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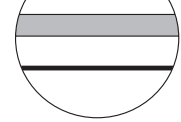
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# Holocene and historical vegetation change and fire history on the north-central coast of California, USA

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and Douglas J Hallett<sup>3</sup>

## Abstract

Pollen, non-pollen palynomorphs (NPPs), and charcoal particle stratigraphies are used to determine environmental change at Glenmire, Point Reyes Peninsula, northcentral coastal California, over the last c. 6200 years. Pollen was not preserved in early Holocene sediments when climate was drier than present. However, groundwater tables rose after c. 6200 cal. BP, allowing for greater subsequent preservation of organic matter. Middle and late Holocene environments were a mosaic of vegetation types, including mixed conifer forest with coastal scrub grassland prior to c. 4000 cal. BP. Subsequently, hardwoods such as alder (*Alnus*) and coastal scrub (e.g. *Artemisia*, *Baccharis*) expanded until c. 2200 cal. BP, followed by tanoak (*Lithocarpus densiflorus*), Douglas fir (*Pseudotsuga menziesii*), and coast redwood (*Sequoia sempervirens*). With increasing amounts of oak (*Quercus*), this mosaic of vegetation types continued to dominate until the arrival of Euro-Americans in the early to mid-1800s. The fire history is probably tied closely to human settlement, since natural ignitions are rare. Elevated charcoal amounts coincide with increased sedentism of the native populations by about 3500 cal. BP. Increased sedentism may have caused a more intense and constant use of the coastal environment around Glenmire. For the most recent centuries, we compared historical records of explorations, Spanish Mission establishment, consolidation of the native Coast Miwok population, ranching by Mexican nationals, and dairying by Americans at the height of California's gold rush with the paleoecological record. The Glenmire record thus documents changing fire use following the AD 1793 fire suppression proclamation; declines in native forest species; introductions of non-native species, including those associated with livestock grazing and land disturbance; and an increase in coprophilous fungi (NPPs) associated with the presence of large numbers of sheep and cattle, among other changes. During the historical period, the sedimentary record of historical fires closely matches the nearby fire-scar tree-ring record.

## Keywords

California, fire history, human impact, non-pollen palynomorphs, Point Reyes, pollen

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## Introduction

Point Reyes is a southwestward protruding peninsula of the central California coast immediately north of the San Francisco Bay area in Marin County (Figure 1). The peninsula is separated from mainland California by the trace of the San Andreas fault, which is expressed (from northwest to southeast) as the Tomales Bay, the Olema Valley, and Bolinas Lagoon. The Peninsula comprises the bulk of the modern Point Reyes National Seashore (PORE), which was established in 1962. It is a unique preserve, being a significant nature reserve and a working, agricultural landscape.

Although the region has a long archaeological and historical record, the context of vegetation and environmental change is not well known. Rypins et al. (1989) examined coastal exposures and a stratigraphic profile in a low-resolution record of vegetation change over the last c. 14,000 years, concentrating on the Late Pleistocene–Holocene transition. Somewhat higher resolution of the most recent c. 1000 years comes from Russell (1983) and Duncan (1992), who studied the pollen and charcoal from sediment cores from Wildcat Lake and Mud Pond, respectively. All these sites are in PORE. Short cores (c. 200 years) of coastal salt marsh sediments on the Peninsula were studied by Mudie and Byrne (1980), who used the occurrence of introduced exotic pollen types to determine changes in salt marsh sediment accumulation rates (SARs).

Russell's (1983) results suggested that fire may have been important in local vegetation changes during the last 1000 years. References to Native American burning practices are widespread

(e.g. Lewis, 1973; Vale, 1998, 2000, 2002; Whitlock and Knox, 2002), and the Coast Miwok were recorded as using fire during hunting, for clearing brush and accidentally (Duncan, 1992; Treganza, 1961). Coast Miwok also used fires to promote and maintain open grasslands, as documented in AD 1816 by the naturalist Adelbert von Chamisso: 'the natives are in the habit of burning the grass, to further its growth' (Chamisso and Choris, 1936). Tree-ring evidence on Point Reyes shows frequent surface fires continued through the 19th and into the early 20th centuries (Brown et al., 1999). Since historical records have shown that lightning fire is rare along California coast compared to other regions in California (Keeley, 2005; Stephens and Libby, 2006), most fires, including those prior and subsequent to Euro-American settlement, were likely human-set fires.

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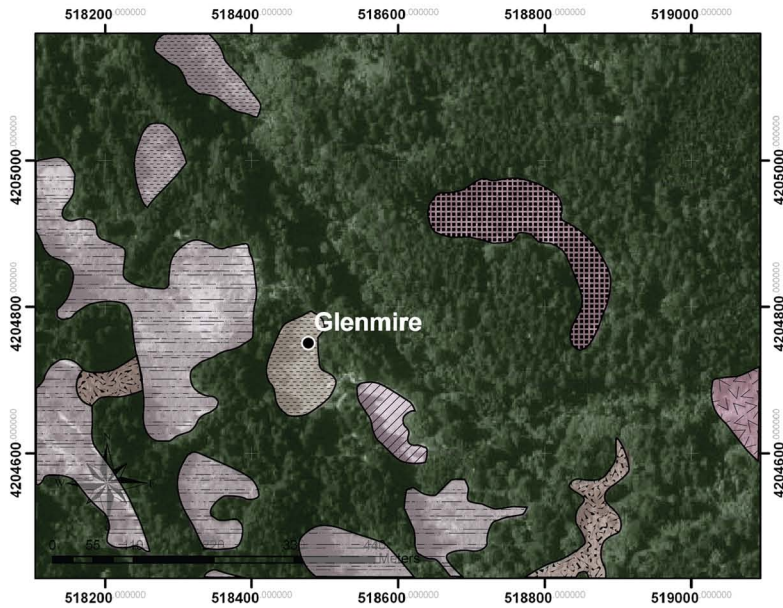
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# GLENMIRE CORE SITE









## Legend

- Core Site

## POINT REYES NATIONAL SEASHORE VEGETATION MAP

### ALLIANCE

- |                                                                                                                       |                                                                                                                |
|-----------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------|
|  <i>Scirpus - Typha - Eleocharis</i> |  <i>Baccharis pilularis</i>   |
|  <i>Umbellularia californica</i>     |  <i>Pseudotsuga menziesii</i> |
|  <i>Rhamnus californica</i>          |  <i>Juncus sp.</i>            |



**Figure 1.** Location of Glenmire study site with vegetation associations directly around the mire.

We report here on a *c.* 6200-year record of vegetation change and fire history from a small site in PORE – Glenmire. This record is important in providing the context of middle and late Holocene vegetation change in the region that has remained somewhat of a mystery. In addition, we also present the first high-resolution fire history for the northcentral coast for this time period and speculate on the influence of human activities on the fire record. The record from Glenmire is also important for determining change in more recent times. We use fine-resolution pollen and spore stratigraphy for sediments deposited during the last few centuries to expand our knowledge of environmental change during the historical period, when documents recorded the progression of Euro-American settlement but not the detailed shifts in plant communities that accompanied those changes. This includes the first comprehensive documentation of non-pollen palynomorphs (NPPs) from a site in California, including those spores most characteristic of local grazing by introduced sheep and cattle. NPPs are microorganisms of diverse origin – for example, fungal spores, algal remains, protozoa, and bacteria – recovered in standard pollen preparations. These remains provide valuable on-site paleoenvironmental and land-use information, such as for grazing, fires, erosion, eutrophication, and water-level oscillations (Van Geel, 2001). As local bio-indicators, they are excellent proxies that supplement the often regional pollen information in paleoenvironmental research. Even though the systematic study of NPPs has become more frequent during the last decade in Europe and elsewhere (e.g. Ejarque et al., 2011; Gauthier et al., 2010; Montoya et al., 2012), their widespread use in latest Holocene sediments from North America is rare.

Such retrospective studies provide important baseline information for land managers (1) to determine appropriate strategies for restoration of ‘natural’ vegetation to National Parks, and (2) to provide significant information regarding the late Holocene cultural shaping of the Point Reyes peninsula’s landscape. Thus, our research may be useful both for re-introduction of natural processes such as fire into locations modified by recent human impacts and fire exclusion policies, as well as the development of sustainable socio-environmental management strategies in future decision making.

## Background on human history of the region

Archaeological studies within the San Francisco Bay region have documented long-term human occupation dating back to the early Holocene. From over 200 prehistoric archaeological sites documented in the Bay area, 28 are located within Marin County and PORE (Milliken et al., 2007). Duncan’s Landing Cave, less than 48 km north of PORE headquarters, is the oldest archaeological site in the North Coast, dating back to *c.* 7000 cal. BC (Kennedy et al., 2005; Wake and Simons, 2000). This mainly shellfish-oriented site documents the reliance on coastal resources by early mobile forager communities inhabiting the Bay region. Around 3500 years ago, peoples related to the Coast Miwok, who existed on a semi-sedentary to sedentary economy of hunting, gathering, and fishing, occupied the Bay and surrounding coastline region (Milliken et al., 2007; Moratto, 1984). The period between 500 cal. BC, and most specifically from 200 cal. BC to 430 cal. AD, marks a ‘cultural climax’ in the region (Milliken et al., 2007),

with the proliferation of coastal sites, including the first occupation of Point Reyes on Tomales and Drake's Bays, a material culture diversification and a focus on acorn-processing as dominant subsistence trait (Stewart, 2003). After a cultural disruption from AD 430 to AD 1050, with the abandonment of several sites and the collapse of regional trade networks, a new level of cultural complexity was reached from AD 1050 up to the contact period, with higher levels of sedentism, increasing social stratification, and wealthier burial offerings (Milliken et al., 2007).

