Table 1)—were collected in October 2018 from
the deepest part of the reservoir, ~65 m SSE of Searsville
Dam, using a vibracorer supported by a floating platform
(Lanesky et al. 1979; Glew et al. 2001). Upper Lake Marsh
core JRUL2020-VC01A was collected in February 2020
using a vibracorer stabilized and extracted using a steel
tripod (Table 1). Cores were sectioned in the field, and
JRBP2018-VC01A was also split and photographed in the

Table 1 Searsville Lake (SL) and Upper Lake Marsh (ULM) cores. Datum is WGS84

Site	Core	Latitude	Longitude	Water depth (cm)	Compaction	Drive depth (cm)	Core length (cm)	Core top (cm)
SL	JRBP2018-VC01A	37.4068	− 122.2378	265	24%	1140	851	289
SL	JRBP2018-VC01B	37.4068	− 122.2379	268	15%	1103	944.5	158.5
ULM	JRUL2020-VC01A	37.4009	− 122.2466	12	15.3%	410.5	351	59.5

field. Core scanning was performed in the core lab at the USGS Pacific Coastal and Marine Science Center in Santa Cruz, California, using a GeoTek rotating X-ray computed tomography (CT) and GeoTek multi-sensor core logger (MSCL) for µX-ray fluorescence (XRF) and line-scanning. CT scans record relative density throughout the cores while XRF scans measure elemental concentration. See Stegner et al. (2023) and La Selle et al. (2023) for further details.

Chronologies

A highly resolved chronology for the Searsville Lake JRBP2018-VC01B core was constructed using a combination of seasonal layer counting enabled by distinctive wet-season/dry-season couplets, radiometric tie-points (^{137}Cs), dates of the dam construction and sediment coring, and correlation of historical events and climate data to geochemical (Cu, Ca, Ti), and sedimentological signals of recorded earthquakes in the cores. The age model for Searsville Lake core JRBP2018-VC01A was constructed by detailed matching of the layers evident in CT scans of both cores, and by alignment of Cu and Ca peaks in the XRF scans from the two cores. A detailed description of the age model construction can be found in Stegner et al. (2023).

For Upper Lake Marsh core JRUL2020-VC01A, a chronology was constructed using radiometric (^{14}C, ^{137}Cs) dating, occurrence of non-native pollen types, and correlation of historical data to the sedimentary signals in the cores. AMS radiocarbon ages (Supplemental 3) were calibrated with the IntCal20 calibration curve (Reimer et al. 2020) using the *Bchron* package (Haslett and Parnell 2008) in R (R Core team 2021). Sediment samples of 1-cm thick and from 60 to 218 cm depths were freeze-dried and analyzed for ^{210}Pb, ^{226}Ra, ^{137}Cs, and ^{241}Am by direct gamma assay in the Environmental Radiometric Facility at University College London (Supplemental 4). Additional chronologic controls for the Upper Lake Marsh core came from the first occurrence of exotic *Eucalyptus* pollen and spore types, compared with historical records (e.g., Mudie and Byrne 1980; Mensing and Byrne 1998).

A Bayesian age-depth model for Upper Lake Marsh was created using 12 chronologic tie points: (1) the core top (59 cm depth) at 2020 CE (− 70 cal YBP), (2) the peak in

^{137}Cs deposition (106–107 cm) at 1963 CE (− 13 cal YBP); (3) the first appearance *Eucalyptus* pollen (180–190 cm), dating to 1870 ± 5 CE (90 ± 5 cal YBP); and (4) 9 of the ^{14}C dates (Supplemental 3). The four ^{14}C dates from bulk sediments and two from charcoal were rejected because they were all older than the oldest plant macrofossil dates, suggesting contamination from old carbon in the watershed. Lignite, or brown coal, is known to occur in small pockets throughout the Santa Cruz Mountains, including in the San Francisquito Creek drainage (Stoffer 2002).

Pollen analysis

We analyzed 40 samples from Searsville Lake core JRBP2018-VC01A and 18 from Upper Lake Marsh core JRUL2020-VC01A. Pollen was absent below 200 cm in Upper Lake Marsh. *Lycopodium* spores (19,855 ± 521 [Upper Lake Marsh] or 39,710 ± 1042 [Searsville Lake]) were added to each sample to enable pollen concentration calculations. Processing followed a modified Fægri and Iversen (1989) technique: suspension in dilute KOH, 180-µm mesh wet-sieving, suspension in dilute HCl, HF, and acetolysis, staining with Safranin-O and storage in silicon oil. Pollen and spores were identified on microscope slides at 400 × magnification (Supplemental 4). In addition to individual pollen and spore types, palynomorphs were grouped into general functional groups, based upon several references about the vegetation of JRBP (Supplemental 4).

We used stratigraphically constrained cluster analysis (CONISS) to search for meaningful zones in two groups: the upland pollen assemblage, including only the top 12 most common types, and the wetland pollen types. We used a broken stick test to test for significant groupings. Analyses were conducted using the R *rioja* package (Juggins 2020).

Total organic carbon

The total organic carbon (TOC) for both JRBP2018-VC01B and JRUL2020-VC01A was measured at the Stanford Stable Isotope Biogeochemistry Laboratory (SIBL). Freeze-dried sediment samples were crushed, loaded into silver capsules, then acidified with 6% H_2SO_3 solution to remove the inorganic fraction, and then sealed (Verardo et al. 1990).

L-glutamic acid (USGS-40) and caffeine (IAEA-600) were used as standards. Samples were combusted using a Carlo Erba NA1500 Series 2 elemental analyzer coupled to a Finnigan Delta Plus isotope ratio mass spectrometer (IRMS) via a Finnigan Conflo II open split interface. TOC concentrations were obtained using the mass 44 chromatography peak on the Delta Plus IRMS.

Results

Searsville Lake

Sediment stratigraphy

Searsville Lake sediments consist of alternating light-, tan- and dark-gray banded layers (Fig. 2a), primarily silt but with clay to very fine sands (Stegner et al. 2023). Annual sedimentation was highly episodic, with most deposition occurring during the wet season (October to April; Stegner et al. 2023). TOC ranged from 1.29 to 3.34%. From ~1900 ± 3 to 1929 ± 2 CE (JRBP2018-VC01B core depths 1104–678.5 cm), TOC was fairly stable but then began to increase and experienced peaks in 1936–1937 ± 2 CE (577.5–595.5 cm), 2004 CE (262.5 cm), and 2008 CE (197.5 cm) (Fig. 3a; Stegner et al. 2023).

Chronology

Searsville Lake cores JRBP2018-VC01A and JRBP2018-VC01B chronological controls include historical events (floods and earthquakes; pesticide residues), ^{137}Cs stratigraphy, and lamina counts (Stegner et al. 2023). The cores span 118 ± 3 years, with the base of both cores corresponding to 1900 ± 3 CE, with age error ranging between ± 0.25 and ± 3 years (Stegner et al. 2023). Sediment accumulation rates (SARs) in JRBP2018-VC01A were highly variable, ranging from 0.5 to 122.5 cm/year with a mean of 18.9 cm/year. Rates were generally higher before ~560 cm (before 1946 ± 0.5 CE, mean = 23.7 cm/year) than after (mean = 8.8 cm/year) (Supplemental 5).

Pollen stratigraphy

Thirty-five of 40 samples from JRBP2018-VC01A contained countable assemblages; degraded pollen averaged 8.9% (± 4.8% SD; min = 2.2%, max = 25%). Because of a high SAR, pollen concentrations were low (average = 8340 ± 6755 grains/cm^3) but increased substantially above a series of barren samples deposited between ~680 and 640 cm depth (Fig. 3). However, palynomorph richness was high, with at least 144 palynomorph types identified.

