

Paleocological assessment of forest-disturbance in upper Hadlock Brook and upper Cadillac Brook watersheds

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Abstract

Paleocological reconstructions of forest stand histories for two upland watersheds at Acadia National Park in Maine (in conjunction with related watershed chemistry studies) support the hypothesis that forest type and fire history influence long-term cycling and storage of atmospheric mercury and nitrogen within watersheds. The reconstructions document major vegetation and disturbance differences in upper Hadlock Brook and upper Cadillac Brook watershed forests during the last several centuries, and allow investigators to compare the processing of these elements in the two different settings.

Pollen and charcoal stratigraphies from organic sediment accumulations from forested wet depressions in the two watersheds indicate that the two watersheds have contrasting histories of vegetation and disturbance during recent centuries. Hadlock Brook watershed has been dominated by spruce (*Picea rubens*) and fir (*Abies balsamea*) for 500 years or more and has not recently burned or been substantially cleared. Cadillac Brook watershed is dominated by a heterogeneous forest of patchy hardwood, mixed wood, and softwood stands. A large portion of the Cadillac Brook watershed burned severely in 1947 and possibly in the 1800s, and has supported heterogeneous successional forests for two hundred years or longer.

Introduction

Pollen and charcoal records in lake sediments and tree-ring analyses have been used extensively to provide landscape-scale evidence for reconstructions of long-term forest dynamics. Lake sediments sample pollen from a large area and thus allow paleocological reconstructions of vegetation and disturbance at a broad landscape-scale (Jacobson and Bradshaw 1981). Dendroecological reconstructions document the lifespan of living or recently dead trees and provide little information about past changes in the species composition of the stand. Forest-hollow

paleocological reconstructions use pollen and charcoal from sediments in small, wet hollows and vernal pools within a forest, where pollen comes mostly from within the surrounding canopy. Therefore, such reconstructions accurately reveal histories of forest composition and disturbance in the local forest stand. We use these local pollen records to document disturbances and vegetation changes for centuries or even millennia within the two watersheds as evidence to test the hypothesis that modern inputs and export of nitrogen and mercury in watershed soils and stream chemistry are linked to major forest disturbances and vegetation history.

Part I of this report describes the broad research context for these reconstructions. Part II describes the paleocological methods and findings in detail.

Part I: Broad research context

This work is the initial phase of a 3-year investigation of Hg and N cycling in forested upland watersheds, funded by US EPA (PRIMENet) and USGS BRD, in collaboration with the National Park Service. Our paleocological and historical reconstructions document the vegetation and disturbance histories of the two watershed forests and provide a basis for investigation of the linkages between the history of vegetation and disturbance and geochemical cycling of Hg and N.

Background: forest disturbance and watershed geochemistry

Watershed disturbance can have immediate and long-term influences on the chemistry of downstream waters. For example, the changes in throughfall interception by the canopy can greatly change the loading of substances to watersheds (Rustad *et al.* 1994, Garcia and Carignan 1999). Forest type and canopy structure affect atmospheric loading. Enhanced dry deposition to coastal softwood sites in Maine may result from marine influences, softwood canopy efficiency at raking the atmosphere, and significant inputs from cloud and coastal fog water (Rustad *et al.*, 1994; Freedman and Prager 1986). Increased deposition may account for chronic and episodic acidification in high elevation ecosystems, particularly compounded with coastal fogs, as they experience high atmospheric loading, extreme conditions, and short growing seasons (Weathers *et al.*, 2000). Watersheds with different or altered landscape features should exhibit patterns of total deposition characteristic of the potential for modification by those features.

Canopy-related differences in pollutant loading may lead to biogeochemical differences in watershed status and response. For example, mercury concentrations in aquatic biota are high in some lakes while low in other nearby and apparently similar lakes (Stafford and Haines 1997).

The unpredictable distribution of high-Hg lakes has led to mercury-related fish consumption advisories in Maine and 39 other states (USEPA 2000). Unexplained differences among lakes in sediment and biological accumulation of mercury likely result from the processes that control loading of mercury from the atmosphere and transport to receiving bodies.

Atmospheric deposition and watershed processing of nitrogen and mercury

Nitrogen saturation in watershed soils may also be influenced by atmospheric deposition, canopy interactions, and soil processes. In the U.S., nitrate concentrations in forest streams in the Northeast are higher than in any other forested region in the U.S., and have increased by a factor of 3 to 4 since 1970 (Helsel, 1996). Nitrogen saturation may be induced directly by atmospheric N deposition, or induced indirectly by increases of N mineralization in forest soils resulting from soil acidification, microbial population shifts, climate change, or forest-disturbance. Here, we examine the possibility that watershed export of N in the Northeast may be, at least in part, influenced by fire history over the past one or two centuries.

A primary goal of the long-term watershed research program at Acadia National Park is to determine how watershed characteristics influence the reservoirs and flux of mercury and nitrogen in watersheds and surface waters. One possible difference between watersheds, though not always immediately evident on the modern landscape, is long-term disturbance history, in particular the history of severe fire. We combine the use of stand-scale paleoecological tools, historic records, and tree-ring analyses with modern stream-chemistry data to identify linkages between long-term vegetation history, disturbance, and the cycling of Hg and N within the watersheds. We hypothesize that severe disturbance by fire may influence the long-term storage and processing of atmospheric contaminants within watershed soils and biota. In particular, burning of soils may release long-term storage of Hg in organic soil layers, and change the ratio of N to other soil constituents that control N flux in streamwater.

Experimental setting: paired watersheds

Acadia National Park is within the southern coastal range limit for spruce-fir forests of northern and eastern Maine and maritime Canada (Davis 1966). Because of its location in mid-coastal Maine (Figure 1), Acadia National Park might appear to be the ideal rural setting for pristine waters, clean air, and low pollutant input. However, years of data on fog chemistry (Jagels et al. 1989; Kimball et al. 1988), frequent ozone advisories (National Park Service and Maine Dept.

of Environmental Protection records), and 17 years of precipitation chemistry (NADP 1982-1998) suggest that numerous polluted air masses moving across the northeastern United States converge over Acadia. The Park's prominent topography – the highest mountains on the east coast of the U.S. – may result in enhanced interception and deposition of pollution from air masses. In addition, the vehicles of three million visitors each year create additional air pollution.