The arrival of Sir Francis Drake and his *Golden Hinde* expedition in the summer of 1579 (Heizer, 1947) began the *encuentro* period (Duncan, 1992) between native and emigrant peoples. Subsequent expeditions recorded the character of the region, including Vizcaíno in 1602, Vancouver in 1792, Von Kotzebue in the 1810, and others (Duncan, 1992). By the *encuentro* period, coastal communities were organized in permanent villages, with at least seven villages identified in the ethnographic literature in or near PORE (Compas, 1998). These villages were of considerable size, as reported by the Portuguese explorer Sebastian Rodriguez Cermeño, who in his Point Reyes expedition of 1595 estimated that there were 150 inhabitants in one of the settlements he encountered (Wagner, 1929). Subsequent changes in both the native populations and the nature of the landscape were severe. The Mission of Our Seraphic Father San Francisco, commonly known as Mission Dolores, was founded near San Francisco in 1776 (Milliken, 1995), but the Point Reyes Peninsula came under jurisdiction of the Mission at San Rafael as late as 1817 (Brown et al., 1999; Livingston, 1994). By the middle of the 19th century, the region played a pivotal role in supplying food and materiel to the growing San Francisco metropolis.

## Site setting

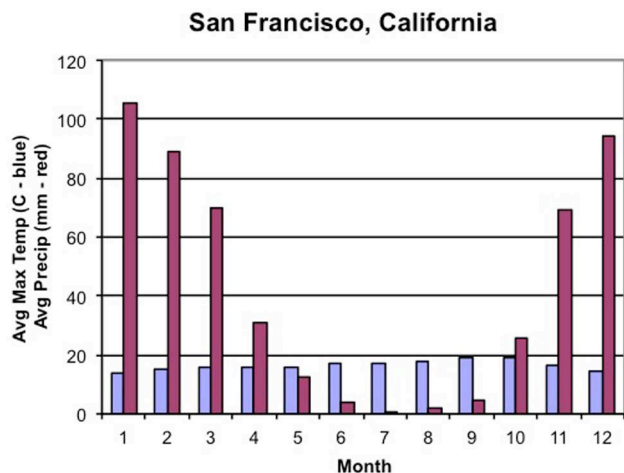
Glenmire (informal name) occurs in the southeastern portion of the Peninsula in western Marin County, California. It is a small wetland depression at 167 m elevation at 37° 59' 24.94" N, 122° 47' 22.61" W. The depression sits within the Wildcat slide complex (Clague, 1969), one of a series of late Quaternary landslides within the weakly consolidated Santa Cruz Mudstone (Upper Miocene), a thin-to-thick bedded siliceous mudstone that partially overlaps the Monterey Formation along the Point Reyes coast (Clark and Brabb, 1997).

### Modern climate

The climate of the San Francisco, Point Reyes region is essentially Mediterranean, with cool, moist winters and cool, dry summers. Long-term climate data for San Francisco c. 40 km southeast of Glenmire, but also near sea level, shows little variability in average maximum temperature during the year, with average monthly highs of 14.1°C and 18.9°C in January and September, respectively (Figure 2; Western Regional Climate Center (WRCC), accessed 15 January 2013). Average monthly precipitation varies from a high of 105.4 mm in January to near absence during July, and an annual average of 508 mm of precipitation.

### Modern vegetation

The vegetation of Point Reyes consists of at least seven distinct types. Primarily, in the southeast of the peninsula along Inverness Ridge is the Douglas fir–mixed evergreen forest, with dominants *Pseudotsuga menziesii*, California bay (*Umbellularia californica*), tanoak (*Lithocarpus densiflorus*), and coast live oak (*Quercus agrifolia*), and a diverse shrub understory. The coast redwood (*Sequoia sempervirens*) forest is found in the extreme southeast, with many species of the mixed evergreen forest. More extensive stands of the tree are found on Bolinas Ridge to the east of the San



**Figure 2.** Modern climate – precipitation and temperature – annual averages for San Francisco, California.

Andreas fault. Bishop pine (*Pinus muricata*) forests occur in the northeast. Other species include madrone (*Arbutus menziesii*), tanoak, coast live oak, and California bay. A dense understory of blue blossom (*Ceanothus thyrsiflorus*) and Marin manzanita (*Arctostaphylos virgata*) often occurs with the pines ([http://www.nps.gov/pore/parkmgmt/firemanagement\\_fireecology\\_vegtypes.htm](http://www.nps.gov/pore/parkmgmt/firemanagement_fireecology_vegtypes.htm)).

Maritime chaparral is rare, limited to the extreme southeast of the peninsula, with common species of Eastwood's and glossyleaf manzanita (*Arctostaphylos glandulosa* and *Arctostaphylos nummularia*), chamise (*Adenostoma fasciculatum*), and giant chinquapin (*Chrysolepis chrysophylla*). Coastal scrub is one of the most widespread vegetation types. Dominants include coyote brush (*Baccharis pilularis*), coffeeberry (*Rhamnus californica*), thimbleberry (*Rubus parviflorus*), California blackberry (*Rubus ursinus*), poison oak (*Toxicodendron diversilobum*), and blue blossom.

Grasslands, both native and grazed lands, cover much of the west and northwest of the Peninsula, primarily at elevations just above sea level. Here, 80% of grasslands are dominated by non-native species, including Italian wild rye (*Lolium multiflorum*), farmer's foxtail (*Hordeum murinum*), and rattail fescue (*Vulpia* spp.). Native grasses include tufted hairgrass (*Deschampsia cespitosa*), California oatgrass (*Danthonia californica*), brome (*Bromus carinatus*), and meadow barley (*Hordeum brachyantherum*). Coastal dune vegetation, found primarily along the western shore, comprises dune sagebrush (*Artemisia pycnocephala*), coast buckwheat (*Eriogonum latifolium*), dune lupine (*Lupinus chamissonis*), and goldenbush (*Ericameria ericoides*) ([http://www.nps.gov/pore/parkmgmt/firemanagement\\_fireecology\\_vegtypes.htm](http://www.nps.gov/pore/parkmgmt/firemanagement_fireecology_vegtypes.htm)).

Glenmire itself occurs within the closed canopy of Douglas fir–mixed evergreen forest with California bay and California live oak, and with adjacent patches of more open coyote brush chaparral (Howell, 1985) (Figure 1). Within the understory, and occurring in patches within the forest, are hazelnut (*Corylus cornuta* var. *californica*), California huckleberry (*Vaccinium ovatum*), coyote brush, California blackberry, thimbleberry, oceanspray (*Holodiscus discolor*), California coffeeberry, and western poison oak and many herbs. Reed canary grass (*Phalaris arundinacea*) dominates the edge of the wetland, along with sedges (*Carex* sp.), bull thistle (*Cirsium vulgare*), fireweed (*Erechtites minima*), cow parsnip (*Heracleum lanatum*), poison hemlock (*Conium maculatum*), coast tarweed (*Madia sativa*), and others. Within the wetland itself, bur-reed (*Sparganium eurycarpum*) and rush (*Juncus effusus*) dominate, with mannagrass (*Glyceria leptostachya*),

cowweed (*Gnaphalium palustre*), common plantain (*Plantago major*), lady's thumb (*Polygonum persicaria*), and knotweed (*Polygonum punctatum*). The terminology follows Hickman (1993).

## Methods

Sediment cores were extracted from the marsh using a modified Livingstone sediment corer (Wright et al., 1984) in *c.* 30 cm of water without a raft. The cores were wrapped in plastic wrap and foil, transported back to the Laboratory of Paleocology (LOP) at Northern Arizona University and placed in long-term storage in a cooler at a consistent 5°C.

In the lab, sediment stratigraphy was determined by splitting the Livingstone cores and noting the location of major stratigraphic and color changes. Magnetic susceptibility (MS; Sandgren and Snowball, 2001) of the sediments was measured with a Sapphire II meter recording MS continuously but through overlapping 5-cm intervals. Pollen analysis followed a modified Fægri and Iversen (1989) procedure. After addition of two *Lycopodium* tracer tablets for calculation of pollen concentration, 1 cc of sediment was treated with KOH for deflocculation, then HCl and HF, and finally acetolysis. Sample residues were stained, suspended in silicone oil, and examined at 400–1000× using a light microscope, with comparison to the modern pollen reference collection at the LOP. Pollen was identified to the lowest taxonomic level possible. Both pines (*Pinus*, both diploxylon and haploxylon) and carrot family (Apiaceae) were differentiated into morphotypes. When possible, members of the Cupressaceae and Taxodiaceae (*S. sempervirens*) were differentiated from each other. Sunflower family (Asteraceae) pollen was identified as wormwood/sagebrush (*Artemisia*), ragweed (*Ambrosia*), thistle (*Cirsium*), dandelion-type (cf. *Taraxacum*, Lactuceae), and other Asteraceae. NPPs were identified in the pollen preparations, and identified by personal collections and published sources (e.g. Haas, 1996; Jankovská, 1991; Van Geel, 2001; Van Geel and Aptroot, 2006). NPP nomenclature follows Miola (2012), and types were assigned to an existing code when already described and published in the specialized bibliography (e.g. type numbers prefixed HdV refer to those identified at the Hugo de Vries Laboratory, University of Amsterdam). The raw counts were transformed to pollen and spore percentages based on the sum of terrestrial pollen. Complete pollen data are deposited in the North American Pollen Database (<http://www.ngdc.noaa.gov/paleo/pollen.html>). We used constrained incremental sums of squares (CONISS) to zone (Grimm, 1987) and C2 software version 1.7.2 (Juggins, 2011) to graph the pollen and spore data.

