Logging Effects on Sediment Flux Observed in a Pollen-Based Record of Overbank Deposition in a Northern California Watershed

Short Title: Logging Effects on Sediment Flux

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ABSTRACT

A palynological approach was used to estimate overbank deposition rates in a forested watershed affected by logging. The palynological approach uses downcore variations in total fossil pollen and fossil pollen assemblage to calculate rates of overbank deposition and has a distinct advantage over radioisotopic approaches in that it is not limited by radioactive decay. Using the approach, we determined that overbank deposition rates increased over 400% within years of logging events and that the increased rates persisted for less than 4 years. After logging-induced deposition peaked, overbank deposition decreased over 60% relative to the pre-logging background values. The decreased deposition rates persisted for over 40 years. The immediate effect of logging in this watershed was to induce mass wasting events in hollows that produced rapidly traveling sediment pulses. In the subsequent recovery period, reduced sediment loading occurred as a result of a reduction in the volume of sediment available for transport. The reduction in sediment load led to a reduction in overbank deposition rates until subsequent logging disturbances destabilized and emptied other hollows.

KEYWORDS: sedimentation, floodplain, forestry, palynology, Navarro

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INTRODUCTION

As historical records of sediment flux, floodplains can provide information relating to the timing and cause of increased sediment delivery into streams, a factor important because of its relation to pollutant transport (Symader and Thomas, 1978) and in-stream habitat quality (Brown *et al.*, 1994). Furthermore, because much of the sediment generated by a drainage basin is stored within it (Trimble, 1977; Ichim, 1990; Milliman and Syvitski, 1992; Dunne *et al.*, 1998), floodplains may be the only locations capable of providing information related to the extent that basins have been affected by land-use change. For example, the increased runoff and sediment production effects of logging are well documented (Hibbert, 1969; Bosch and Hewlett, 1982; Guthrie, 2002), but there is considerable uncertainty regarding how rapidly and to what extent the sediment is transported through the stream network (Lewis, 1998). Assuming that a portion of the introduced load generated by logging is stored on floodplains, an examination of a fine-resolution overbank deposition record over a sufficiently long period should allow us to determine how logging has altered sediment loading relative to natural conditions. Fine-resolution records for long-term patterns of sedimentation within disturbed watersheds would aid our understanding of the long-term ramifications of logging and the development of sound watershed-management practices.

Unfortunately, many of the current methods used to calculate rates of overbank deposition provide insufficient temporal resolution and length of record for determining contextual anthropogenic effects on sediment flux. Among modern floodplain studies, ^{210}Pb and ^{137}Cs radioisotopes are commonly used to construct 40- to 120-year-averaged records of overbank deposition (*e.g.*, Nicholas and Walling, 1997; Allison *et al.*, 1998; Goodbred and Kuehl, 1998; Walling *et al.*, 1998). Although they have provided useful records of floodplain sedimentation, ^{210}Pb and ^{137}Cs records are limited to the time scale over which they are applicable due to radioactive decay and, in the case of ^{137}Cs, very recent introduction to the environment. Furthermore, methods employing ^{210}Pb and ^{137}Cs cannot provide information related to rapid, short-lived changes in sediment flux because they generate time-averaged values of overbank deposition instead of point-based measurements. Different methods to measure overbank deposition are necessary if floodplain records are to be used to their full potential. Here, we apply a palynological approach to determine fine-resolution overbank deposition rates in a small, mountainous catchment impacted by logging and show how a fine-resolution record can be used to determine the extent of watershed alteration by land-use change.

STUDY AREA

The Flynn Creek basin, draining ~19.3 km^2 of mixed-conifer forest dominated by *Sequoia sempervirens* (Coastal redwood) and *Pseudotsuga menziesii* (Douglas fir), is located within the tectonically active Navarro watershed of the northern California Coast Range. We chose the fourth-order Flynn Creek basin as the study site because its small size and steep drainage would minimize sediment storage and thus promote transport of sediment pulses through the system (Pearce and Watson, 1986; Benda and Dunne, 1997).

The Navarro watershed represents the southernmost extent of natural spawning ground for the endangered *Oncorhynchus kisutch* (Coho salmon). Intensive land use and the highly erodible nature of the underlying Franciscan Complex have led the Environmental Protection Agency to establish strict sediment regulations for the Navarro basin in an effort to protect habitat for *Onco. kisutch* and the threatened *Onco. mykiss* (Rainbow trout) (US EPA, 2000).