Small, high-elevation watersheds within Acadia National Park provide a natural experimental setting for investigating long-term influences of forest-type and disturbance history on watershed geochemistry. Pollen records from Mount Desert Island and other coastal settings in Maine suggest that large-scale, stand-replacing disturbances of coastal forests were infrequent prior to European colonization of the region in the mid- and late-1700s. Fires are estimated to have burned at 300 to 500 year intervals during the two thousand years prior to European settlement (Schauffler 1998, Patterson *pers. comm.*). However, beginning in the late 1700s and extending through most of the 1800s, the majority of land along Maine's coast was cleared for timber and sheep grazing (see McLane and McLane 1989, Tolonen 1983, and others). Both accidental and intentional fires frequently accompanied European settlement, as did clearing of the coast of Maine. Can such major disturbances, even two centuries later, influence modern ecological processes such as soil and stream chemistry and processing of atmospheric pollutants within a watershed?

Objectives

To characterize the histories of forest vegetation and disturbance in each setting, we analyzed fossil pollen and charcoal in organic accumulations from small-hollow deposits in two watersheds with different recent histories of disturbance. Hadlock Brook watershed is dominated by older growth spruce (*Picea rubens*) and fir (*Abies balsamea*) and has no apparent record of recent fire. Cadillac Brook watershed contains a heterogeneous and patchy mix of hardwoods and softwoods and is known to have burned in 1947. These watershed histories are reconstructed and discussed here in terms of the chemistry of the streams draining each watershed. Our specific hypothesis is that severe fire induced changes in soils and vegetation that largely removed historical accumulations of atmospheric pollutants, including Hg and N. We postulate that these changes in ecosystem pools led to current differences in biogeochemistry and bioaccumulation of mercury, as well as the export of nitrogen from the watersheds.

This part of our investigation focuses on two objectives. We have:

1. reconstructed the stand histories of two upland watersheds and characterized differences in vegetation and disturbance histories during recent centuries based on paleoecological and historical data; and
2. compared paleoecological results with stream chemistry to refine the initial hypothesis that stream export of Hg and N is lower in the burned watershed where element reservoirs in upper soil horizons have been depleted by fire.

Part II: Paleocological methods and findings

Methods

Reconstructions of vegetation and disturbance history are based on historical evidence, aerial photographs, and paleoecological analysis of locally derived pollen and charcoal preserved in small, partially forested bogs and forested wet hollows within the watersheds. Pollen deposited each season in forested bogs and wet depressions is derived from sources dominantly within 50 m (Sugita 1995, Calcote 1995). In many settings, it is stratigraphically preserved, providing a decade-to-century scale record of changes in local dominant tree taxa. The studied wet depressions range from one to several tens of meters in diameter with sediments between 20 and 50 cm deep. They are often covered by a mat of lush *Sphagnum* moss, or they may contain partially decomposed forest duff that holds standing water during wet seasons and would be classified as vernal pools. Although the hollows may appear dry at the surface in summer and fall, trapped drainage and the absorbent organic material keep the underlying sediment wet year-round, creating anaerobic conditions in which pollen is preserved.

Site selection and description

We selected for study the upper sections of two watersheds of similar size but with different landscape features (Table 1). The watersheds were selected based on the location of the 1947 fire that burned one-third of the Park. The Hadlock Brook watershed did not burn in 1947 and thus provides the older-growth comparison to the young forest in the largely burned Cadillac Brook watershed. Both watersheds have upper spruce-fir and sub-alpine scrub zones with relatively fresh, polished bedrock surfaces as a result of continental glaciation that ended about

14,000 years ago. Soils throughout the watersheds are thin Spodosols over till or Histosols on the Cadillac Granite bedrock of Devonian age (Gilman et al. 1988).

	Elevation	Hectares	Aspect	Average slope	Dominant forest cover type
Hadlock watershed	137-380 m a.s.l.	47.2	W-SW	20%	coastal spruce-fir (see Davis 1966)
Cadillac watershed	122-468 m a.s.l.	31.6	E-SE	28%	patchy, mixed hardwood and softwood

Table 1. Physical attributes and dominant forest cover types of Hadlock and Cadillac watersheds.

Sediment cores

Three wet hollows were selected in each watershed for sampling and analysis of pollen and charcoal preserved in sediments. Core sites were on flat terrain, either in closed canopy forest stands (Hadlock I, Cadillac I, III, and IV) or in small partially-forested bogs (Hadlock II and III) (Table 2).

Location	Core depth	Hollow depth	Community type	Sediment matrix	Estimated basal age of core	¹⁴ C dates	GPS coordinates
Hadlock I	44 cm	44 cm	spruce/fir forest	organic soil	1300 bp	(post-bomb)	
Hadlock II	50 cm	100 cm	acidic fen, partially forested	peat	1500 bp	29 cm=310 bp	
Hadlock III	25 cm	25 cm	acidic fen, partially forested	fibrous peat	500 bp	not dated	
Cadillac I	21 cm	30 cm	mixed hardwood/softwood forest	organic soil	1947 fire	not dated	
Cadillac II	25 cm	25 cm	spruce/cedar canopy, alpine shrubs	organic soil/peat	(hiatus?)	not dated	
Cadillac III	46 cm	48 cm	spruce-fir forest	peat	1500 bp	basal=1470 bp	

Table 2. Descriptions of the sediment cores and the communities surrounding core sites.

Estimated basal ages are based on stratigraphic indicators in the pollen record, including the rise in ragweed (*Ambrosia*) pollen which corresponds to the settlement of Europeans agricultural colonies on Mount Desert Island in the 1760s, and the regional rise in spruce pollen around 750 to 1000 years ago.

Sediments from all locations except Hadlock I were sampled by extracting a 10-cm-wide monolith to the base of the sediments or 50 cm deep, whichever was less. Monoliths were wrapped in plastic and packaged in PVC trays for transport to the laboratory where they were stored at 5°C until analysis.

At the Hadlock I site the higher mineral content and drier nature of the sediment required sampling contiguous 1cm sub-samples by hand *in situ* from the side of a pit. Sub-samples were placed into whirlpaks, labeled, and transported back to the laboratory for cold storage.

Pollen analysis

For pollen analysis, 0.5 cc of sediment was sub-sampled from each core at 1.0- to 3.0-cm intervals (depending on core length). One cc of sediment was sub-sampled at the top of cores where pollen concentrations were low in the less-compacted sediment. Sub-samples were soaked in 10% KOH, sieved through 143µm mesh, and *Lycopodium* spore tablets were added for calculation of pollen concentration (Stockmarr 1972). Pollen was extracted using HF and acetolysis, and then suspended in silicon oil, according to standard procedures used in the Laboratory for Paleoecology and Paleohydrology at the University of Maine (modified from Fageri and Iversen, 1984).