High-resolution sedimentary charcoal analysis involved 5-cc contiguous (every 5-mm of depth) sediment samples using the method of Whitlock and Anderson (2003). A total of 10 mL of sodium hexametaphosphate was added to each sample in a beaker for dispersing the sediment. The sediment mixture was stirred, disaggregated for 48–72 h, then sieved through 125- and 250-µm mesh sieves. Charcoal particles were identified and tallied using a binocular dissecting microscope. Charcoal influx (number of particles/cm<sup>2</sup>/yr) was calculated by multiplying the concentration (particles/cm<sup>3</sup>) by the SAR (cm<sup>2</sup>/yr).

The chronology for Glenmire was developed by a combination of methodologies. For the upper portion of the record, we assigned two historical ages, one corresponding to the suppression of Native American burning and the other to the initiation of Euro-American settlement on the Peninsula. The settlement period was identified by increases in pollen indicators of grazing and land disturbance (i.e. dock (*Rumex*), plantain (*Plantago*), filaree (*Erodium*), *Eucalyptus*) as well as the increase in spores of coprophilous fungi. Older portions of the cores were dated by <sup>14</sup>C

accelerator mass spectrometry (AMS) on macroremains, or in the case of the lowest age, by bulk dating. All ages were calibrated to calendar years before present using CALIB 6.0 (<http://calib.qub.ac.uk/calib/calib.html>), which is based on the IntCal09 calibration data set (Reimer et al., 2009). Ages are reported in calendar years before 1950 (cal. BP). We used CLAM v2.0 (Blaauw, 2010) to produce the age–depth model. CLAM calculates the best-fit age–depth using different curve types, and as the weighted average of 10,000 iterations.

## Results

### Stratigraphy and chronology

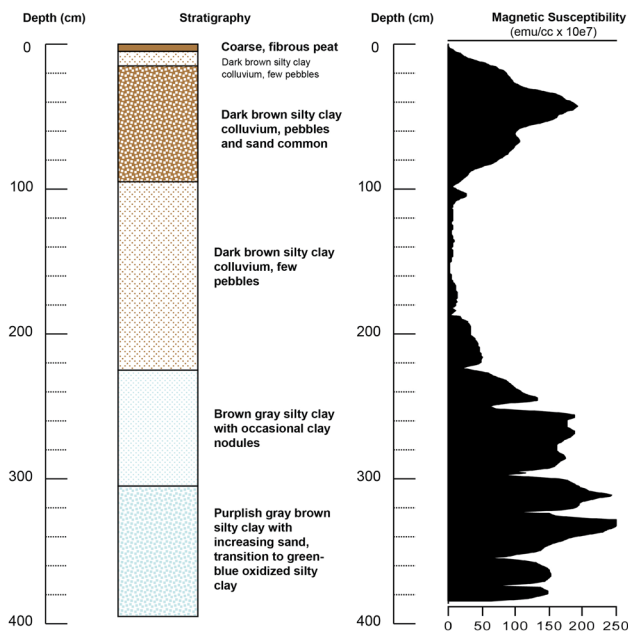
Glenmire core 98-03 consists primarily of 385 cm of silty clays. A coarse fibrous peat cap of 5 cm overlays dark brown silty clay colluvium with little sand and few pebbles to *c.* 225 cm depth (Figure 3). However, depths of 17–89 cm within that section contained abundant sand and fine pebbles. Below this, to *c.* 306 cm was a brown-gray silty clay with occasional clay nodules. From *c.* 306 to the core bottom, a purplish-gray-brown silty clay with increasing sand occurs, with evidence of oxidation of sediments at the core bottom.

The chronology of the core comes from seven AMS <sup>14</sup>C ages and the two historical ages (Table 1). Radiocarbon ages occurred in stratigraphic sequence. Unfortunately, not enough organic matter was located to obtain a date on the bottommost sediments, and in fact, organic matter was much less below *c.* 220 cm than above. We considered the potential for a middle Holocene hiatus between *c.* 220 and 240 cm depth. However, we found no direct stratigraphic evidence for this, and the occurrence of well-preserved pollen in this interval also argued against a hiatus.

We determine historical ages of the sediments from changes in charcoal, pollen, and spores. We relate the decline in charcoal influx values between 104 and 102 cm to the 1793 fire suppression of Governor José Joaquín de Arrillaga banning ‘all kind of burning’ by the Indians in the Alta California under Spanish jurisdiction (Car, 1959). Regional settlement by the Spanish commenced by AD 1817 (see above), though one of the earliest ranches on Point Reyes was the Punta de los Ranches Sobrante, dating from 1839. Locally, however, ranching was established at the site by 1879 at the Shafter family’s Glen Ranch (Livingston, 1994, 1995). Using changes in pollen and spores indicative of local grazing, we determined that *c.* 100 cm depth corresponded to 1850, the time when a major development of an extensive dairy industry began at the Point Reyes Peninsula (Livingston, 1994). The first occurrence of the introduced *Eucalyptus* in the pollen record a few centimeters above this depth substantiates this date as *Eucalyptus* trees were first planted in San Francisco in 1850 and locally in southern Point Reyes in the early 1870s (Johnson, 1971; Mudie and Byrne, 1980). The resulting age–depth curve was based upon linear interpolation between historical and radiometric ages (Figure 4).

SARs are variable throughout the core. Below *c.* 220 cm, the SAR is *c.* 0.008 cm/yr (132.7 yr/cm). From *c.* 220 to 100 cm SAR varies from *c.* 0.023 to 0.079 cm/yr (12.7–42.7 yr/cm). Above 100 cm depth, the SAR increases substantially to *c.* 0.714 cm/yr (1.4 yr/cm). Increasing SAR in the upper part of the core allowed for fine-resolution pollen and NPP analyses for the historical period, with intervals between samples ranging from 2 to 14 years. MS values generally parallel the SARs. MS is generally high below *c.* 225 cm depth (Figure 3). Above *c.* 200 cm depth, however, MS values decline to near-zero values, corresponding with the visual increase in organic matter in the core. MS values for most of the upper 90 cm rise again, but fall to near-zero values near the top of the core.

# GLENMIRE CORE 98-03



**Figure 3.** Stratigraphy and MS for Glenmire core 98-03. MS: magnetic susceptibility.

## Pollen, NPP, and charcoal stratigraphy

Pollen and NPP preservation is excellent in the core for the most recent 6200 cal. yr (*c.* 245 cm), but pollen is essentially absent below *c.* 260 cm depth. Pollen percentages of the most common tree and shrub taxa (Figure 5), herbs, introduced and riparian pollen taxa, and spores (Figure 6) are shown. Figure 7 displays main NPPs percentages found at Glenmire. Charcoal was not recovered from sediments dating older than *c.* 4200 cal. BP (i.e. below 230 cm depth). Charcoal particles influx obtained is shown in Figure 8. CONISS analysis of the terrestrial pollen assemblages identified three pollen zones above the sterile section at the core bottom.

**Zone GM-III (251–190 cm; *c.* 7000–2050 cal. BP).** Throughout this zone, terrestrial pollen is dominated by conifers – *Pinus*, *Pseudotsuga menziesii*, and Cupressaceae/Taxodiaceae, with minor amounts of *S. sempervirens* – along with small amounts of *Quercus* and *Alnus* (probably *Alnus rubra*). Important terrestrial non-arboreal pollen types include members of the aster family (Asteraceae), *Artemisia*, Rhamnaceae, Rosaceae, *Eriogonum*, and Poaceae (Figure 5) and members of the Amaranthaceae (Figure 6). *Pinus* exhibits two distinct peaks in abundance, at *c.* 5400 and 2700 cal. BP, with Poaceae pollen dominating the intervening period (Figure 5). After *c.* 4000 cal. BP *Alnus* and *C. cornuta* var. *californica* become more important (Figure 5), followed by the establishment of *L. densiflorus* and a substantial increase in *S. sempervirens* after *c.* 2200 cal. BP. Dominant wetland pollen and spore types include sedges (Cyperaceae) and ferns (Figure 6) with the aquatic *Azolla* (waterfern). Other NPP (Figure 7) dominants include zygnetaceous spores of green algae such as *Spirogyra* and increasing amounts of *Zygnema*-type after *c.* 4000 cal. BP. Charcoal influx to Glenmire is minimal, but not non-existent, in this zone. A slight increase in charcoal influx occurs near the end of the zone (Figure 8).

**Zone GM-II (190 cm–103 cm; *c.* 2050 cal. BP–AD 1793).**

Conifers continue to dominate pollen assemblages during this zone but with dominance by *S. sempervirens* and *P. menziesii* (up to *c.* 1000 cal. BP) instead of *Pinus* and Cupressaceae (Figure 5).

Pollen of *Quercus*, *Alnus*, *Lithocarpus*, and *Corylus* dominates the hardwood component. Asteraceae, *Artemisia*, and Rosaceae continue to dominate the shrub pollen, though at somewhat lesser amounts than in the previous zone, but with increased California lilac (*Ceanothus*). After an initial decline, Poaceae pollen reaches its late Holocene maximum. However, after *c.* 1000 cal. BP, *P. menziesii* declines, while pollen of Asteraceae increases.