We found no significant groupings in Searsville Lake upland pollen (Fig. 3a, b) using CONISS, but detected two significant groups in the wetland pollen (Fig. 3c): 1140–742 cm (1900 ± 3–1925 ± 2 CE) and 720–298 cm (1928 ± 2–2014 CE) (Supplemental 6), allowing us to recognize two pollen units:

SL Unit 1 (1140–742 cm [1900 ± 3–1925 ± 2 Common Era]) Pollen concentration increases from ~1606–2094 grains/cm^3 early in the unit to 1614–14,589 grains/cm^3 later (Fig. 3a). *Quercus* spp. and *Sequoia sempervirens* are generally common but fluctuate in abundance. *Pinus* (Monterey pine type; *P.* cf. *radiata*) initially increases and then declines sharply toward the top of the unit. Other tree pollen includes *Notholithocarpus densiflorus*, *Umbellularia californica*, *Aesculus californica*, walnut (*Juglans* sp.), maple (*Acer* sp.), and birch (*Betula pendula/occidentalis*), along with blue gum (*Eucalyptus*) and olive (*Olea*) (Fig. 3a; Supplemental 7), with sporadic elm (*Ulmus americana/parviflora*; first appearance at 997–994 cm, 1907 ± 3 CE), *Fraxinus* (at 977–969 cm, 1908 ± 3–1909 ± 3 CE) and *Populus* (at 839–836 cm, 1921 ± 2 CE).

Shrubs are dominated by the sunflower family (Asteraceae). Also present were sagebrush (*Artemisia*), *Ceanothus*, chinquapin (*Chrysolepis*), hazel (*Corylus* cf. *cornuta*), Ericaceae (probably *Arctostaphylos*), lemonade bush (*Rhus*), buckthorn (*Rhamnus*), and others. Common herbs include grasses (Poaceae), with the ruderals of the goosefoot family (Amaranthaceae), plantain (*Plantago*) and dock (*Rumex*), as well as ferns (Fig. 3a, c; Supplemental 7). Cereal grains (Cerealia, Fig. 3a) regularly occur.

Wetland plants include *Alnus* cf. *rhombifolia*, willow (*Salix*), sedges (Cyperaceae), horsetail (*Equisetum*), and cattail (*Typha latifolia*), with an initial colonization by aquatic macrophytes, including *Sparganium* and quillwort (*Isoetes*) (Fig. 3c). There is a major increase, then decline, in *Alnus* through this unit, and *Salix* increases modestly. Watermilfoil (*Myriophyllum*) and watershield (*Brasenia schreberi*) first appear late in this unit, at 910–906 cm (1914 ± 2–1915 ± 2 CE) and 852–847 cm (1919 ± 2 CE) respectively. Important algae species—*Debarya* and *Pediastrum*—peak in the upper part of the unit (Fig. 3c).

SL Unit 2 (720–298 cm [1928 ± 2–2015 ± 0.5 Common Era]) Pollen concentrations are consistently higher than in the previous unit (from ~3144 to 30,183 grains/cm^3; Fig. 3a). *Sequoia sempervirens*, *Pseudotsuga menziesii*, and *Quercus* spp. pollen increases. *Eucalyptus* and *Olea* pollen percentages are at their maximum in the record. The introduced tree of heaven (*Ailanthus*) first appears at 563–558 cm (1943 ± 0.25–1947 ± 0.25 CE) (Fig. 3a).
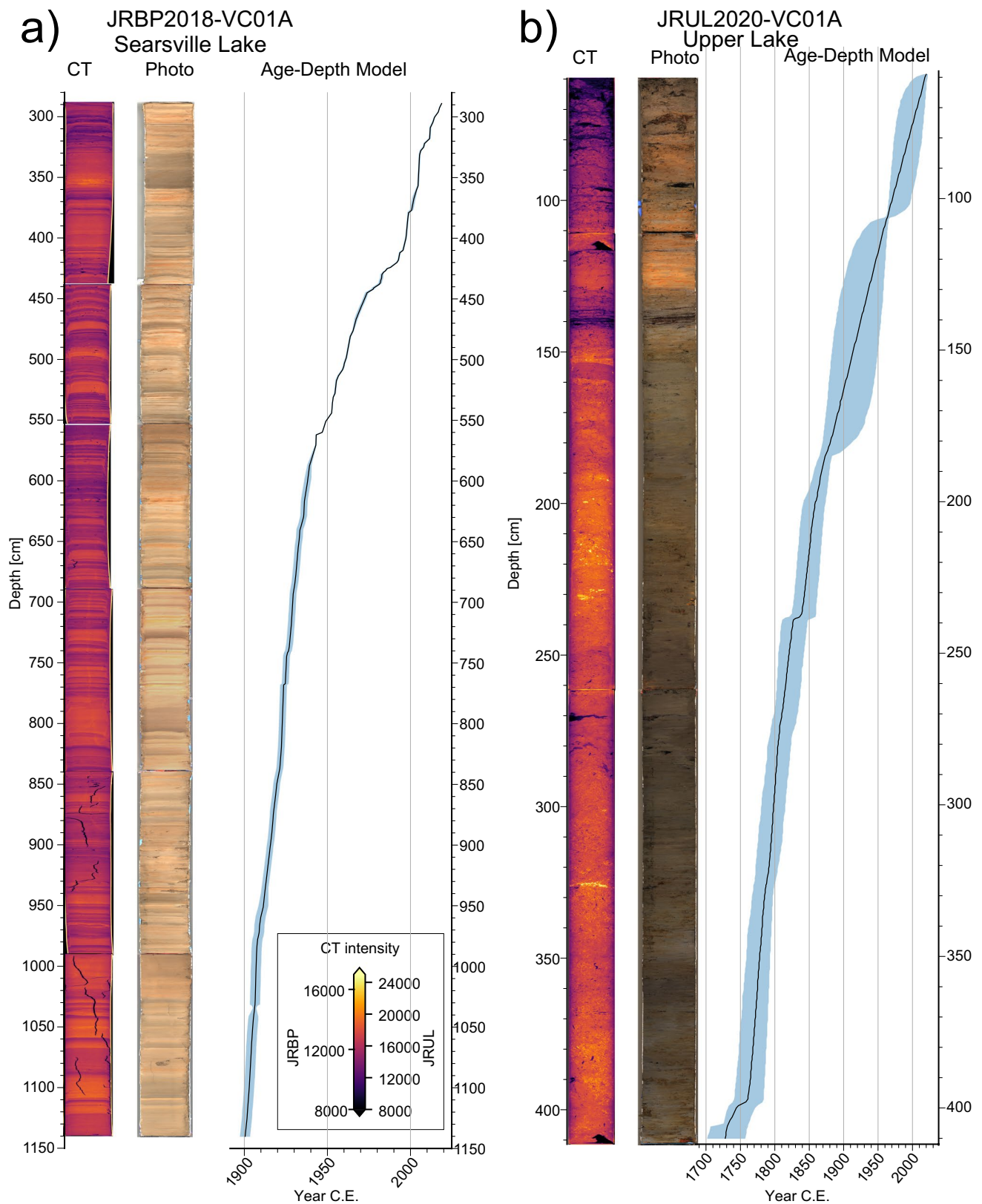
Fig. 2 Sediment stratigraphies and chronologies for **a** Searsville Lake and **b** Upper Lake Marsh. In each panel, the left column shows a color-enhanced orthogonal view of the Computed Tomography scan, the middle column shows a high-resolution line-scan, and the right column show the age depth model, with error bars in light blue

A similar shrub pollen flora continues, but *Ceanothus* and *Chrysolepis* increase. Poaceae increases while Asteraceae and Cerealia grains decline. Few herbs are noted, and the ruderal species are unchanged from levels below. Ferns also continue to be abundant (Fig. 3a; Supplemental 7).