At least 300 terrestrial pollen grains of arboreal, shrub, and herbaceous taxa were counted at each stratigraphic interval at 400x magnification (1000x was used for verification when necessary). Pollen percentages for taxa were based on the sum of total terrestrial pollen (arboreal (tree and shrub) pollen plus non-arboreal (herb) pollen) and were calculated and diagrammed using TILIA and TILIAGRAPH software (Grimm, 1994). Data from these studies will be made available in the North American Pollen Database (NAPD).

Charred-particle analysis

Sub-samples of sediment (3.0 cm³) at contiguous 1-cm intervals along each core were sieved through 425-µm mesh for quantitative analysis of macroscopic charred particles. Amounts of charred material are based on the area covered by charred fragments in each 3.0 cm³ sub-sample, determined by counting the number of 1 mm grid squares covered by charred fragments (12X magnification). The total area of charred macrofossils was summed and is expressed in terms of volume of sediment sub-samples (mm² charred material/cc sediment). The number of fragments

that were larger than 1.0 mm² and the size of the largest fragment in each sub-sample are also reported.

Microscopic charcoal was noted as present or absent on pollen slides and ranked as a small amount (i.e. < 20 fragments per slide), a moderate amount, or an uncountable amount which darkens the slide and obscures all other material including pollen. A large proportion of microscopic charred material suggests the occurrence of a fire in the immediate vicinity. When present, the relative abundance of microscopic charred material is represented in the first column in the pollen diagrams.

Radiometric dating

Stratigraphic chronologies are based on the marked rise in ragweed (*Ambrosia*) pollen and other non-arboreal pollen types indicating the beginning of European settlement in the region (Clark 1988, Swain 1973), and on calibrated accelerator mass spectrometry (AMS) dates from plant macrofossils picked from the sediments. Macrofossils were dried, weighed, and analyzed by reduction to graphite according to standard AMS procedures used by The University of Arizona and Beta Analytic in Miami, FL. Calibrated dates were determined using the Pretoria Calibration Curve (Vogel et al. 1993, Talma and Vogel 1993). Conventional radiocarbon ages, ¹³C/¹²C ratios, and calibrated ages with 2σ error terms are reported in Table 3.

Site and Lab number	Dept h (cm)	Conventional ¹⁴ C BP (±1σ)	Calibrated ¹⁴ C age (cal BP) (±1σ)	Basis	¹³ C/ ¹² C
Hadlock I					
*AA33426	27	*post-bomb		spruce needle	-26.2
*AA33016	42-43	*post-bomb		leaf fragment, spruce needle	-28.4
Hadlock II					
AA33015	29-30	310±65	cal bp 467-296	seeds	-29.1
*AA33014	49-50	*375±50		woody fragments	-26.0
Cadillac III					
Beta-132205	45-46	1470±40	cal bp 1407-1399	charred material, seed	-28.2
*Beta-132304	23	*108.2 ±0.5% of modern ¹⁴ C	*post-bomb	seed and leaf fragments	-26.5

Table 3. Data for AMS radiocarbon dates submitted for this study. Asterisks denote dates considered likely to have been contaminated with modern carbon because of poor preservation and fragmentation of plant macrofossils in the cores. Calibrations are based on the Pretoria calibration curve (Talma and Vogel 1993). Analyses were made by Beta Analytic (Beta) and the NSF-Arizona AMS Facility (AA).

Sediment chronologies

There is a high risk of confounded AMS dates in forest-hollow pollen stratigraphies because of the likelihood of root material growing in old sediment and because of generally poor preservation of seeds and leaves. Several of the plant macrofossils submitted for AMS dates were determined to contain modern (post-bomb) radiocarbon. The Hadlock I forest core contained almost no preserved plant material large enough to separate from the matrix and only extremely small charred fragments. All three pollen stratigraphies closely match regional and other forest-hollow pollen records, so that the estimated chronologies are considered to be reasonable. The rise in ragweed pollen – evident in all cores except those with charred sediment in the Cadillac Brook watershed – provides a reliable indication of the time of European settlement around 200 years ago.

Historic records of fire and land use

Prior to European settlement in the late 1700s, fires burned infrequently – once every 500 years or so – in forests on the coast of Maine (Patterson, personal comm.). The mid-1800s to early 1900s was a period of many major fires on Mount Desert Island and elsewhere along Maine's coast, resulting from accidental and intentional burning associated with slash removal and land-clearing activities (Moore and Taylor 1927).

Patterson *et al.* (1983) conducted a study of the fire history of Acadia National Park for the National Park Service based on pollen in pond and lake sediments and on changes in forest stand structure and composition in plots throughout the Park. Barnicle 1984, Moore and Taylor 1927 also document vegetation and fire history in Acadia National Park.

Aerial photographs

Aerial photographs from 1944, 1949 and 1997 were scanned and imported into Erdas IMAGINE remote sensing software and geographically referenced using topographic landforms, roads, trails, and buildings as ground control points. Vegetation types were classified into hardwood, softwood, mixed wood, scrub-shrub/woodland, and exposed ledge/pavement using a supervised classification procedure defined with reference to original aerial photographs, knowledge of the present landscape, and consultation with contemporary photographs (Figs. 2a & b, 3a-c).

Specific community types as described by the National Park Service included in each grouping are listed in Table 4. From these three sets of maps, changes in the proportions of hardwood and softwood cover during the last 50 years and as a result of the 1947 fire were calculated for each watershed (Table 5).

Subjectivity in the interpretation of the aerial photographs is potentially significant because of differences in time of day (i.e. shadow effects), exposure, film-type, and scale (i.e. altitude) among the aerial photographs taken in 1944, 1949, and 1997. All photographs were exposed in May during early leaf-out. Although the vegetation maps derived from the photographs probably lack fine-scale precision for the reasons stated above, large-scale patterns of changes in forest cover are apparent and can be corroborated by paleoecological and other historical data, and by modern ground surveys.

Tree-ring data

Increment cores from 11 trees within 50 m of the Cadillac I site and 12 trees from the Hadlock 1 site were collected to determine the ages of the largest size-classes of trees in each stand. Wood cores were dried and finely sanded, and seasonal growth rings counted. Counts are considered minimum ages because in many cases cores did not reach the pith and cores were not cross-dated and checked for missing rings.