Dominance by Cyperaceae and ferns in the previous zone gives way to pollen of species of Apiaceae (carrot family) and *Typha latifolia* (cattail). A higher presence of *Azolla* spores and the later appearance of *Potamogeton* (pondweed) are also reported (Figure 6). Among algal remains, the NPP record include a maximum in *Spirogyra*, with a higher representation of the type HdV-130, and *Zygnema*-type spores, together with increasing values of *Botryococcus*. This is concomitant with the occurrence of oocytes of the *Turbellaria* class flatworms, including *Gyatrix hermaphrodites*, and the later reporting of rotifer resting eggs (*Anuraeopsis fissa*) (Figure 7). The increasing recording of fungal spores, including the fire-related fungus *Gelasinospora* sp., is also recorded in this zone.

Charcoal influx increases substantially in the period between *c.* 2200 and 1000 cal. BP, with three obvious spikes in charcoal at 2040, 1552, and 1035 cal. BP (Figure 8). Charcoal influx declines by almost an order of magnitude after *c.* 1000 cal. BP, in concert with a decline in Douglas fir pollen. Charcoal is nearly absent in sediments of the late 18th to early 19th centuries.

**Zone GM-I (103 cm to core top; *c.* AD 1793 to present).** Major changes at the beginning of this zone include the decline of almost all arboreal pollen types – including the essential elimination of *Sequoia* and *Pseudotsuga* – with the continued importance of members of the Asteraceae and Poaceae (Figure 5). Instead, pollen of species considered exotic or invasive – filaree (*Erodium cicutarium*), plantain (*Plantago*), and members of the Amaranthaceae, Liguliflorae, Brassicaceae, Caryophyllaceae, Polemoniaceae, and particularly dock (*Rumex*) – increase at the opening of the zone (Figure 6), followed by thistle (*Cirsium*) somewhat later. In addition, the first occurrence of gum tree (*Eucalyptus*) pollen occurs. At the top of the record, in sediments dating since *c.* AD 1955, pollen percentages of *P. menziesii*, *Quercus*, and *Corylus* increase (Figure 5).

Pollen and spores of other wetland species are much diminished in this zone. This includes the near absence of *Spirogyra* (Figure 7). NPP percents include the highest amount of undifferentiated fungal spores in the record, as well as occurrence or maxima of several coprophilous fungi, including *Sporormiella*-type, *Sordaria*-type, *Cercospora* sp., *Podospora* sp., *Coniochaeta* cf. *lignaria*, and *Chaetomium* sp. (Figure 7). Oocytes of the *Turbellaria* class disappear along the zone to reappear at the uppermost part, together with the renewal of rotifer eggs (*A. fissa* and *Brachionus*).

Charcoal influx values rise again after *c.* AD 1850, reaching some levels of influx found during the previous zone. However, in sediments deposited subsequent to *c.* 1963, little charcoal is found (Figure 8).

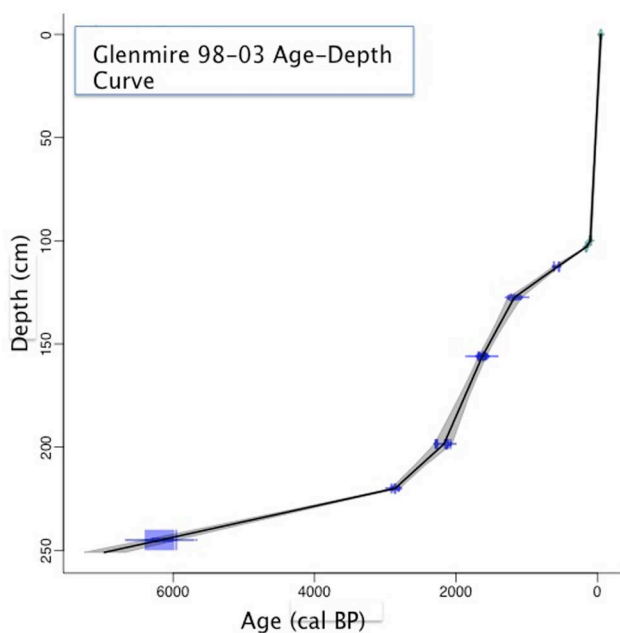
## Discussion

Few sites from lakes or bogs along the middle California coast extend back into the Pleistocene. Consequently, the long-term vegetation history of the region remains poorly known. The longest record to date is found at Laguna de las Trancas, near Santa Cruz, *c.* 95 km south of Point Reyes (Adam et al., 1981; Heusser, 1982), which spans perhaps the last 55,000 years (Anderson et al., 2004). There, a *Pinus*–*Pseudotsuga menziesii*–*Abies* forest transitioned to one dominated by *Pseudotsuga menziesii*, *S. sempervirens*, *Alnus*, and *Quercus* by the start of the Holocene with grassland openings

**Table 1.** Dating of sediments for the Glenmire Core 98-03, Point Reyes Peninsula, California.

Laboratory number	Depth (cm)	Age (Historic, <sup>14</sup> C)	Standard deviation (±)	<sup>13</sup> C/ <sup>12</sup> C	Cal. BP (2 SD)	Median probability	Date type	Material dated
N/A	0	AD 1998	N/A	N/A	-48	-48	Surface	N/A
N/A	100	AD 1850	N/A	N/A	100	100	Historic/pollen	N/A
N/A	103	AD 1793	N/A	N/A	157	157	Historic/charcoal	N/A
UCIAMS 77392	112–113	550	15	-28.1	527–557	547	AMS	Charcoal, insects, misc. plant fragments
Beta-157440	127–128	1240	40	-30.9	1068–1270	1179	AMS	<i>Pseudotsuga</i> needles
Beta-157441	156	1710	40	-26.8	1536–1708	1619	AMS	<i>Pseudotsuga</i> needles
UCIAMS 77393	174	1720	15	-25.2	1566–1638	1630	AMS	Wood, misc. plant fragments
UCIAMS 69110	196–201	2150	20	-28.6	2096–2159	2143	AMS	Leaf fragments, charcoal
UCIAMS 69111	219–221	2770	20	-28.3	2791–2925	2863	AMS	Rootlets, leaf fragments
Beta-125978	240–250	5410	110	-25	5982–6402	6189	Bulk	Sediment

AMS: accelerator mass spectrometry.



**Figure 4.** Age–depth relationships for the Glenmire core 98-03.

(Anderson et al., 2004). Perhaps due to the low-resolution record, few changes were noted in the pollen-stratigraphy of the Holocene (Adam et al., 1981). Regionally, the pollen from ODP Site 1019 of the northern California coast shows Late Pleistocene assemblages dominated by *Pinus* and *Artemisia* into the Younger Dryas (YD) cold interval (Barron et al., 2003). By the close of the YD at *c.* 11,500 cal. BP, decline in both *Artemisia* and *Pinus* occurred with increases in *A. rubra* and *Quercus* that persisted into the Holocene. In studying the Pleistocene–Holocene transition at Point Reyes, Rypins et al. (1989) examined three sites on the Peninsula. Prior to *c.* 14,000 cal. BP, the peninsula supported a *P. menziesii*–*Abies* forest. However, between *c.* 12,000 and 10,600 cal. BP, forest gave way to coastal sage scrub and grassland as a generally modern climatic regime became established. Again, little change was noted in the Holocene portion of this record.

Russell (1983) examined a *c.* 3-m core from nearby Wildcat Lake, which was believed to record the most recent 1000 years of vegetation change there. Situated presently within the coastal sage scrub community but near the coastal forest, little change in vegetation occurred during this time period beyond the

fluctuations in percentages of grass and coastal scrub pollen. However, the introduction of non-native species such as *Erodium*, *Plantago lanceolata*, and *Rumex* was registered near the top of the record. The nearby Mud Pond record (Duncan, 1992) is also a 1000-year record, documenting a mixture of mixed conifer–*Quercus* forest and grassland openings there. These studies leave a gap in our understanding of middle and late Holocene environments, and the record from Glenmire helps to fill that gap.