Wetland *Alnus* is reduced relative to Unit 1, while *Salix* increases. Emergent aquatic species—*Typha latifolia* and *Sparganium*—are common. *Myriophyllum* disappears early in this unit at 689–684 cm (1929 ± 2–1930 ± 2 CE), *Potamogeton* first appears at 481–479 cm (1963 ± 0.5–1964 ± 0.5 CE), and aquatic algae are rare (Fig. 3c). Coprophilous fungi are somewhat reduced (with the exception of *Endophragmiella* and *Diprotheca*); some additional fungal types are reduced, e.g., vesicular–arbuscular (VA) fungi, while others increase (e.g., *Helicoon*). Protozoans and rotifers are much reduced in this unit relative to lower in the core (Fig. 3c).

Upper Lake Marsh

Sediment stratigraphy

Upper Lake Marsh sediments indicate a relatively gradual change from an apparent terrestrial deposit without pollen below, to a low-energy organic-rich silt with pollen preserved above. The lower 260 cm of the core is dark brown and gray, massive silt (Fig. 2b). The silt from 236 to 195 cm contains sand, including a very poorly sorted, well-rounded sand layer (silt to pebble-sized) from 221 to 210 cm with a relatively sharp (3 mm) basal contact. A 3-cm-thick poorly sorted, sub-angular, and very fine to coarse sand layer with very sharp (2 mm) upper and lower contacts separates the lower silty section of the core from the more organic-rich, peaty silts and silty peats from 150 to 59.5 cm. Finely rooted peat and detrital plant material are pervasive throughout the upper 90 cm of the core.

TOC ranged from 0.64 to 6.20%. Below 80 cm, TOC remained below 3%; above 80 cm, TOC increased steadily to the maximum value at the top of the core. This rise may have begun as early as ~150 cm (Fig. 4a).

Chronology

Unsupported ^{210}Pb dating was not possible because total ^{210}Pb activities were almost in equilibrium with supported ^{210}Pb, and unsupported ^{210}Pb activities were low and/or less than the relevant counting errors, possibly due to high sedimentation rates at the top of the core. ^{137}Cs activities were detected between 110 and 96 cm (50.5–36.5 cm below the sediment–water interface) corresponding with the year 1963 CE. The Bayesian age model for Upper Lake Marsh shows that the sediments bearing identifiable pollen, 201–59 cm,

span from 1858 (95% CI: 1840–1872 CE, 110–78 cal YBP) to 2020 CE (Fig. 2b). The average SAR was ~1 cm/year (Supplemental 8).

Pollen stratigraphy

Only one (150 cm) of the 18 pollen samples reported here was barren. Palynomorph richness (84 types) was lower than Searsville Lake but still reasonably high.

CONISS detected no significant groups in the upland pollen but identified a major split between samples at 160.5 and 140.5 cm. In the wetland pollen, we found three significant groups: 201–160 (ULM Unit 1), 141–140, and 131–60 cm (Supplemental 9). We combine 141–140 with the upper group, 131–60 cm, and also subdivide samples from 141 to 60 cm into two groups—141–100 cm (ULM Unit 2) and 91–60 cm (ULM Unit 3)—which recognizes a fourth but non-significant CONISS group. In particular, ULM Unit 1 is characterized by an elevated percent of VA fungi, along with higher degraded pollen (14.1 vs. 5.3%), and lower average pollen concentration (11,594 vs. 64,478 grains/cm^3, respectively) than subsequently (Fig. 4a).

ULM Unit 1 (201–160 cm [~ 1858–1903 Common Era; 95% CI = 1840–1943 Common Era]) Pollen concentration vary from ~9147 to 21,013 grains/cm^3 (Fig. 4a), with an SAR of ~1.2 cm/year (Supplemental 8). *Sequoia sempervirens* and Taxaceae-Cupressaceae (TC) dominate the trees, with small amounts of *Pinus* sp. and *Pseudotsuga*, and with only minor *Quercus* and the introduced *Eucalyptus* and *Olea* (Fig. 4a). Asteraceae dominates the shrubs, but with some *Corylus* and *Chrysolepis* (Fig. 4a). Common herbs include Poaceae, with ruderals such as Amaranthaceae, *Plantago*, and *Rumex*, and several fern species (Fig. 4a, b). Cyperaceae is most abundant here, with small amounts of *Alnus* and traces of *Salix* and *Potamogeton*. NPPs are dominated by VA mycorrhizal fungi, but also coprophilous fungi (*Sordaria*, *Sporormiella*, *Podospora*), which are most abundant in this unit (Fig. 4c).

ULM Unit 2 (141–100 cm [~ 1924–1971 Common Era; 95% CI = 1888–1997 Common Era]) Pollen concentrations increase to 23,578– 105,332 grains/cm^3 (Fig. 4a) and the SAR is ~0.8 cm/year. The pollen of *Sequoia sempervirens* increases from Unit 1 and then declines somewhat toward the present. *Pinus*, *Notholithocarpus densiflorus*, and *Eucalyptus* are more abundant in Unit 2 than in Unit 1, and *Pseudotsuga* remains important. *Quercus* increases roughly fivefold from below. Random pollen grains of *Olea*, *Carya*, *Betula*, *Juglans* sp., and *Picea* (spruce) are also found (Fig. 4a, Supplemental 10).
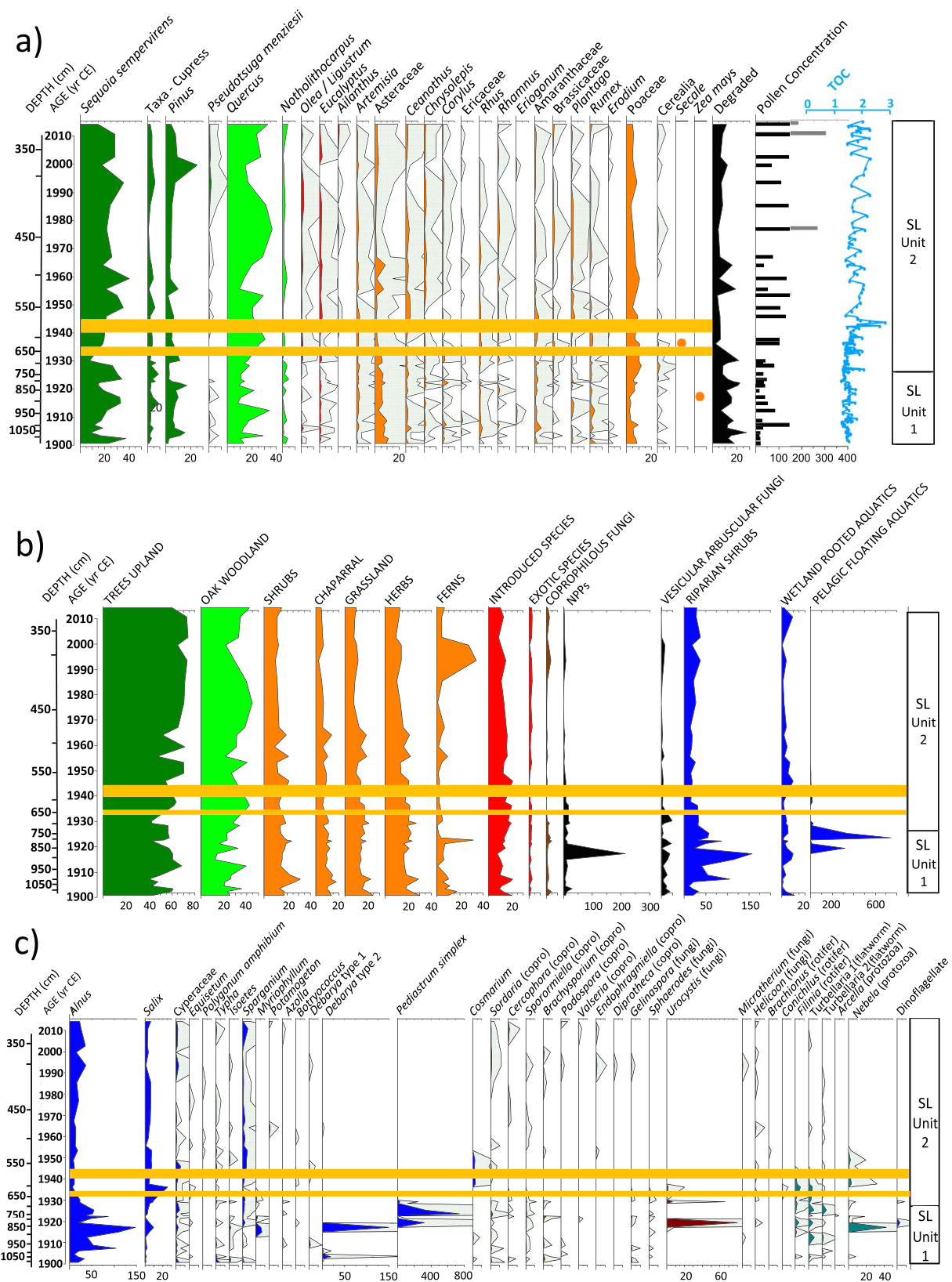
Fig. 3 Searsville Lake (core JRBP2018-VC01A) selected pollen and spore percentage stratigraphies of important species. **a** Percentages of trees, shrubs, herbs, and ruderals, with pollen concentration×100 grains/cm³ and % total organic carbon (TOC; Stegner et al. 2023); **b** total percentages of dominant functional vegetation groups; **c** percentages of wetland, aquatic, and NPPs (non-pollen palynomorphs). Silhouette is 10×exaggeration. The horizontal yellow bars show depths analyzed but where no pollen was recovered