Forest cover types, Figures 4c and 3c	Specific community types included
Hadlock watershed (Figure 2c)	
Softwood	<i>Picea rubens</i> - <i>Abies</i> (<i>Betula</i>) (<i>Acer rubrum</i>) forest <i>Picea rubens</i> - <i>Acer rubrum</i> - <i>Nemopanthus</i> saturated woodland
Mixedwood	<i>Picea rubens</i> -(<i>Pinus strobus</i>)- <i>Betula</i> spp.- <i>Acer rubrum</i> -mixed forest
Hardwood	<i>Acer saccharum</i> - <i>Betula allegheniensis</i> - <i>Fagus</i> - <i>Viburnum</i> forest
Scrub/shrub/woodland	<i>Vaccinium</i> - <i>Sorbus americana</i> dwarf shrubland <i>Picea rubens</i> - <i>Vaccinium</i> woodland <i>Nemopanthus</i> - <i>Viburnum</i> / <i>Kalmia</i> woodland <i>Thuja</i> - <i>Abies</i> - <i>Alnus</i> - <i>Carex</i> saturated woodland <i>Picea rubens</i> - <i>Betula populifolia</i> / <i>Nemopanthus</i> woodland summit
Cadillac watershed (Figure 3c)	
Softwood	<i>Picea rubens</i> - <i>Abies</i> (<i>Betula</i>) (<i>Acer rubrum</i>) forest
Mixedwood	<i>Picea rubens</i> - <i>Pinus strobus</i> - <i>Betula</i> spp.- <i>Acer rubrum</i> -mixed forest
Hardwood	<i>Populus</i> (<i>tremuloides</i> , <i>grandidentata</i>)- <i>Betula</i> (<i>populus</i> , <i>papyrifera</i>) forest <i>Acer saccharum</i> - <i>Pinus strobus</i> / <i>Acer pensylvanicum</i> forest
Scrub/shrub/woodland	<i>Vaccinium</i> - <i>Sorbus americana</i> dwarf shrubland <i>Picea rubens</i> - <i>Betula populifolia</i> / <i>Nemopanthus</i> woodland summit <i>Nemopanthus</i> - <i>Viburnum</i> / <i>Kalmia</i> woodland

Table 4. Specific community types included in softwood, hardwood, mixedwood, and scrub-shrub/woodland forest cover categories in the maps in Figure 2c and 3c. The specific community types are as described by the National Park Service (NPS 2000).

Cadillac Brook watershed (1944-1949)

Total area: 31.82 ha

Forest type	1944 % cover	1949 % cover	change (44-49)
Softwood	19%	13%	-6%
Mixedwood	19%	23%	4%
Hardwood	24%	21%	-3%
Shrub/scrub	31%	29%	-2%
Exposed bedrock	7%	14%	7%
total forested	62%	57%	-5%

Cadillac Brook watershed (1949-1997)

Total area: 31.82 ha

Forest type	1949 % cover	1997 % cover	change (49-97)
Softwood	13%	10%	-3%
Mixedwood	23%	36%	13%
Hardwood	21%	12%	-9%
Shrub/scrub	29%	70%	41%
Exposed bedrock	14%	0%	
total forested	57%	57.8%	1%

Hadlock Brook watershed (1944-1997)

Total area: 47.19 ha

Forest type	1944 % cover	1997 % cover	change (44-97)
Softwood	46%	68%	22%
Mixedwood	17%	1%	-16%
Hardwood	9%	2%	-7%
Shrub/scrub	22%	29%	7%
Exposed bedrock	6%	1%	-5%
total forested	72%	71%	-1%

Table 5. Changes in proportions of vegetative cover-type in Hadlock Brook watershed between 1944 and 1997 and in Cadillac Brook watershed between 1944 (pre-fire), 1949 (post-fire) and 1997, based on aerial photograph interpretations.

Results

Sediment cores

Sediment cores contain well-preserved pollen and span the last 300 to 1000 years, with the exception of Cadillac I and Cadillac II which have evidence of recent deposition of eroded

charred material and sediment, likely from the 1947 fire (Table 2). In these burned locations, pre-fire palynological stratigraphy was destroyed or obscured by charred sediment.

As a result, our forest reconstructions in the Cadillac Brook watershed rely heavily on historic information and pre-fire (1947) aerial photographs. Pollen stratigraphies in the other cores (Cadillac III and all three cores from the Hadlock watershed) match well with other coastal and regional pollen records (Schauffler and Jacobson 2001, Anderson et al. 1986, 1992) and include distinct markers of European settlement such as the rise in ragweed pollen.

Hadlock watershed reconstruction (unburned)

The three pollen stratigraphies from the Hadlock Brook watershed indicate that spruce has been locally dominant for 500 years or more (Figures 4a-c). Aerial photographs and pollen records suggest that some clearing of forests occurred in the watershed during the nineteenth century. The dominance of softwood appears to have increased slightly since 1944 (Table 5). This consistency in forest pattern suggests that cutting in the previous century was selective and not enough to remove the softwood regeneration in the understory.

The pollen data support the conclusion that the Hadlock Brook watershed was only partially cut during the colonial era. Increases in non-arboreal pollen (NAP) percentages are moderate (<10% in the forested site) and although pollen percentages of major tree taxa decrease, spruce pollen persists in moderately high proportions. A stand of hardwoods 75-100 m southeast of the Hadlock I core site – the only significant stand of large hardwoods in the watershed – may have been significantly cut or disturbed, resulting in its present dissimilarity from the rest of the watershed forest. This scenario would also account for the recent increases in hardwood pollen at the top of the nearby Hadlock I site pollen stratigraphy (Figure 4a).

Tree rings indicate that the largest red spruces in this stand are older than 100 years (Table 6). The canopy consists of multiple age-classes and the 12 trees that were cored range in age from ca. 40 to 124 years old. No single age-class is dominant, suggesting there has not been significant disturbance in this stand for a century or more.

tree species	growth form	tree/core sample no.	DBH (cm)	age	comments
CADILLAC					
<i>Betula populifolia</i>	single stem	C-Bp1	10.2	38+	near pith
	single stem	C-Bp2	10.5	34+	near pith
	single stem	C-Bp3	14.7	39+	near pith
	stump sprout	C-Bp4/ a	26.5	~60	uncertain due to obscured/crowded rings
	stump sprout	C-Bp4/ b	26.5	40+	short of pith
<i>Acer rubrum</i>	single stem	C-Bp5	12.8	32+	near pith
	single stem	C-Ar1	14.2	46	to pith
	stump sprout	C-Ar2	18.5	41+	rotten pith
	stump sprout	C-Ar3/ a	18.0	43+	rotten pith
<i>Abies balsamea</i>	stump sprout	C-Ar3/ b	18.0	42+	rotten pith
	single stem	C-Ab1	11.4	32+	near pith
<i>Thuja occidentalis</i>	single stem	C-Ab2	19.3	33+	near pith
	single stem	C-To1	37.0	73+	far short of pith
HADLOCK					
<i>Picea rubens</i>	single stem	H-Pr1	42.0	73+	short of pith
	single stem	H-Pr2	29.0	101	near pith
	single stem	H-Pr3	43.0	107	hit pith
	single stem	H-Pr4	24.0	91	hit pith
	single stem	H-Pr5	28.5	88	hit pith
	single stem	H-Pr6	55.0	124+	short of pith
	single stem	H-Pr7	21.5	90	45-yr suppression
	single stem	H-Pr8	9.5	62	hit pith
<i>Betula allegheniensis</i>	single stem	H-Ba1	14.0	66+	center rot
	single stem	H-Ba2	15.0	77	hit pith
<i>Acer rubrum</i>	single stem	H-Ar1	18.0	30+	short of pith
	single stem	H-Ar2	23.0	45+	short of pith