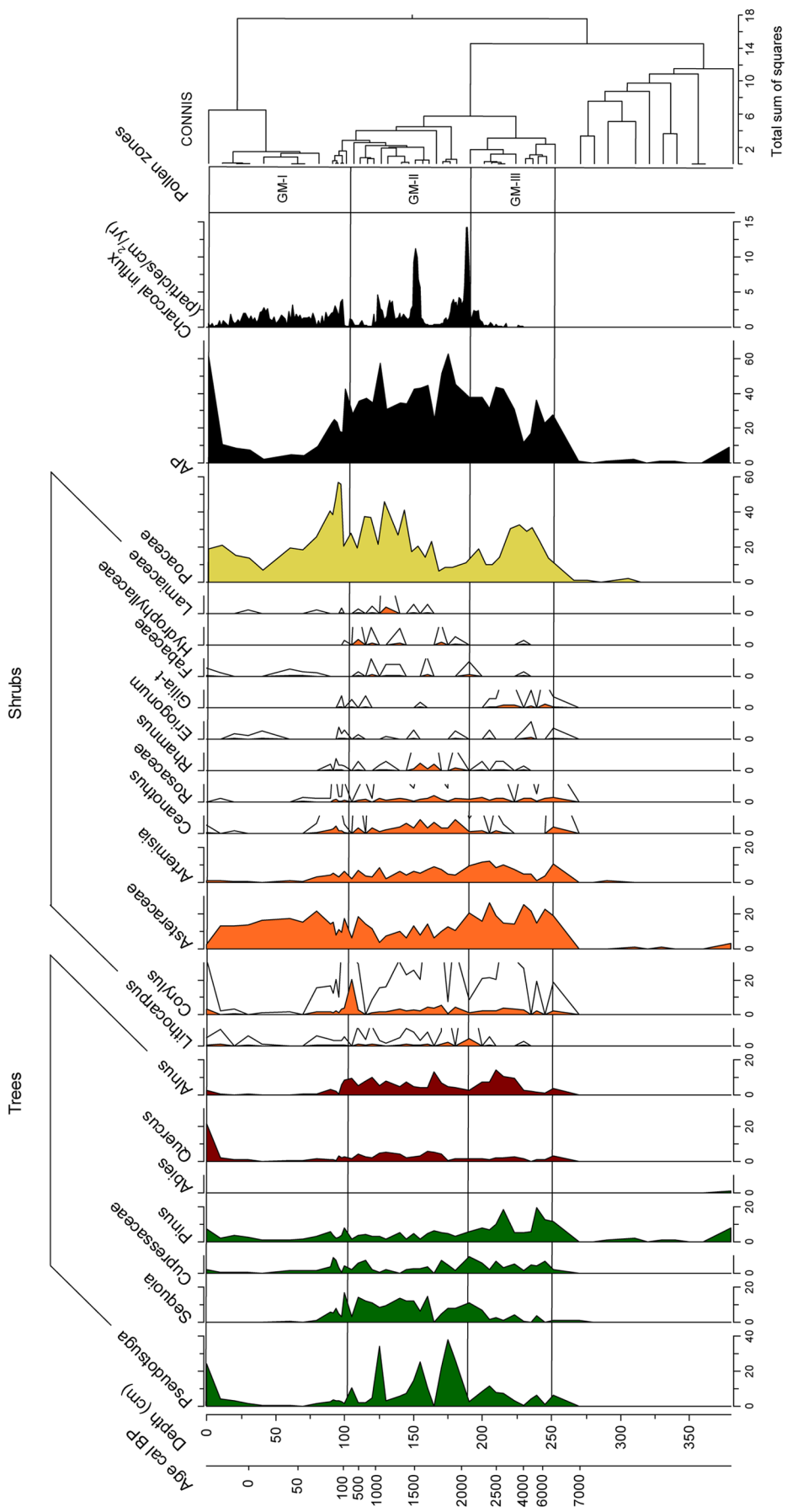
#### Early to middle Holocene

Marine cores from northern California suggest vegetation and climate change linked in part to oceanic circulation. An enhanced northerly flow of warmer subtropical waters increased sea surface temperatures up to *c.* 1.5°C (Barron et al., 2003) prior to *c.* 9000 cal. BP (Barron and Bukry, 2007). Pollen evidence (Barron et al., 2003) showed regional coastal vegetation dominated by *Alnus* and *Pinus*, which were interpreted as warmer winters and drier conditions onshore. These conditions persisted into the middle Holocene, when by *c.* 5200 years ago, the pollen record became dominated by *S. sempervirens*, indicating more mesic conditions with cooler summers. This situation was interpreted by Barron and Anderson (2011) as a greater persistence of La Niña-like or negative Pacific Decadal Oscillation (PDO) phase as compared with today. Similarly, the early Holocene record from Glenmire suggests local conditions were generally more arid at that time. Sediments deposited before *c.* 6200 cal. BP (essentially the bottom 1.5 m) contain little organic matter, including virtually no charcoal or palynomorphs. This suggests to us that groundwater tables were either quite low, or fluctuated widely, a situation that would not have allowed for organic matter preservation at this site.

#### Middle to late Holocene at Glenmire

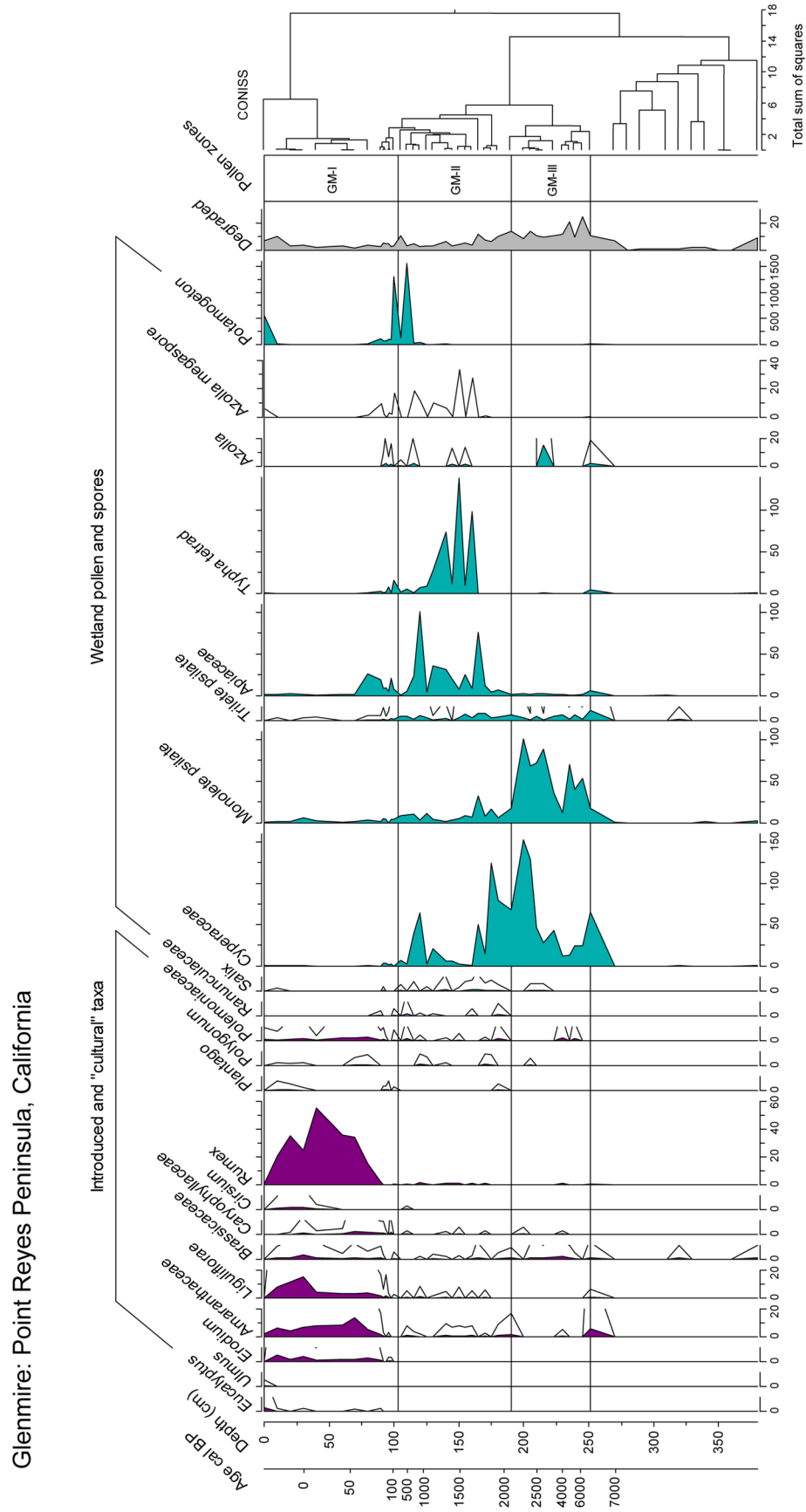
The record from Glenmire is little different than regional pollen record of Barron et al. (2003). At Glenmire, by *c.* 6200 cal. BP, the abundance of sedges and ferns, high concentrations of *Spirogyra*, and the recording of *Zygnema*-type spores suggest a more permanent shallow freshwater environment, perhaps existing under somewhat eutrophic conditions (Van Geel et al., 1989). However, very slow SARs and high MS values are consistent with continuation of intense decomposition of organic matter in the marsh during this time. Certainly, by the middle Holocene, the modern coastal *P. menziesii*–mixed conifer–hardwood forest