The most important shrub here is *Chrysolepis*, but *Ceanothus*, *Corylus*, Ericaceae (probably *Arctostaphylos*), Rosaceae, and *Rhus* are also present. Though herb species are generally less important than in Unit 1, Poaceae, Asteraceae, Amaranthaceae, and ferns decline, while *Artemisia*, Brassicaceae, and Cerealia pollen are consistently higher in Unit 2 (Fig. 4a, b; Supplemental 10).

Wetland types are more abundant in Unit 2 than in Unit 1. This includes *Alnus*, which remains important, as well as *Salix*, *Potamogeton*, lady's thumb (*Polygonum persicaria*), *Sparganium*, and *Typha*, along with spores of *Azolla* (water fern) and *Botryococcus*, an aquatic alga; only the Cyperaceae declines (Fig. 4c). The NPPs diminish in this unit.

ULM Unit 3 (91–60 cm [1982–2018 Common Era; 95% CI 1968–2020 Common Era)])

Pollen concentration generally increases again, from 43,955 to 113,208 grains/cm^3, with an SAR of ~ 0.5 cm/year. Tree pollen fluctuates through this unit—*Sequoia sempervirens* and *Eucalyptus* decline from Unit 2; *Quercus* briefly declines and then increases above levels seen previously; *Olea* also increases. *Notholithocarpus densiflorus* declines through Unit 3 while *Pinus* and *Pseudotsuga* remain important. *Chrysolepis* remains important but declines slightly as *Ceanothus* increases. Herbs fluctuate: several increase in abundance, including *Ambrosia*, Fabaceae, Poaceae, *Plantago*, and *Rumex*, while ferns decline further in Unit 3. (Fig. 4a, b; Supplemental 10).

Many wetland (*Typha*, Cyperaceae) and rooted aquatic (*Myriophyllum*, *Potamogeton, Sparganium*) plants increase considerably in Unit 3. *Alnus* declines slightly but *Salix* remains important. *Spirogyra* appears for the first time (Fig. 4c). Some of the coprophilous fungi make a small recovery in Unit 3.

Discussion

The records reported here trace human environmental impacts and vegetation changes in the Searsville Lake watershed of the San Francisco Peninsula (CA, USA) since the mid-nineteenth century, a time of increasing population following the Gold Rush in 1849 (Supplemental 1). Though our record begins during the transition out of a significant late Holocene cool period—the Little Ice Age (Heusser et al. 2015)—most events recorded in the pollen and NPPs can be ascribed to local and/or regional patterns of logging, agriculture, and urbanization that took place across the west coast of North America.

The Searsville Lake and Upper Lake Marsh records are complementary and together provide a detailed picture of environmental change over the last ~ 160 years (Fig. 5). Even so, differences between the two sites are important and may contribute to variability between their vegetation records. These differences include contrasts in (1) catchment characteristics for each watershed and in the ways in which they sample the pollen record and (2) sediment accumulation rates, sample resolution, and temporal length for each of the cores. In the first case, drainage basin size and occurrence of inflowing streams will affect the pollen record. Though urbanization has probably changed drainage patterns through time (Kittleson et al. 1996), today, Searsville Lake receives virtually all of its inflow from Corte Madera Creek (Fig. 1), whereas Upper Lake Marsh is near the terminus of Alambique Creek and has less than half the drainage basin of Searsville Lake. Historical evidence suggests that the two basins were connected when the reservoir first filled (SL Unit 1, Upper LM Unit 1): Upper Lake Marsh was evidently a willow and tuleen water of Middle Lake and Searsville Lake (Fig. 5b). In 1920, the height of the dam was increased, a road was constructed separating Upper Lake Marsh from Middle and Searsville Lakes (Figs. 1a and 5), and a large culvert was built to conduct Alambique Creek into Middle Lake. In 1929, a levee (called The Causeway) was constructed to trap silt in Middle Lake (Fig. 1a) before it entered the main body of the reservoir (Bocek and Reese 1992; Kittleson et al. 1996). Historical photos and maps in the JRBP archives show that open water actually increased at Upper Lake Marsh subsequently and has persisted more or less until the present day (Fig. 5). The dam-height increase, road, and levee construction served to increase Upper Lake Marsh water depth while simultaneously dividing it from Searsville Lake, causing the transition from Unit 1 to Unit 2 in both sites.

Furthermore, the Upper Lake Marsh record nearly always contains more *Sequoia* pollen from the upland coniferous forest, while Searsville Lake contains more pollen from oak woodland, shrub, and herb communities (Figs. 3b and 4a), suggesting each drainage picks up slightly different local pollen signals. However, grassland and chaparral community and coprophilous fungi (measuring impact of herbivores) records are nearly identical between the sites (Figs. 3a, c and 4a, c). Though the patterns for these changes are similar, implying broader scale vegetation change, these absolute amounts suggest local variations between the sites.