Table 6. Tree ring counts from increment cores sampled in 1999 from 11 trees in the stand surrounding the Cadillac I core site and 12 trees surrounding the Hadlock I core site. At the Cadillac site there were three recognizable stand cohorts (A) 5-6 large *Acer saccharum* (DBH 47 cm, 45 cm, 34 cm) and *Thuja occidentalis* (all 3 *Acer* have fire scars at the base); (B) mid-sized clumped and single stems of *Betula papyrifera* and *Acer rubrum*; (C) smaller understory stems of *Betula*, *Acer*, *Abies* 6 cm DBH or less.

Summaries of historic fires in Acadia do not mention any specific or major fires that burned in the Hadlock Brook watershed, although the watershed is included in the 'burned' region depicted in a large-scale island map published by Moore and Taylor (1927).

Fires near the Hadlock Brook watershed are documented for 1864, starting in a lumber camp at the south shore of Jordan Pond and burning up the south slopes of Pemetic and Penobscot Mountains burning vegetation and soil (Moore and Taylor 1927). In 1930 a fire burned for

several days in an area of small growth in the Aunt Betty's Pond – Sargent Mountain area for several days (Patterson et al., 1983). Both of these fires appear to have been entirely outside the Hadlock Brook watershed. Charcoal from pre-European settlement fire is evident in sediment from Sargent Mountain Pond, approximately 0.5 km over the ridge to the northeast of the Hadlock Brook watershed (Patterson and Backman, 1988).

The presence of macrofossil charcoal associated with increases in alder pollen suggests local fires may have occurred at or near the Hadlock II and Hadlock III sites. These charcoal bands are coincident with the *Ambrosia* rise and probably indicate burning at the time of European settlement. There is no evidence of local burning (i.e. charcoal peaks corresponding with changes in pollen) in the soil core from the forest site at Hadlock I.

Cadillac watershed reconstruction (burned)

Reconstruction of vegetation history in areas of patchy vegetation requires a high density of forest-hollow pollen records (Sugita 1995). Such high-density sampling was not available in the Cadillac Brook watershed because of the predominance of thin soil and steep, boulder slopes, and because of charred sediment in the burned portions of the watershed. Therefore, our paleoecological reconstruction of forests pertains specifically to the upper part of the Cadillac Brook watershed, which did not burn. Reconstructions of the lower part of the watershed are based on historic accounts, aerial photo interpretations, and tree-ring increment cores.

Lower (burned) section of the watershed. The two sediment cores from the lower section of the watershed contained large amounts of microscopic charcoal and low concentrations of pollen in a wide band approximately 10 cm below the surface, consistent with the 1947 fire (Figures 5a and 5b). These two cores were not radiocarbon dated because of the likelihood of a hiatus in the chronology that could result from burned soil or excessive deposits of charred material, and the expectation that sediments were younger than the range of radiocarbon dating.

Large fires occurred on Cadillac Mountain in 1889 and 1896 or 1898 (Moore and Taylor 1927), and in 1947. Boundaries of the nineteenth century fires are not known, although Moore and Taylor report that at least one of them burned the north ridge of Cadillac Mountain, and may have burned down into the Cadillac Brook watershed. Another fire reportedly burned the southeast slope of Cadillac Mountain from Otter Creek, and may have burned up into portions of

the Cadillac Brook watershed in the late 1800s. The 1947 fire burned the lower two-thirds of the Cadillac Brook watershed.

Increment cores sampled from the largest age-class of trees in the stand at Cadillac I suggest that the thick layer of charcoal in sediments came from the fire in 1947. The stand contains three recognizable cohorts of trees: (a) a few large sugar maples and red cedars (*Acer saccharum*, *Thuja occidentalis*) (DBH 47 cm, 45 cm, 34 cm), (b) a large number of mid-sized single and clumped stems of white birches and red maples (*Betula papyrifera*, *Acer rubrum*) (DBH 10.2 – 26.5 cm), and (c) smaller understory stems of birch, red maple, and fir (*Abies balsamea*) (<6 cm DBH). The majority of the trees in the stand are birches and red maples in the mid-sized cohort.

The mid-sized birches and maples had between 32 and 46 seasonal growth rings (counted at breast height), suggesting that cohort was established soon after the 1947 fire 52 years ago (Table 6). Many of the cores from these trees came near, but did not encounter the pith and do not include the years of growth prior to trees achieving breast height; although some of the ring counts likely underestimate actual ages by several years, none had evidence of pre-dating the fire.

An increment core sampled from the cedar in the oldest cohort (37 cm DBH) did not reach the pith and had 73 rings, suggesting that the tree and others of its size were established before 1947 and survived the fire. All of the large sugar maples have fire scars at the base of the stems.

Upper (unburned) section of the watershed. Only one of the three Cadillac watershed cores (Cadillac III from the upper, unburned section of the watershed) had a continuous well-preserved pollen stratigraphy. The stand is in a ravine on the southeast slope tens of meters below the top of Cadillac Mountain, protected from prevailing northwest winds. The pollen stratigraphy indicates that spruce, fir, birch, and maple have been locally dominant for the last several centuries. The chronology for the Cadillac III core is based on the *Ambrosia* rise and one basal AMS date at 49 cm. (cal BP 1400). As with the Hadlock cores, the pollen stratigraphy matches other pollen records from Maine and the chronology is considered to be reasonable.

The notably few major changes in the pollen stratigraphy suggest that this high-elevation stand has remained a stable community of mixed spruce-fir, birch, and maple for at least the last 500-1000 years. This stand type is ecologically plausible in a high-elevation ravine where the microclimate has likely been consistently cool and moist.