Glenmire: Point Reyes Peninsula, California



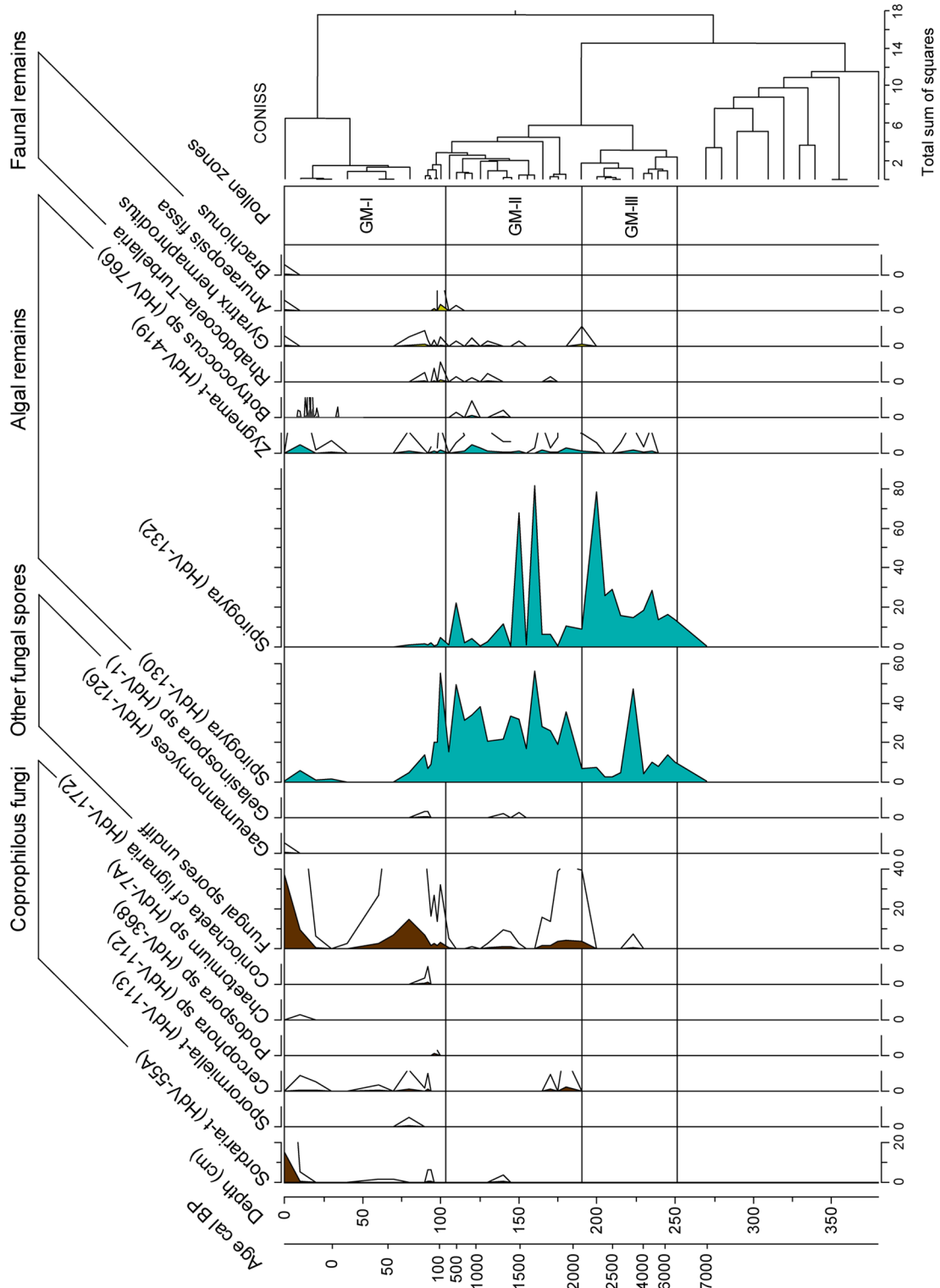
**Figure 5.** Summary of terrestrial pollen percentages for Glenmire core 98-03, along with CONISS cluster analysis zonation and charcoal particle influx. Exaggeration curve is 10 $\times$ . CONISS: constrained incremental sums of squares.





**Figure 6.** Summary exotic introduced and wetland pollen and spores for Glenmire core 98-03, along with CONISS cluster analysis zonation. Exaggeration curve is 10 $\times$ . CONISS: constrained incremental sums of squares.

# Glenmire: Point Reyes Peninsula, California

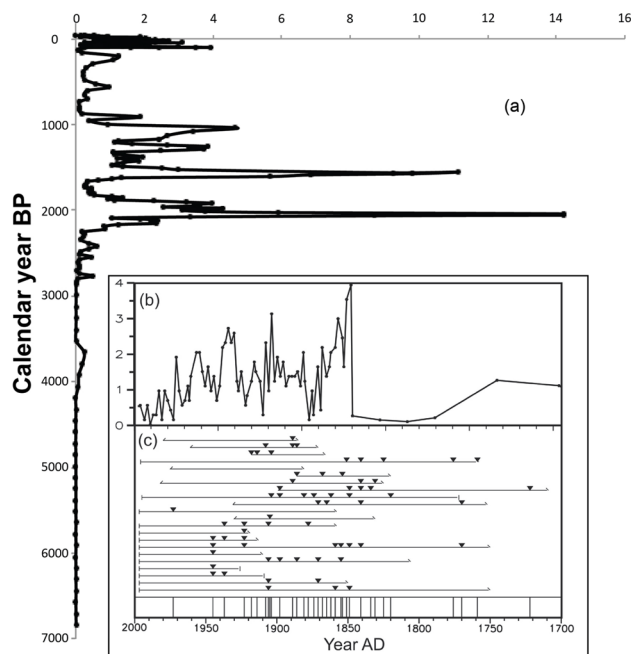


**Figure 7.** Summary NPP spores for Glenmire core 98-03, along with CONISS cluster analysis zonation. Exaggeration curve is 10x. NPP: non-pollen palynomorph; CONISS: constrained incremental sums of squares.

was established near the site. This forest consisted not only of Douglas fir, but also coast redwood and pines with minor amounts of oak, red alder, and hazelnut. Significant openings in the forest occurred as witnessed by the importance of pollen of coastal scrub and chaparral species, as well as members of the aster family and of grasses. Today, these openings are occupied by abundant coyote brush (*B. pilularis*) and California sagebrush (*Artemisia californica*), and it is likely that was the case in the middle Holocene as well.

After c. 4000 cal. BP, vegetation around the marsh shifted toward greater *P. menziesii*, *Alnus*, and *Corylus*, followed by increases in *S. sempervirens* and *Lithocarpus* by c. 2200 cal. BP. These vegetation changes are consistent with trend toward increasing moisture – and perhaps fog precipitation – that would have particularly favored *S. sempervirens* and *P. menziesii* at the expense of pines. The change at c. 4000 cal. BP could be partially explained by a recent reconstruction of regional El Niño Southern Oscillation (ENSO) for the eastern north Pacific which suggests

# CHARCOAL INFLUX (particles / cm<sup>2</sup> / yr)



**Figure 8.** (a) Charcoal particle influx (particles/cm<sup>2</sup>/yr) for the c. 6200 cal. BP Glenmire record. (b) Insets are the charcoal influx for the most recent 250 years compared with (c) the record of fire scars from tree-rings from the Pine Grove Redwoods site of Brown et al. (1999).

enhanced El Niño-like or positive PDO-like conditions here (Barron and Anderson, 2011). Certainly by c. 2000 cal. BP, the modern mixed conifer-hardwood forest with patches of coastal scrub and grassland was in place around Glenmire. The recording of fungal spores at this period can be related to increasing organic matter decomposition from the surrounding hardwood forest. During this latter period, the wetland flora continued to differentiate, with abundant shallow water green algae (*Spirogyra*, *Zygnema*-type, and *Botryococcus*) and floating *Azolla* along with patches of *T. latifolia*, and willows (*Salix*) and members of the Apiaceae growing along the water's edge. The occurrence of both Rhabdocoela oocytes (*Turbellaria* and *G. hermaphrodites*) and *A. fissa* resting eggs indicates low water-tables with higher organic matter input (Ejmsont-Karabin, 2012; Haas, 1996), also suggested by the sharp decline in MS values. Water-levels may have been considerably lower for a period from c. 1600 to 800 years ago, when *T. latifolia* and Apiaceae predominated, and may have been higher just before Euro-American settlement, when pondweed (*Potamogeton*) was abundant.

Charcoal influx in sediments prior to c. 4000 cal. BP is minimal, but small amounts of charcoal were deposited consistently in sediments between c. 4000 and 2200 cal. BP, with a higher influx after 2540 cal. BP. After c. 4000 cal. BP, pollen evidence suggests the beginning of development of the modern vegetation characteristics around Glenmire, not only with abundant conifers, *Alnus*, and *C. cornuta* var. *californica* (Figure 5) but also with continuing importance of open *B. pilularis* coastal scrub grassland. The increasing charcoal deposition is coincident with the settlement of the area by semi-sedentary communities around 3500 cal. BP (Milliken et al., 2007) and the proliferation of new coastal sites, including the first local settlement of Point Reyes from 2450 cal. BP (Stewart, 2003). This supports our contention that the small amounts of charcoal may be consistent with the presumed frequent surface fire regime of the native populations of the coast

(Keeley, 2002; Timbrook et al., 1982). More systematic and radiocarbon-dated archaeological research would be needed to corroborate this hypothesis, but results obtained in this study seem to support that the use of fire may be a distinctive cultural trait, among others – that is, use of mortar and pestle, and semi-permanent shell-mounds settlements (Milliken et al., 2007) – of the prehistoric communities related to the Coast Miwok, which populated the area during this period. Alternatively, small amounts could suggest that delivery of charcoal to the basin was ineffective at this time.