Second, sediment accumulation rates, sample resolution, and length of record also contribute to the variation between records. The Searsville Lake record spans from ~ 1900 to 2018 CE, and the 851 cm-long core allows for a high-resolution
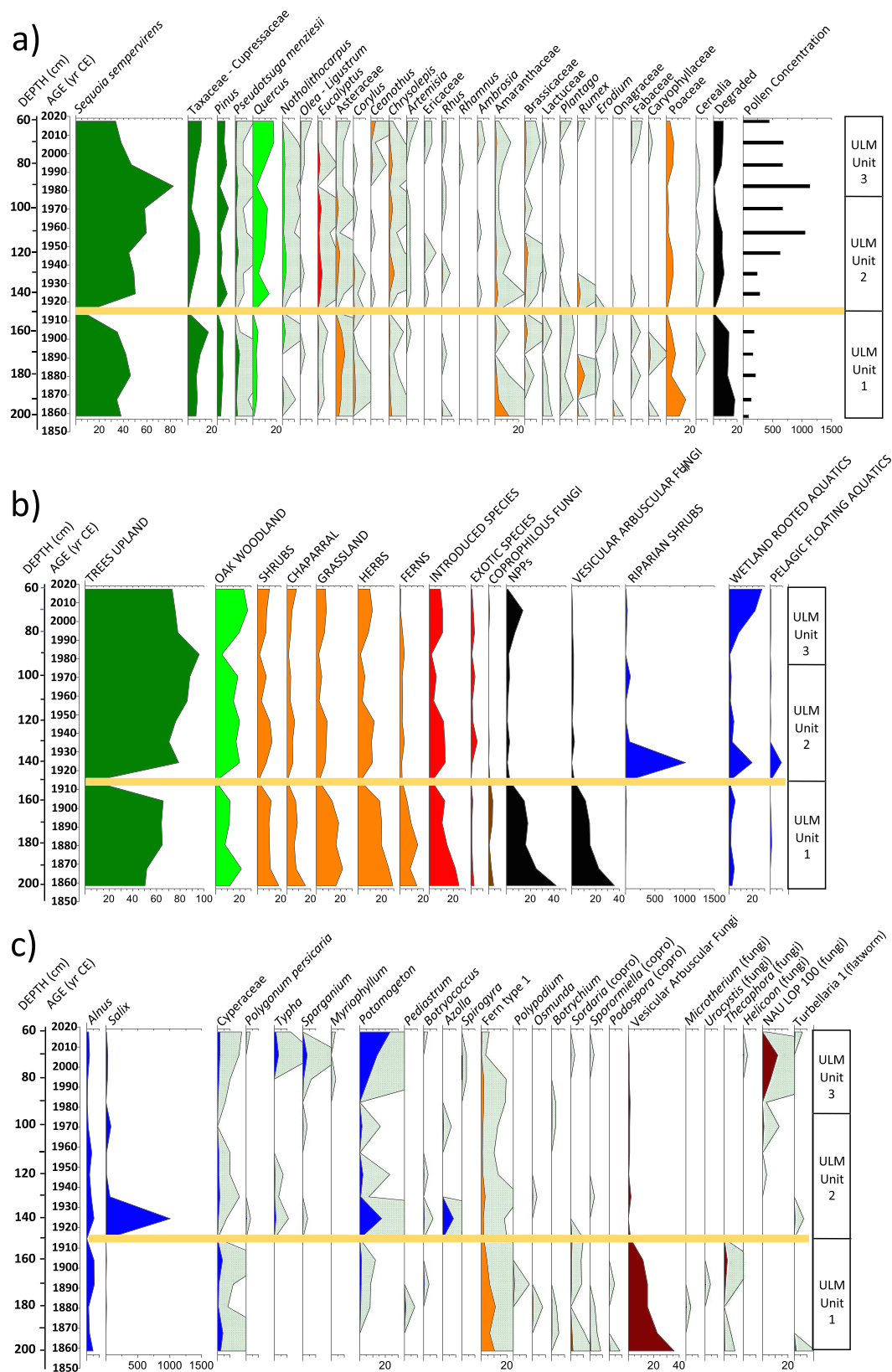
Fig. 4 Upper Lake Marsh (core JRUL2020-VC01A) selected pollen and spore percentage stratigraphies of important species. **a** Percentages of trees, shrubs, herbs, and ruderals, with pollen concentration×100 grains/cm³ and % total organic carbon (TOC); **b** total per-centages of dominant functional vegetation groups; and **c** percentages of wetland, aquatic, and NPPs. Silhouette is 10×exaggeration. The horizontal yellow bar shows depths analyzed but where no pollen was recovered

pollen stratigraphy for the twentieth century. By contrast, the ~ 1.4 m of Upper Lake Marsh sediment begins around 1858 CE, adding ~ 42 years to the Searsville Lake record but at a much lower temporal resolution. The sedimentation rate in ULM Unit 1 is higher than in Unit 2, before Searsville Dam was emplaced, possibly because the heavily logged hillsides were more susceptible to erosion early in the record. In ULM Unit 2, the sediment accumulation rate is an order of magnitude lower than Searsville Lake for the same period, while the pollen concentration at Upper Lake Marsh is ~ 5 × greater than at Searsville Lake (Figs. 3a and 4a). The slower SAR in ULM Unit 2 likely reflects some combination of vegetation recovery (Kittleson et al. 1996), fault-controlled stream and sedimentation differences, a change in the base level of the drainage due to damming of Searsville Lake, and/or local land modifications and road building.

Primary vegetation trends

Late nineteenth century (~ 1858–1900 Common Era)

Vegetation trends of the late nineteenth century are summarized in Fig. 5. ULM Unit 1 contains abundant vesicular–arbuscular (mycorrhizal) fungi (Fig. 4b), indicating in situ soil (Kolaczek et al. 2013) or erosion of basin soils from the catchment area (Anderson et al. 1984). When Searsville Dam was built, Upper Lake Marsh was inundated and became part of the reservoir (Fig. 1a). The pollen stratigraphy, showing a shift from soils toward a sudden increase in wetland and aquatic species, as well as higher TOC in ULM Unit 2, therefore suggests that Unit 1 predates the existence of the reservoir and/or the increase in the height of the dam in 1920.
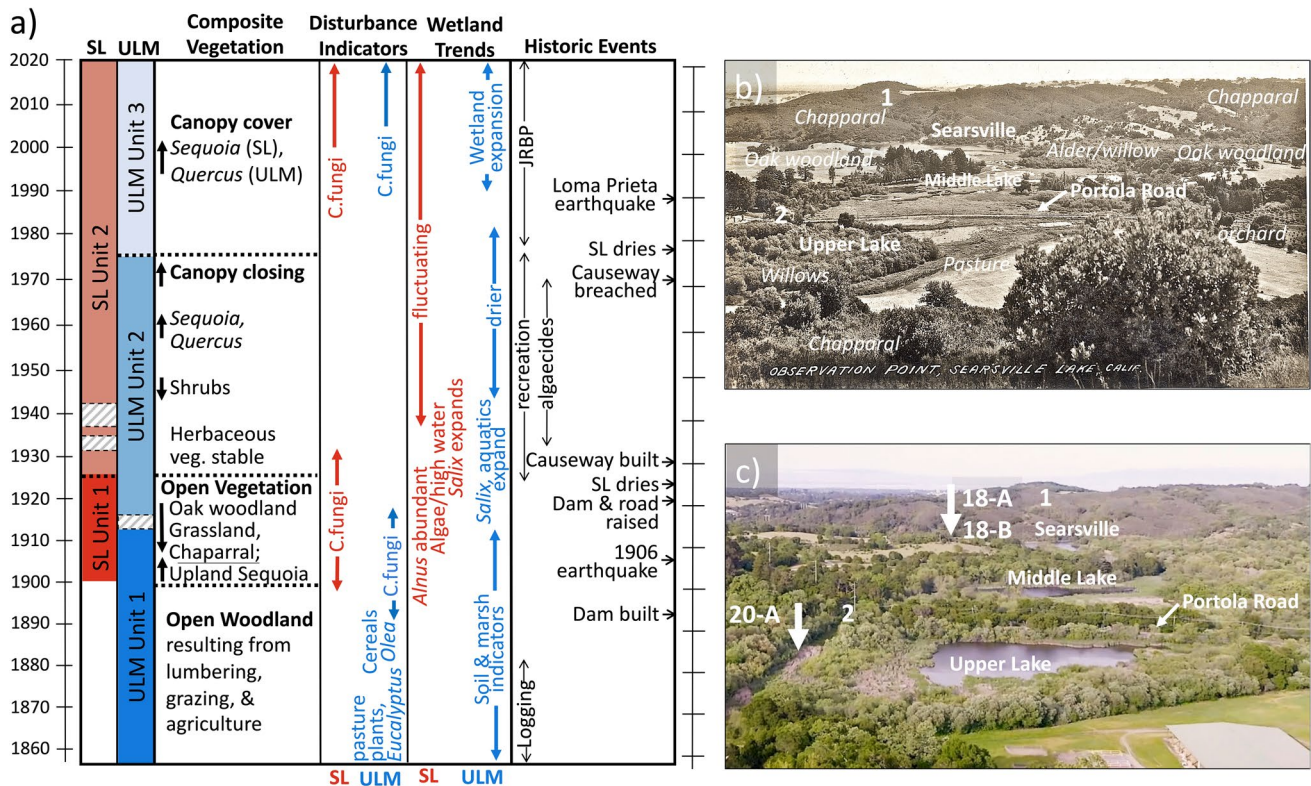