Aerial photographs. The comparison of aerial photographs taken in 1944 (pre-fire) and in 1949 (post-fire) indicate decreases in softwoods and increases in shrub-scrub cover in the lower and mid-sections of the watershed, supporting the evidence from the sediment cores that this section of the watershed burned (Figure 3a-c and Table 5). The softwood stand at the Cadillac III core site is evident in all three photographs, also corroborating the sediment records.

Discussion

Watershed vegetation changes and disturbance histories

Although the relationship between macroscopic charred particles in forest hollow sediment and the intensity, frequency, or proximity of local fires is not well documented, we assume that local fire is represented by charred particles in a broad range of size classes (Wein et al. 1986, J. Clark et al. 1998). Also, peaks in macrofossil charcoal that correspond to changes in pollen percentages suggestive of fire disturbance (such as increases in birch or alder) are interpreted as evidence for local fire. When only small charred fragments ($<2 \mu\text{m}$) are present and do not correspond to changes in pollen, they may have come as smoke from large fires within the region, or from a smaller fire nearby, and are not likely from a large fire within the local stand.

The Cadillac watershed has probably sustained a patchy, heterogeneous mixture of hardwoods and softwoods during much of the last two centuries, in part due to periodic recurrence of fire. It is likely that thicker organic soils (in contrast to Hadlock) have not developed in this watershed because of one or more severe fires during the last two centuries. There is no evidence that soils in the Hadlock watershed have been disturbed during the last several centuries, and the spruce-fir canopy there has remained largely intact. These contrasting forest stand histories may also influence differences in soil characteristics and chemistry identified by Parker et al. 2001, 2002)

Implications for forest dynamics

Pollen and charcoal records from the forest stands in these two watersheds provide further examples that differences in forest type can be sustained for long periods of time (centuries to millennia) as a result of differences in disturbance patterns (Schauffler and Jacobson, 2001, M.B. Davis et al., 1994). Data also support the hypothesis that coastal spruce forests on Mount Desert Island have a fire recurrence interval of 200 years or more. The only spruce stand in the Cadillac Brook watershed is in the unburned portion, where spruce has dominated for hundreds of years.

The large proportion of pioneer hardwoods in the rest of the watershed is almost certainly a consequence of fire disturbance.

Conclusions

1. *Reconstruction of watershed vegetation changes:* Spruce has dominated the Hadlock Brook watershed for at least 500 years. The Cadillac Brook watershed has apparently supported patchy, heterogeneous forests of hardwoods, softwoods, and hardwood-dominated mixed stands for the last two centuries, except in protected sites near the top where spruce-dominated stands of spruce-fir, birch, and maple have grown for 500 years or more.
2. *Watershed disturbance histories:* Although pollen data do not suggest that the Hadlock Brook forests were cleared during the 1800s, we cannot exclude the possibility that selective cutting occurred. There is no evidence that large fires (i.e. fire intense enough to burn soil or leave large charred fragments) burned in the Hadlock watershed. In the Cadillac watershed at least one large fire burned much of the watershed intensely in 1947; other fires apparently burned some or all of the area in the late 1800s. The mixed stands of spruce-fir, birch, and maple growing at the top of Cadillac Brook watershed do not appear to have been affected by fire and have apparently not changed much during the last 500 years or more.