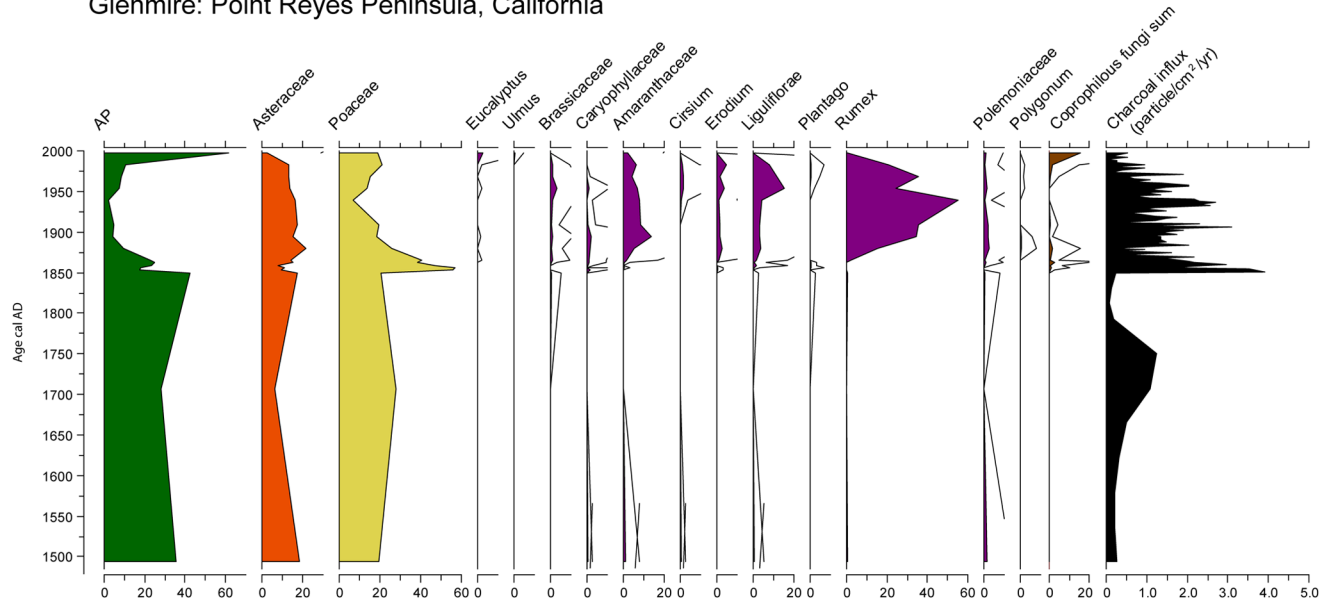
However, charcoal influx increases substantially in the period between c. 2200 and 1000 cal. BP, when *P. menziesii*, *S. sempervirens*, and *Lithocarpus* reach their maximum expansion. All of these species are either tolerant or dependent on fire (Stuart and Stephens, 2006). Three obvious spikes in charcoal at 2040, 1552, and 1035 cal. BP (Figure 8) are nearly synchronous with the increase in pollen of *S. sempervirens* and the period of three large spikes (prior to c. 1934, 1612, and 1073 cal. BP) in pollen of *P. menziesii* (Figure 5). Unlike the earlier record of fire for this site, these pollen and charcoal stratigraphies suggest a tight coupling of fire history and vegetation change around Glenmire during this time period. Our explanation is supported by the significant decline by almost an order of magnitude in charcoal deposition after c. 1000 cal. BP, in concert with a decline in *P. menziesii* pollen. Alternatively, these spikes also occur during the proliferation of coastal sites by sedentary communities and the first local occupation of Point Reyes between 2450 and 1520 cal. BP (Stewart, 2003), a period stressed as a 'cultural climax' in the region (Milliken et al., 2007). A more intense and constant use of the coastal environment around Glenmire together with an environment more prone to burning may have coupled to explain increasing fires at this moment.

**Historic period at Glenmire.** Major changes in the pollen and spore flora document the beginning of the historical period, including changes in the use of fire, clearing of forest, and expansion of introduced species. Little is known about the area surrounding Glenmire prior to 1879, when Glen Ranch became a thriving dairy operation (Livingston, 1994). However, little significant contact between the two groups occurred until the establishment of the Spanish Mission system, originally at San Diego in 1769, but progressing northwards thereafter. Mission Dolores was founded near San Francisco in 1776 (Milliken, 1995), but the Point Reyes Peninsula came under jurisdiction of the Mission at San Rafael as late as 1817 (Brown et al., 1999; Livingston, 1994).

Despite this, a significant number of Native Americans were baptized and moved from Point Reyes and nearby areas to the Mission, and by 1805, the majority of the tribe Olema, inhabiting the coast of the Marin Peninsula to the north of Bolinas Bay, joined the Mission (Milliken, 1995). This process particularly affected the Coast Miwok groups, and it is estimated that 2000 of the 3000 Coast Miwok were missionized during the Mission period (Cook, 1976). Along with the missionization process, Spanish authorities soon moved to control native land-use systems and protect their own exploitation interests on colonial land. It is important to note that Arrillaga's 1793 fire suppression policy for Alta California specifically states his intention was to 'uproot this very harmful practice of setting fire to pasture lands' (Car, 1959). Such active landscape management policies impacted the traditional land-use system of the coastal environment practiced by the Miwok.

Some grazing of cattle from Mission San Rafael may have occurred on the peninsula as early as the 1820s, but few ranchers lived there permanently (Livingston, 1994). Under Mexican jurisdiction, ranching continued to develop during the 1830s with both sheep and cattle, and in 1839, the study area formed part of the Rancho Punta de los Reyes Sobrante, accounting for 200 head of

## Glenmire: Point Reyes Peninsula, California



**Figure 9.** Simplified diagram for Glenmire plotted against mean calibrated ages and showing main pollen, coprophilous fungi totals and charcoal influx for the historical period. Exaggeration curve is  $10 \times$  AP: arboreal pollen sum. NPP: non-pollen palynomorph.

cattle in 1851 and more than 5400 head of sheep, cattle, and horses in 1854 (Livingston, 1994). During the 1850s and 1860s, the Point Reyes Peninsula saw the major development of an extensive dairy industry to provide milk and butter to growing San Francisco. By 1866, the last of over 9000 sheep were removed from the Peninsula (Livingston, 1994), leaving the region to support only cattle.

The pollen, NPP, and charcoal particle stratigraphies are critical to our understanding of the historical period near Glenmire, reinforcing and expanding our knowledge of these former environments. One important outcome of this research is a greater understanding of the timing and impact of exotic species. Our knowledge of the timing of exotic plant introductions into the Peninsula is rudimentary. At least four of these species produce abundant pollen, and have been important in identifying prehistoric from historical sediments. For instance, Frenkel (1970) and others hypothesized that an Old World invasive, *Erodium*, became established in southern California with the advent of the Mission system in 1769. However, Mensing and Byrne (1998) provided convincing evidence for an earlier introduction, perhaps by 1755. *Rumex acetosella* was probably introduced during the Mexican Period (1825–1848) (Frenkel, 1970), being widespread in California by 1864 (Watson, 1880 in Mudie and Byrne, 1980). *P. lanceolata* may have been introduced somewhat later, perhaps in the 1850s (Frenkel, 1970). In their pollen studies of sediments from Drake's Estero and Bolinas Lagoon on Point Reyes, Mudie and Byrne (1980) used this evidence to assign ages of 1840 and 1860 for the rise in *Rumex* and *Plantago*, respectively. Finally, several species of *Eucalyptus* trees were first introduced to the San Francisco region in the early 1850s (Santos, 1997) but were planted in the early 1870s in southern Point Reyes (Johnson, 1971; Mudie and Byrne, 1980). In addition to these four types, pollen of the mustard family (Brassicaceae) is common from ruderal plants in that family.

At Glenmire, pollen of *Plantago* and *Erodium* first appear at 100 and 98 cm, respectively, with both *Rumex* and *Eucalyptus* increasing at 90 cm depth. The occurrence of *Plantago* at this depth dates 100 cm to *c.* 1850, but suggests a late introduction of *Erodium* this far north (Figures 6 and 9). The first occurrence of *Eucalyptus* at 90 cm dates that depth at *c.* 1870, but this suggests

a late increase in *Rumex*. The increase in *Plantago*, *Erodium*, and *Rumex* – species that thrive under landscape disturbance regimes (Frenkel, 1970) and more easily invade grasslands (Burcham, 1957; Mensing and Byrne, 1998) – is entirely consistent with the continuing development of habitats for grazing during the middle of the 19th century that occurred on the Point Reyes Peninsula (Livingston, 1994). The later and near synchronous arrival of these introduced species is also consistent with the later settlement of this region, compared to southern California which witnessed Spanish influence as early as the 1770s (Mensing and Byrne, 1998; Mudie and Byrne, 1980).

In addition, the occurrence of coprophilous fungi can be important in dating sediments and characterizing environments associated with grazing activities. Coprophilous fungi have been commonly identified in paleoecological contexts from Europe (e.g. Cugny et al., 2010; Ejarque et al., 2011; Feeser and O'Connell, 2010) and Greenland (Gauthier et al., 2010; Schofield and Edwards, 2011). Of the numerous potential species, only the ascomycete *Sporormiella*-type has been commonly identified in North American studies (see Davis and Shafer, 2006, and references therein). *Sporormiella*-type spores also occur at 80 cm in the Glenmire record, but with several additional spores of dung-related fungi, including *Podospora* sp, *Sordaria*-type, *Cercospora* sp, *Coniochaeta cf. lignaria*, and *Chaetomium* sp, with first occurrences at 98, 94, 92, 92, and 10 cm, respectively (Figures 7 and 9). Unlike *Sporormiella*-type species included in those types and genus are non-strictly coprophilous, but they commonly grow on herbivore dung (Krug et al., 2004; Van Geel and Aptroot, 2006) and have been largely documented in modern dung samples from domesticated animals and modern grazed vegetation contexts (e.g. Cugny et al., 2010; Ejarque et al., 2011). If all of these species are associated with the occurrence of dung of sheep and/or cattle around Glenmire, the occurrence of these fungi above 98 cm is consistent with the historical record both of the initiation of grazing mid-19th century and of the introduction of exotic species at the same time.