Fig. 5 Historical vegetation changes. **a** Summary of key vegetation changes and historical activities. SL, Searsville Lake (red shading/lettering); ULM, Upper Lake Marsh (blue shading/lettering); C. fungi = Coprophilous fungi; gray hatched areas denote barren samples with no pollen recovery; arrows denote increasing (up) or decreasing (down) vegetation trends. **b** Searsville Lake, Middle Lake, and Upper Lake Marsh, ca. 1923 ("Searsville Lake near La Honda Calif." ca. 1923), looking northwest. **c** Searsville Lake, Middle Lake, and Upper Lake, ca. 2022, looking northwest. 18-A, 18-B: Searsville Lake coring locations; 20-A: Upper Lake Marsh coring location; 1, 2 indicate matching locations in the historical and modern photos; Portola Road was raised in 1920

Low tree pollen percentages of *Sequoia sempervirens*, *Pseudotsuga menziesii*, *Notholithocarpus densiflorus*, and *Eucalyptus* suggest a relatively open vegetation existed during ULM Unit 1 (Fig. 4b). Historical records suggest logging in the area began around 1777 (Corte Madera Creek, Spanish for "wood cutting," was named for this) and by 1880 most of the valuable timber in the area was gone (Bocek and Reese 1992; Fig. 5, Supplemental 1). *Sequoia sempervirens* was logged intensively locally and regionally (Bocek and Reese 1992), though a small population continued to exist around Upper Lake Marsh into the late nineteenth century (Map of the Rancho of Cañada de Raymundo 1856; Plat of the Rancho Cañada del Corte de Madera 1879). *Pseudotsuga menziesii* was generally cut only when found in redwood stands, but *Notholithocarpus densiflorus*, which is never particularly abundant in ULM Unit 1, was exploited heavily for firewood and for leather tanning (Bocek and Reese 1992). Following logging, an area was often clear-cut or burned to open the land for pasture or agriculture (Bocek and Reese 1992), which likely explains the high proportion of open environment and grassland taxa (Fig. 4a, b). Pollen also indicates a few oak trees, which were harvested for firewood (Bocek and Reese 1992). Wood was cut along Alambique Creek in the 1840s to fuel a series of stills (*alambique* being Spanish for "still"), to build fences along roads, and for construction (Bright 1998; Dengler 1997). Historical illustrations also attest to the presence of large estates with manicured gardens, fields of grain, and livestock (Moore and De Pue 1878).

Though chaparral was locally common in the late 1850s (Rancho de Canada de Corte Madera Map 1857), chaparral was cleared in the 1870s for the planting of commercial orchards and vineyards and was much reduced by the late nineteenth century (Bocek and Reese 1992). However, pollen assemblages—Asteraceae, *Corylus*, and *Chrysolepis*—show chaparral or sage scrub occurred here into the late nineteenth century (Fig. 4a). Herbaceous flora was more diverse than subsequently, with higher percentages of Poaceae, Lactuceae (dandelion type), and others (Fig. 4a), including ferns (Fig. 4b). Ruderal plants (e.g., Amaranthaceae, *Plantago*, *Rumex*), as well as abundant coprophilous fungi (associated with animal dung), were most common, a reflection of the importance of livestock and grazing (Bocek and Reese 1992) during the Spanish (1770s–1822 CE) and Mexican (1822–1846) periods. Wheat and barley fields began to replace the cattle ranches in the region after 1865, though cattle were grazed in and around JRBP sporadically until 1960 (Bocek and Reese 1992; Franco 1976).

Early twentieth century (~ 1900–1925 Common Era)

Vegetation during the early twentieth century trends toward greater openness (Fig. 5). Lowest tree pollen percentages in the Searsville Lake record (Fig. 4b), including oak woodland species, suggest a somewhat open vegetation during the time of initial infilling of the reservoir. Even so, local tree diversity was high, with *Pseudotsuga menziesii*, *Notholithocarpus densiflorus*, *Aesculus californica*, *Juglans*, *Betula*, *Eucalyptus*, and others (Fig. 4a, b). *Sequoia sempervirens* pollen is more abundant here than later, again perhaps representing individuals located along drainages.

Grasses and grassland herbs (Figs. 3a and 6a) and chaparral species increased (Fig. 3b). Pollen of Asteraceae, *Ceanothus*, *Chrysolepis*, *Rhus*, and others (Figs. 3a, b and 4a, b; Supplemental 7 and 10) suggest that remnant patches of chaparral continued to exist locally (Fig. 5b), perhaps in areas unsuitable for agriculture. A diverse herbaceous flora, including ferns and others (Figs. 3a, b and 4a, b; Supplemental 7 and 10), continued to be important, and ruderal plants were integral (see below). *Alnus* probably expanded along lake margins and streams (Figs. 3c and 4c).

Mid-twentieth century (~ 1924–1971 Common Era)

Vegetation trends during the mid-twentieth century reflect the increasing closure of the canopy. *Sequoia sempervirens* began a decades-long increase in abundance, as did *Quercus*, perhaps in response to natural reforestation, but also to a decline in grazing pressure (Figs. 3a and 4a). Franco (1976) noted a significant increase in the regeneration of oak saplings after the cessation of grazing at JRBP in 1960, but this did not occur at the adjacent Stanford Linear Accelerator where grazing was still taking place. The differences in oak recruitment with and without grazing suggest that the increase in oaks seen in our pollen records may correspond to local and regional declines in cattle. Furthermore, Herwitz et al. (2000) documented an increase in the crown area of oaks from 1974 to 1995 at JRBP, with the greater crown coverage presumably also affecting oak pollen production (Molina et al. 2009; Katz et al. 2020). An increase in oak cover and/or crown area, at the expense of grassland, is also seen by comparing historical to modern photos available in the JRBP archives (e.g., Fig. 5b, c).