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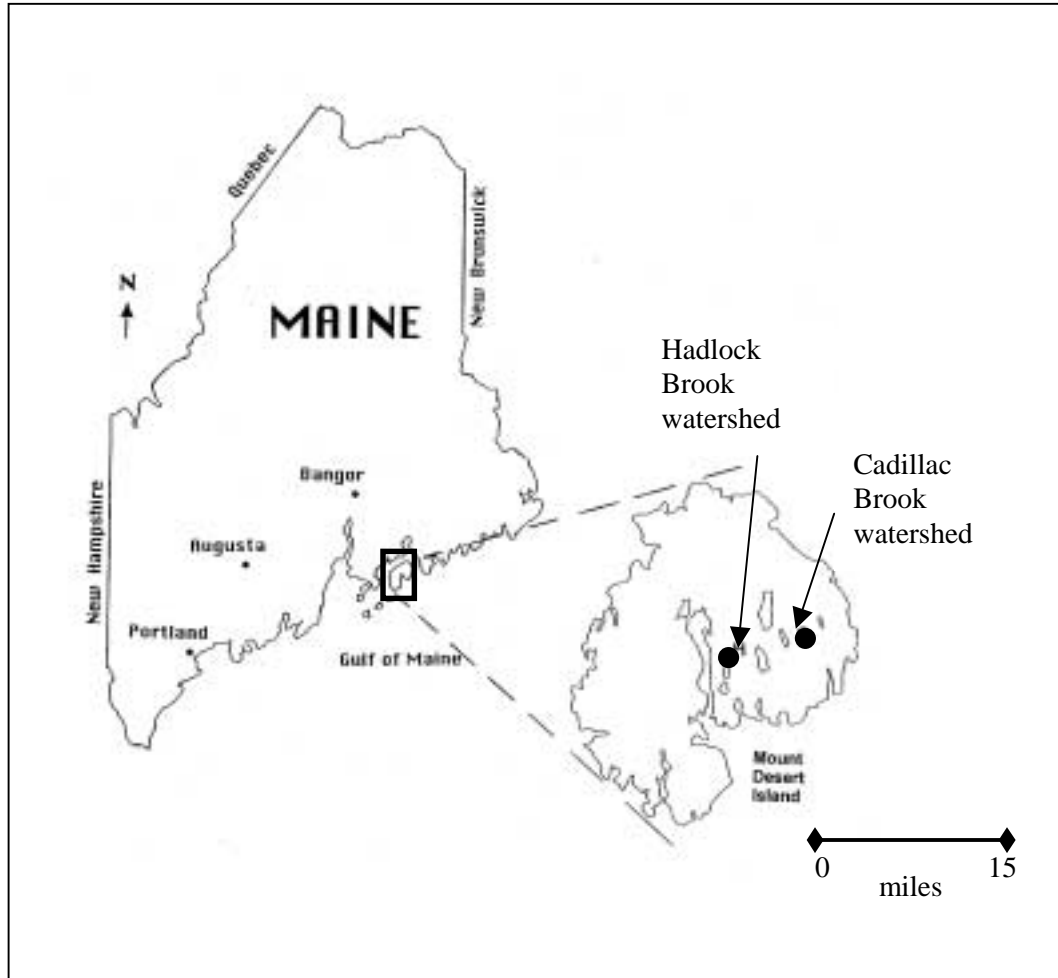
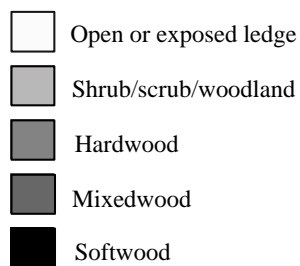
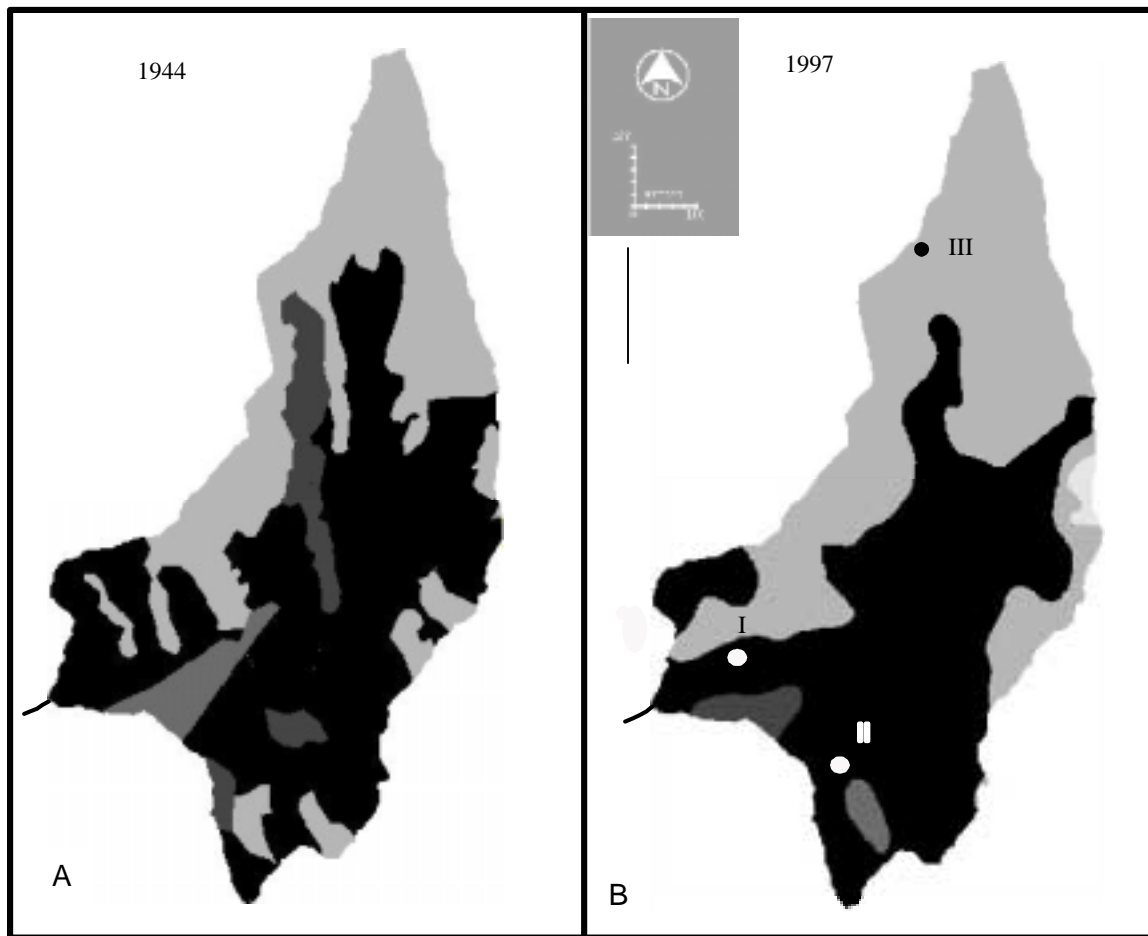


Figure 1. Locations of Hadlock Brook and Cadillac Brook watersheds on Mount Desert Island.



Hadlock Brook watershed

Figure 2. Forest cover types in Hadlock Brook watershed in 1944 (2a) and 1997 (2b), interpreted from aerial photographs. Figure 2b is based on cover types within the watershed as summarized by a recent Park-wide vegetation survey. Specific modern forest types included in each of the broad categories are listed in Table 3. Softwood stands are outlined in Fig. 2a to facilitate comparison. Locations of sediment core sites at Hadlock I (forest stand), Hadlock II (acidic fen), and Hadlock III (acidic fen) are labeled in Fig. 2b.