Mid-century also witnessed local felling of woods, not only for opening land for grazing but also for timber. By 1869, some areas near Glenmire (Glen Ranch) became part of the Shafter Ranches (South Tract) and were still wooded (Livingston, 1994).

The increase in pollen of exotic species is mirrored by the steep decline in conifer pollen, particularly *P. menziesii* and *S. sempervirens* (Figures 5 and 9). At the time of Euro-American expansion, abundant forests of these trees plus bishop pine (*P. muricata*) and others covered much of the east slope of the Peninsula, which provided firewood and wood for lumber for the developing ranches (Livingston 1994). Our pollen record supports the historical accounts, recording the existence of both conifer and deciduous woodland until 1850, when the decline of all tree taxa begins (Figure 9). This is consistent with a map of Punta de los Reyes Rancho dating from 1854 (US District Court, California, Northern District. Land case 236, Bancroft Library; [http://content.cdlib.org/ark:/13030/hb6489p0cp/?query=punta\\_de\\_los\\_reyes&brand=calisphere](http://content.cdlib.org/ark:/13030/hb6489p0cp/?query=punta_de_los_reyes&brand=calisphere)), which depicts a fairly open landscape for the peninsula with some tree stands remaining along the coastal mountain range. Initial logging may have targeted oak and other hardwoods during the contact period (Duncan, 1992; Munro-Fraser, 1880), but as development of towns in the area proceeded, logging focused on conifers, such as *Sequoia* and *Pseudotsuga*. Declines in these species at Glenmire are probably a result of that local logging which commenced shortly after Euro-American settlement. Toogood (1980) reported that lumbering of redwood stands occurred in the Olema Valley and on Bolinas Ridge from 1849 to 1858. A maximum of four lumber mills were in operation in that area during that time (Brown et al., 1999). Munro-Fraser (1880) reported steamers bringing cordwood to San Francisco well into the 1850s, as lumbering, shipbuilding, and even papermaking operations were established on major streams that fed into both Tomales Bay and Bolinas Lagoon. It seems reasonable to assume that other small operations operated in much the same manner during the mid-19th century. As noted by Duncan (1992), these activities promoted the establishment and expansion of ruderal plants along roads and within camp. In the most recent decades of the 20th century, pollen of both *Pseudotsuga* and *Pinus* increases, suggesting a recovery of these species locally, while *Sequoia* has not recovered. At least for *Pseudotsuga*, this is consistent with studies of age of trees in local forests (Brown et al., 1999).

The sharp decline of charcoal influx observed at the beginning of the historical period should be linked to the Spanish fire suppression of AD 1793. Charcoal influx values rise again during the historical period (Figures 8 and 9), with influx in some levels approaching values found in the previous zone. Little was known about the prehistoric fire regimes on the Point Reyes Peninsula until the work of Finney (1990) and Brown et al. (1999). Brown et al. (1999) examined *Pseudotsuga* and *Sequoia* trees with fire scars to develop estimates of fire frequency for portions of the peninsula. The record from the Pine Grove Redwoods (closest to Glenmire) exhibited multiple fire scars from the beginning of the record in the late 18th century to AD 1945, while the Limantour Road and Five Brooks sites showed periodic fire until c. AD 1905 (Five Brooks) or AD 1918 (Limantour Road). Mean Fire Intervals (MFIs) for all stands from the early 1800s to c. 1900 was 7.7–8.5 years – characteristic of a surface fire regime on the Peninsula. Finney (1990) examined fire scars on coast redwood trees of Bolinas Ridge and the Kent Lake region, and found presettlement MFI of 7.5 years for small fires, and <20 years for larger fires. The MFI during the last half of the 20th century was an order of magnitude longer.

The fire-scar record from Pine Grove Redwoods is very similar to Glenmire's charcoal influx record for the last 200 years (Figure 8). Fire scars record fires with MFIs of  $8.1 \pm 2.7$  and  $13.0 \pm 4.6$  years for the period 1841–1945, with no fires recorded after 1945. Maximum charcoal deposition at Glenmire occurs between c. AD 1850 and AD 1945 (Figure 8). This pattern suggests that events such as forest clearance by burning during the historical period produced abundant charcoal locally. The lack of fire scars

after 1945 but continuing deposition of small amounts of charcoal may simply be a function of redeposition of older charcoal in the basin, a conclusion supported by stratigraphic evidence (e.g. high MS and deposition of sand and pebbles; Figure 3). Finney (1990) and Brown et al. (1999) believed that the change in fire regime in the 20th century was a direct result of cessation of the surface fire regime that probably existed during the prehistoric period, especially by the California Department of Fire and Forest Protection beginning in 1935. We ascribe the much lower amounts of charcoal in the pre-AD 1850 sediments to either a different surface fire regime (Finney and Martin, 1989) or mode of delivery of charcoal to the basin.

## Conclusion

The pollen, charcoal, and sedimentary data from the Glenmire site suggest a complex relationship between vegetation type, climate, human settlement history, and fire occurrence, and although the chronology of environmental change on the Point Reyes Peninsula is incompletely known, the record from Glenmire provides greater detail than previously available for the middle to late Holocene. This is important because our previous knowledge has been limited to Pleistocene–Holocene transition (Rypins et al., 1989) and the latest Holocene (Duncan, 1992; Russell, 1983). The Glenmire record suggests that the early Holocene was quite dry as organic sediments are not preserved in the bottom 1.5 m of sediments. Pollen evidence from a marine core (Barron et al., 2003) to the northwest suggested warm winters and drier conditions onshore in the early Holocene, which persisted into the middle Holocene. However, groundwater tables apparently rose after c. 6200 cal. BP, allowing for greater subsequent preservation of organic matter, perhaps reflecting a greater persistence of La Niña-like or negative PDO phase as compared to today (Barron and Anderson, 2011). We cannot, however, exclude any tectonic effect on local groundwater-levels due to any earthquake activity along nearby faults. During the middle and late Holocene at Glenmire, the site was surrounded by a mosaic of vegetation types, including mixed conifer forest with coastal scrub grassland prior to c. 4000 cal. BP. Subsequently, the site witnessed an increase in hardwoods such as alder and expansion of coastal scrub (e.g. *Artemisia*, *Baccharis*) until c. 2200 cal. BP when tanoak, and particularly *Pseudotsuga* and *Sequoia*, expanded. With increasing amounts of oak, this mosaic of vegetation types continued to dominate until the arrival of Euro-Americans in the early to mid-1800s.

Significant changes occurred over a very short period of time, beginning in the late 1790s but accelerating in the mid-1800s. These included the arrival of the Spanish Franciscans, removal of the native Coast Miwok population, the subsequent settlement for ranching by Mexican nationals, and land clearance for ranching and dairying by the Americans at the height of California's gold rush. The Glenmire record documents these changes with the (1) decreasing charcoal input following the 1793 fire suppression proclamation, (2) decline of native forest species, (3) arrival of non-native weedy invasive species associated with livestock grazing and land disturbance, (4) introduction of non-native trees for firewood and windbreaks, (5) an increase in coprophilous fungi associated with the presence of large numbers of sheep and cattle, and (6) changes in sedimentation type and rates associated with increased erosion around the site. Several other studies have documented one or more of these changes associated with Euro-American settlement (Anderson et al., 2010; Mensing and Byrne, 1998; Mudie and Byrne, 1980; Russell, 1983) within coastal California. One unique aspect of this study is the identification of a diverse suite of NPPs, which include the coprophilous fungi and other organisms not often studied in sediment profiles from the Western United States.

Our study also documents changing fire regimes through the middle and late Holocene here. Charcoal influx increases slightly after 4000 years ago, with a much larger increase after *c.* 2200 years ago. The explanations for this are probably complex. The pollen data document a change to generally wetter climate during the late Holocene, with increased groundwater tables contributing to more persistent wetlands or higher lake levels. Wetter climates may have fostered additional vegetation growth, which could have burned more frequently during the summer dry season. For much of the most recent *c.* 2200 years, the charcoal influx is strongly linked to vegetation change of the local conifers, and particularly to the occurrence of *Pseudotsuga*. Major influx peaks occur coincident with peaks in *Pseudotsuga* pollen, and a long-term decline in charcoal influx occurs with a decline in *Pseudotsuga* beginning about 1000 years ago.

However, the change from hunter–gatherer to greater sedentism of the native populations by about 3500 cal. BP may have caused a more intense and constant use of the coastal environment around Glenfire. Today, natural fires are very rare, and most fires are human caused. Anthropogenic burning by Native populations at the time of European contact is well documented (Keeley, 2002; Timbrook et al., 1982; many others), although the degree to which Native Americans may have altered vegetation distributions is the subject of considerable debate (Keeley, 2002; Vale, 1998, 2000). We suggest that an environment more prone to burning combined with anthropogenic triggers may have conspired during this period to explain coastal fire increases.

The sedimentary record of historical fires closely matches the nearby fire-scar tree-ring record of Brown et al. (1999), with influx of sedimentary charcoal declining precipitously after the 1960s. The occurrence of small amounts of charcoal in modern sediments reflects, we believe, redeposition of older charcoal into the basin.

## Acknowledgements

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