Late twentieth and early twenty-first century (~ 1982–2018 Common Era)

This period encompasses roughly half of the Searsville Lake core (Fig. 3). Canopy cover continued to increase, and included several introduced species (*Eucalyptus*, *Olea*, and *Ailanthus*; see below; Figs. 3a and 4a). At Upper Lake Marsh, *Sequoia* is more abundant, and *Quercus* less abundant, than in Searsville Lake (Figs. 3a and 4a), which may be related to Upper Lake Marsh's greater proximity to upland *Sequoia sempervirens* forests, and Searsville Lake being surrounded by *Quercus agrifolia* woodland, as well as to potential

differences in pollen delivery to the two locations. While we cannot directly tie the frequent fluctuations of oak during this time to specific ecological events, this period witnessed pruning for power lines at JRBP, and disease since at least the 1980s (Nona Chiariello, *personal communication*), when blue oak (*Q. douglasii*) dieback became a regional problem, followed by Sudden Oak Decline in coast live oak (*Q. agrifolia*) and black oak (*Q. velutina*) (UC Berkeley Forest Pathology and Mycology Lab 2022), perhaps exacerbated by warming climates (Dwomoh et al. 2021).

Local differences appear between the records in the late twentieth and early twenty-first century. At Upper Lake Marsh, shrubs and herbs increased in abundance at the expense of trees whereas in Searsville Lake, chaparral scrub and grassland declined (Figs. 3a, b, 4a, b, and 5b, c). Declines in the Asteraceae and perhaps *Artemisia* and *Rhus* account for the first group, while changes in the ruderal group (Figs. 3a and 4a) account for the declines in the grassland.

At both Searsville Lake and Upper Lake Marsh, wetland/riparian vegetation increased in the 1980s–2010s, along with TOC (Figs. 3c and 4c). Searsville Lake shows a major but brief peak in ferns in the 1990s (Fig. 3b), possibly in response to above-average rainfall (Menne et al. 2012a,b), or habitat expansion fostered by accelerated reservoir infilling.

Invasive, non-native species, agricultural and disturbance indicators

Here, we used only pollen species specifically identified as invasive, as determined by JRBP references (JRBP 1995; 2016). Those present early in the Upper Lake Marsh record include *Plantago*, *Rumex*, *Erodium*, Amaranthaceae, Brassicaceae, and *Urtica* (Fig. 4a). *Plantago*, *Rumex*, and *Erodium* have been associated with the introduction of agriculture and pasturing by the Spanish (Mensing 1998; Mensing and Byrne 1998; Plater et al. 2006; Anderson et al. 2013; 2015; Cowart and Byrne 2013; Ejarque et al. 2015; others), and their introduction into the local area undoubtedly predates Upper Lake Marsh and Searsville Lake sediment records.

Some grass pollen in the records certainly includes introduced grasses, though it is difficult to distinguish non-native from native grass species pollen, except for cereal grasses. In the 1850s, wheat (*Triticum* sp.) was grown extensively around JRBP, and settlers planted orchards and vegetable crops (Bocek and Reese 1992). Between 1860 and 1890, the grassland to the east of Searsville Lake was periodically used for grain crops (Bocek and Reese 1992). Only sporadic Cerealia (cereal) pollen is found in ULM Unit 1 corresponding to this time (Fig. 4a), but cereal pollen does not disperse widely and may not have reached Upper Lake Marsh. In Searsville Lake, one level contained *Zea mays* (maize), while another contained *Secale* (rye) (Fig. 3a), suggesting a nearby source field.

Regionally, grain fields gave way to mixed horticulture starting around 1875 (Bocek and Reese 1992; Supplemental 1). However, the pollen of agricultural crops, including those from orchard trees, is rare in both Upper Lake Marsh and Searsville Lake records. *Olea* (olive) was first introduced into California by Spanish missionaries in the eighteenth century (Carter 2008) and subsequently was planted in most missions. *Olea* occurs in Upper Lake Marsh sediments after ~ 1891 (Fig. 4a) and throughout Searsville Lake sediments (Fig. 3a). *Juglans* pollen occurs sporadically in these records (Supplemental 7 and 10); however, this could represent either native walnut trees (*J. californica*) or nut crops.

Eucalyptus trees were introduced into the San Francisco region in the early 1850s (Bulman 1988; Santos 1998), and in nearby San Jose dating from 1856 (Santos 1998). *Eucalyptus* is found throughout both records but is absent from the oldest Upper Lake Marsh sample (Fig. 4a). In Searsville Lake, we also find *Ailanthus altissima*, first introduced into California by Chinese Gold Rush miners (Bossard et al. 2000).

Coprophilous fungal spores occur in both records (Fig. 3c, 4c) and directly reflect grazing animals nearby (Fig. 5). This richness indicates a thriving herbivore community and a continuing influence of grazing activities on sediment deposition of the reservoir. Spore occurrence at the top of the Upper Lake Marsh record is consistent with the presence of horse stables in the watershed today and a known history of the flood runoff from nearby stables into Upper Lake Marsh.

Lake and wetland dynamics

The history of the sites' aquatic communities is preserved in the sedimentary palynomorphs. Sedges (Cyperaceae) dominated marginal lacustrine areas in the Upper Lake Marsh core (Fig. 4c), particularly in the late nineteenth and early twentieth century. Since the 1920s, small amounts of *Potamogeton* pollen and spores of *Azolla* and *Botryococcus* algae suggest at least periodic inundation of the Upper Lake Marsh coring location. An extensive *Salix* grove dominated the Upper Lake Marsh wetland by the start of ULM Unit 2, which may have declined through time with the slow infilling of sediment.

The transition to ULM Unit 2 by ~ 1924 closely follows several major local historical events (Fig. 5), which influenced wetland communities here. First, the 1906 magnitude 7.9 earthquake along the San Andreas Fault, which runs beneath Upper Lake Marsh, caused major offsets and upthrusts in the JRBP area and increased water flow over Searsville Dam (Kittleson et al. 1996; Lawson et al. 1908). Resulting changes in hydrology may also have increased water flow to Upper Lake Marsh, as the earthquake caused a horizontal offset of several meters in the land surface nearby (Taber 1906; Gilbert et al. 1907). Second, the height of Searsville Dam was increased by 3 m in 1920, increasing the reservoir depth

(Kittleson et al. 1996) and likely contributed to the increase in the water depth at the Upper Lake Marsh basin as well (see above; Fig. 5b, c). Third, in 1929, The Causeway (Fig. 1a) was constructed to trap silt from several creeks before entering the main body of Searsville Lake (Bocek and Reese 1992; Kittleson et al. 1996). This levee separated Searsville Lake from Middle Lake and the wetlands to the south (Fig. 1a), impacting water delivery and retention to Upper Lake Marsh.

Rooted aquatic plants—*Salix*, Cyperaceae, *Typha latifolia*, *Equisetum* (horsetail)—became established early during the infilling of Searsville Lake, while *Isoetes* (quillwort) grew in shallow water (Fig. 3c). *Salix* may have become established from watercourses leading into the reservoir. Only later during the mid-late 1910s did floating leaved aquatic plants, such as *Myriophyllum* and *Brasenia*, become established in the reservoir and *Alnus rhombifolia* expanded along lake margins (Fig. 3c).