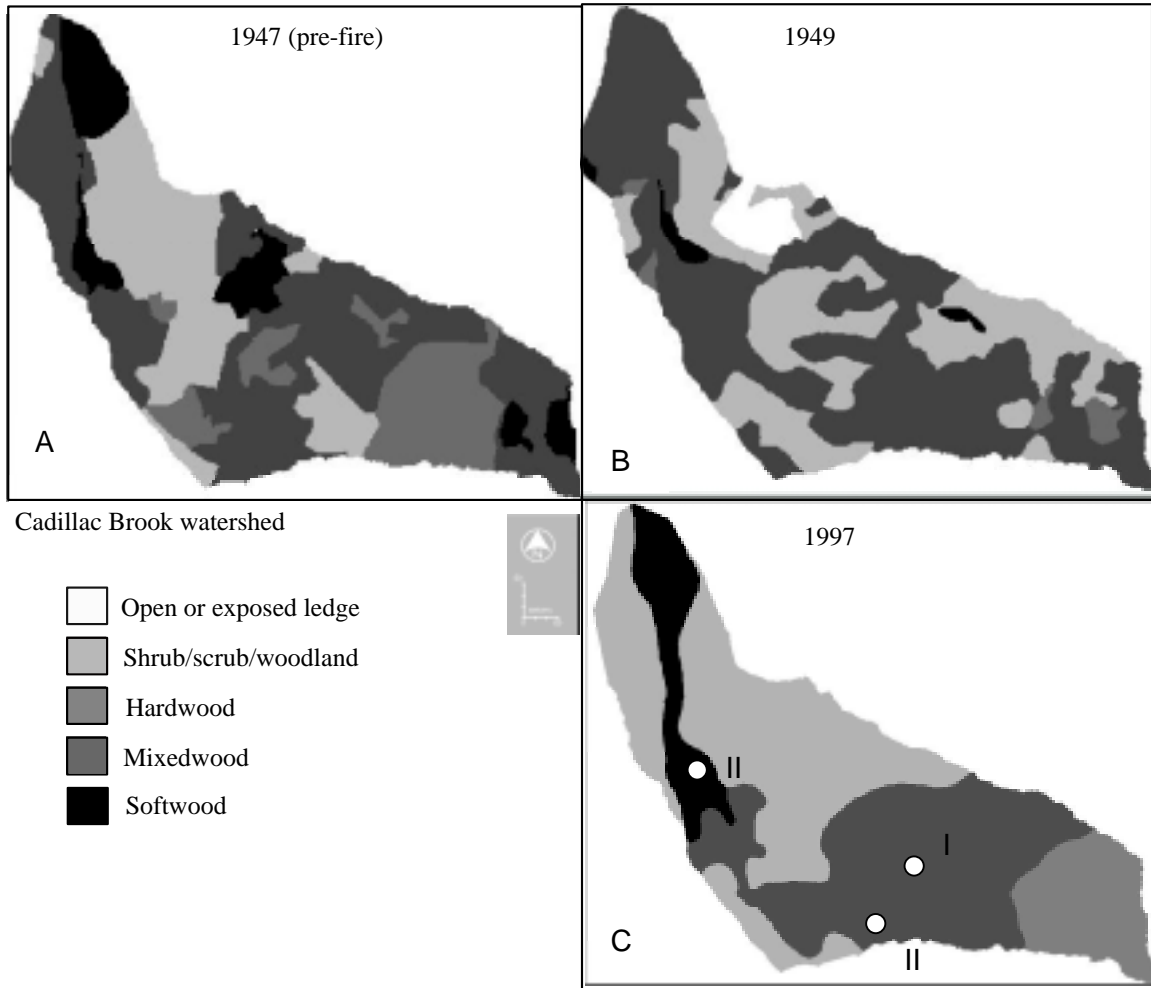


Figure 3. Forest cover types in Cadillac Brook watershed in 1944 (3a), 1949 (post-fire) (3b) and 1997 (3c), interpreted from aerial photographs. Figure 3c is based on cover types within the watershed as summarized by a recent Park-wide vegetation survey. Specific modern forest types included in each of the broad categories are listed in Table 3. Softwood stands are outlined in (a) and (b) to facilitate comparison. Locations of sediment core sites at Cadillac I, Cadillac II and Cadillac III (all forest hollows) are labeled in Fig. 3c.

Figure 4. Pollen stratigraphies for sediment cores from the three sites in the Hadlock Brook watershed. Charcoal sums include only macrofossil fragments $>425\mu$. Patterned silhouettes indicate exaggerated values (2x). X-axis values indicate percentage of the terrestrial pollen sum (unless labeled otherwise).

Figure 5. Pollen stratigraphies for sediment cores from the three sites in the Cadillac Brook watershed. Charcoal sums include only macrofossil fragments $>425\mu$. The core from Cadillac I (5a) contained significant amounts of microscopic ($<425\mu$) charred material in the lower half of the core. Shaded sections in Fig. 5a and 5b indicate levels containing overwhelming amounts of charcoal and little or no pollen and are interpreted as hiatuses due to erosion deposits or burning of the organic soil. X-axis values indicate percentage of the terrestrial pollen sum, (unless labeled otherwise).

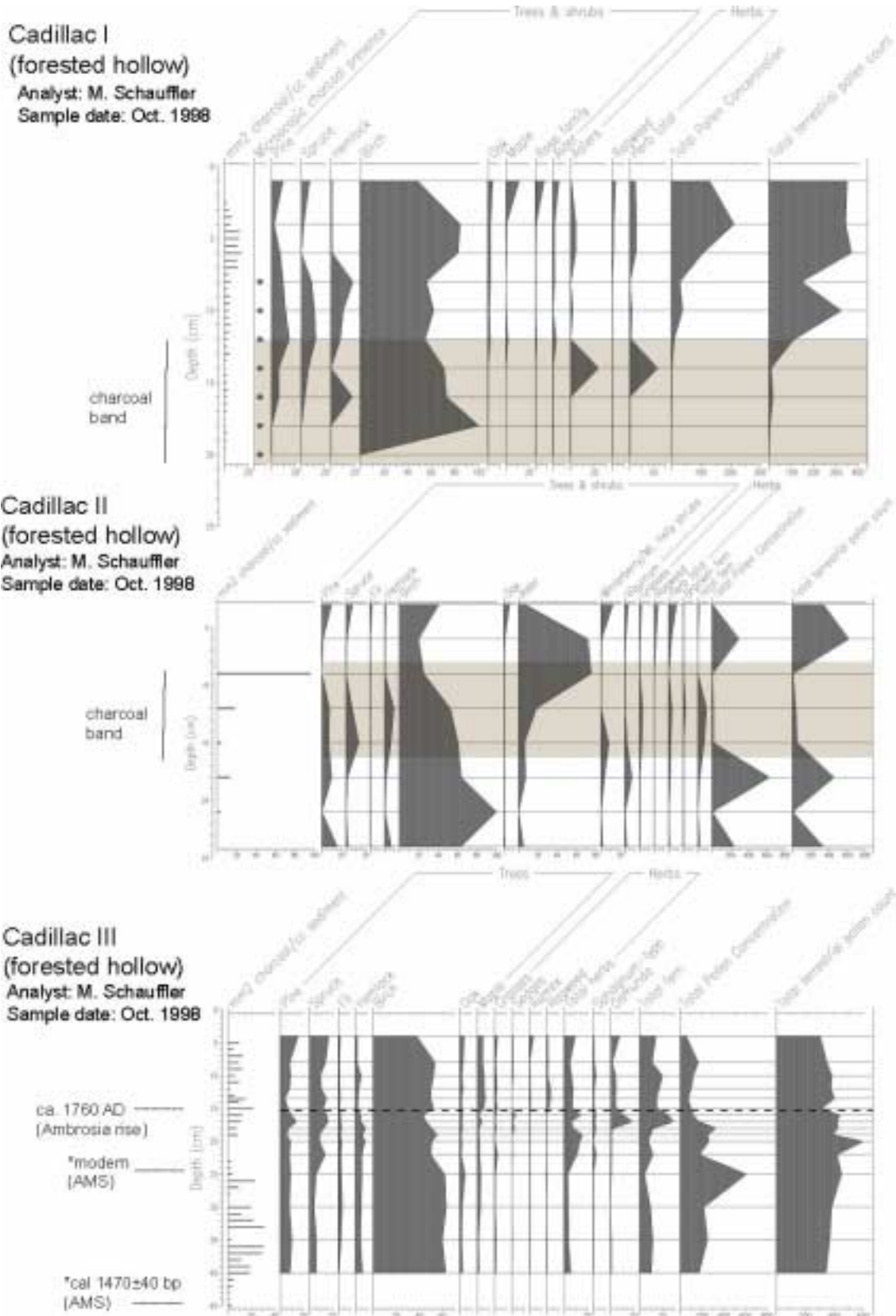


Figure 5