Myriophyllum is common in Searsville Lake sediments between ~908 and 680 cm (~1915 $\pm$ 2–1930 $\pm$ 2 CE) (Fig. 3c). The loss of *Myriophyllum* may record changes in water levels, or more probably follows the use of herbicides, applied aggressively in the reservoir from the early 1940s (possibly earlier) through 1975 to curb aquatic weeds (Smith 1963; Jones 2021) and, unsuccessfully, to control a runaway infestation of *M. aquaticum*, an invasive non-native milfoil likely introduced into California by 1933 (Wersal et al. 2022; Sutton 1985). *M. aquaticum* is dioecious and only female plants are found outside of South America (Orchard 1981). Consequently, here, it produces no pollen and propagates only vegetatively from shoot fragments (Hussner and Champion 2012), and so the disappearance of *Myriophyllum* pollen in Searsville Lake may ironically reflect an increase in *M. aquaticum* and an extirpation of a congener. In Upper Lake Marsh, which was apparently not treated with herbicides, *Myriophyllum* pollen is found throughout ULM Unit 3.

Historical records may also explain peaks in algal remains (*Botryococcus*, *Debarya*, *Pediastrum simplex*, *Cosmarium*), which are found in the lower section of the Searsville Lake core (Fig. 3c). Ecological data for *Debarya* are sparse and conflicting (Van Geel and van der Hamman 1978), but *Pediastrum* is interpreted as an indicator of oligotrophic to mesotrophic water conditions (Hielsen and Sørensen 1992; Kaufman et al. 2010; Anderson et al. 2020), as is *Cosmarium* (Spijkerman and Coesel 1998). The co-occurrence of abundant *Pediastrum* and *Myriophyllum* may suggest rather high-water levels with low turbidity conditions during that time period. The abrupt increase in *Pediastrum* from ~850 to ~745 cm (1919 $\pm$ 2–1925 $\pm$ 2 CE) may have been driven by the increase in the dam height, and subsequent water depth.

Pediastrum subsequently remained abundant in the sediments until 1929 $\pm$ 2–1930 $\pm$ 2 CE. It may have disappeared because of either the construction of The Causeway or reduced lake volume. More likely, it was eradicated by herbicide and algaecide treatments beginning no later than 1937 (Felin 1940) and continuing into the late 1960s (Smith 1963; Jones 2021). Between 34 and 45 kg of chloride of lime (CaOCl₃) was used every 2 weeks from May to September to reduce algae for swimmers (Felin 1940). Large quantities of copper sulfate were also used from 1943 to 1947 and again in 1952 and 1953 to control algae (Erwin 1947; "Note on copper sulfate and benechlor 1952–1953" 1952–1953; Jones 2021). Notably, all of the major peaks in *Pediastrum*, and the peak in *Debarya*, are followed by significant peaks in calcium detected by XRF analysis, corresponding to chloride of lime application (Stegner et al. 2023; La Selle et al. 2023).

By the 1920s, the entire south end of Searsville Lake had silted in, and an extensive willow wetland had taken hold (Bocek and Reese 1992). In sediments dating from ~1928 $\pm$ 2 to 1982 $\pm$ 1 CE, other wetland plants—Cyperaceae, *Typha latifolia*, and *Sparganium*—increased, which, along with elevated *Botryococcus*, a colonial alga often interpreted as a shallow water indicator (Batten and Grenfell 1996; Guy-Ohlson 1992), supports the historical record for exposure of former littoral sediments due to lowered reservoir levels. Following the 1929 construction of The Causeway, the lake expanded to the west, occasionally flooding nearby roads, and a delta began to form to the southwest in Middle Lake (Bocek and Reese 1992). Felin (1940) noted that the area to the south of the levee had become more like a pond than a lake, with shallow margins that supported the growth of *Chara*, *Potamogeton*, *Sparganium*, and deeper waters supporting *Polygonum*, *Typha*, and dense *Salix*. Pollen data provide strong support for these historical observations.

Most recently, several indicators suggest at least periodically higher lake levels. The increase in *Alnus* and Cyperaceae at Searsville Lake beginning around 415–410 cm (1993 $\pm$ 0.5–1995 $\pm$ 0.5 CE), and possibly an increase in *Sparganium* around 322–316 cm (2008 $\pm$ 0.5–2011 $\pm$ 0.5 CE) (Fig. 3c) are indicative, along with increases of Cyperaceae, *Typha*, *Sparganium*, *Myriophyllum*, and *Potamogeton* at Upper Lake Marsh above 81 cm (~1995 CE).

Conclusions

Records such as these from Upper Lake Marsh and Searsville Lake are critical in illuminating the environmental history of natural areas like Jasper Ridge. The microfossil record—along with the extensive historical record—has contributed to (1) a reconstruction of species and vegetation assemblages, (2) data on introduced species and species associated with human activities, (3) changes in limnological indicators of water quality and lake levels, and (4) potential information on the origin of wetlands and other aspects of the paleoenvironmental history of Jasper Ridge Biological Preserve for the last ~160 years.

Pollen assemblages suggest a discontinuous hydraulic connection since the mid-nineteenth century. At times, Searsville Lake and Upper Lake Marsh acted as separate basins, recording differences in local vegetation, yet throughout recording also longer-term trends in landscape evolution. Widespread logging and grazing resulted in a relatively open vegetation with minimal oak and sequoia during the nineteenth century, overprinting any climatic record from the end of the cool Little Ice Age. Greater development of forest and oak woodland, and perhaps chaparral, occurred in the twentieth century, with the recovery of forests composed of *Sequoia sempervirens*, *Quercus*, *Notholithocarpus densiflorus*, and planting of *Eucalyptus*, among others. Forest expansion occurred at the expense of more open-ground plants, including ruderal species, as the impact of grazing animals declined.

Little evidence of invasive species introductions was encountered in these sediment core, probably because many had become established prior to the initial deposition of our records. Invasive species include those associated with pasturage (*Rumex*, *Plantago*), landscape disturbance (*Urtica*, Amaranthaceae), planting for wood production and wind barriers (*Eucalyptus*), and agriculture. Cereal crops were more common in the early twentieth century than subsequently, but cultivated trees—*Juglans* and *Olea*—are more common since the 1930s. These changes testify to the complex landscape history of the region.

The aquatic and wetland and microfossil record represents an important component of the total paleoenvironmental story. Early, evidence of rooted aquatic plants is nearly non-existent, probably because of a low groundwater table. When groundwater tables later rose, floating leaved aquatic plants became established. The paucity of pelagic algae suggests shallow water at Upper Lake Marsh throughout the record. Rooted aquatics became established early in the history of Searsville Lake; only later did floating-leaved aquatic plants become established, and pelagic algae suggest higher reservoir levels possibly associated with the raising of the dam or levee construction.

The adjacent wetland area showed complex changes, often associated with fluctuating lake levels and local construction, highlighting the effects of reservoir management and suburban development on vegetation. *Alnus rhombifolia* became quite common by the early twentieth century then declined beginning around 1920, when the dam was raised, flooding this area of the drainage. Higher in the Searsville Lake profile, in the 1990s and early 2000s, wetland indicators increased substantially as sediment influx reached the point where open water transformed into the land that supported a prograding riparian woodland.

The stratigraphies of several microfossils are tied to known historical events, for example, the raising of the dam which led to deeper water and environments favorable for *Pediastrum*, or the development of the Corte Madera and Middle Lake deltas which created a habitat for *Salix*. Near the top of the Upper Lake Marsh profile, wetland and shallow water indicators increase substantially, perhaps suggesting consistently higher water levels.

Analysis of the different sedimentary proxies from these cores is a powerful interpretive tool. By pairing the paleoecological and historical records, we have been able to reconstruct the previously undocumented ecological outcomes of human activities, including changes in land use, pesticide application, water level modification, and recreation, among others. Studies such as these provide fundamental information to managers and researchers by expanding the scope of observations conducted over the lifetime of any individual. Using this information, managers can determine pathways to achieve the best possible results for management and preservation.

Declarations

Competing Interest The authors have no relevant conflicts of interest to disclose.

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