Historically, land use in the Flynn Creek basin was dominated by logging activities, which principally targeted *Sequoia* stands. Although the extent of the first period of logging, which began in the 1850's (Palmer, 1967; Holmes and Lawson, 1996), is unclear, photographs document that a second period of logging and a 1931 wildfire completely deforested the basin by 1936 (Figure 1A) and that a third-generation forest developed by 1998 (Figure 1B). A third cut of *Sequoia* stands began in the region during the 1990's.

METHODOLOGY

Site Selection and Sediment Coring

We chose a wetland floodplain near the mouth of Flynn Creek as a coring location (Figure 2) because its frequent inundation and location at the end of the channel network, with minimal sediment storage, allow the site to more fully integrate upstream geomorphic events through the process of overbank deposition. A vibracore was taken from the site to a depth of 350 cm, and the top 87 cm were examined for this study. After collection, the core was soon moved to a laboratory setting, analyzed for physical properties including inorganic grain size distribution, and divided into 3-cm increments. Subsequently, 12 subsamples through the first 42 cm and 5 subsamples through the remaining 45 cm were chosen for palynological analysis according to Faegri and Iverson (1975). Two wood samples were removed from core horizon boundaries at 24 cm and 87 cm depth, and were sent to Beta Analytic, Inc. (Miami, FL) for accelerated-mass-spectrometry ^{14}C dating. The conventional ^{14}C ages for the upper and lower samples were 170 ±40 ybp (1718-1823 cal AD) and 840 ±50 ybp (1152-1280 cal AD) (Constantine *et al.*, 2003). All dates reported hereafter are in units of cal AD. Overbank deposition rates were calculated using the palynological approach described below.

The Palynological Approach

For unvarved sediments, downcore variations in total fossil pollen and fossil pollen assemblage have been demonstrated to resolve short-term fluctuations (~1-20 years) in sediment deposition over a significant time span (~500-1500 years) that includes both climatic change and human activities. The method has been used successfully in lake, delta, coastal wetland, and estuarine environments (*e.g.*, Brush, 1989; Cooper and Brush, 1991; Khan and Brush, 1994; Pasternack *et al.*, 2001) and has been successfully tested against basal-sediment ^{14}C dating (Brush and Hilgartner, 2000) and ^{210}Pb dating (Brush *et al.*, 1982; DeFries, 1986).

According to the palynological approach (Figure 3), individual horizons in the profile are first identified and dated using ^{14}C where sufficient organic material is available or using available pollen or geochemical markers with known local histories. The method assumes that the regional species composition for the period between two dated horizons is similar and, thus, that the pollen influx is uniform when averaged over years to decades (Cooper and Brush, 1991). However, the assumption of uniform influx becomes less valid in regional ecosystems whose plant composition is undergoing rapid change. The larger the area undergoing rapid change, the more variability will occur in the influx of pollen to a study site. In our study, most of the ecosystem change has been focussed in the North Fork Navarro basin, of which the Flynn Creek catchment is a part. The North Fork Navarro basin is only 23% of the total watershed and is likely a much smaller component of the total airshed. We argue, therefore, that the palynological approach is valid in the Flynn Creek catchment and that the yearly to decadal pollen influx is independent of local changes in species composition.

The palynological approach assumes that pollen influx is primarily from the atmosphere. Considering that a floodplain is inundated once every few years, the amount of pollen derived from fluvial transport must be very small relative to the continual atmospheric influx. Furthermore, sediment cores taken from the mouths of large watersheds are often devoid of upland pollen species (Brush and Defries, 1981; Roger Byrnes, pers.comm.), signifying the limited role of fluvial influx for pollen even when basin sediment storage is high. As such, the source of most pollen is independent of the sediment source, and the sedimentation rate in any small core interval may be determined as

$$R_i = \left(\frac{\bar{n}}{n_i} \right) \cdot \bar{R} \cdot \rho_i \,, \tag{1}$$

where R_i (g cm^{-2} yr^{-1}) is the sedimentation rate of interval *i*, $\bar{n}$ is the average number of pollen grains per unit area between dated horizons, n_i is the total number of pollen grains per unit area in interval *i*, $\bar{R}$ (cm yr^{-1}) is the average sedimentation rate based on horizon dates (ybp), and ρ_i is the sample bulk density within interval *i* (g cm^{-3}) (Brush *et al.*, 1982; Brush, 1989).

RESULTS AND DISCUSSION

Overbank Deposition Rates

The interval sedimentation rates determined by Equation (1) (Table 1; Figure 4A) are interpreted as rates of overbank deposition, rather than lateral migration, based on the relatively uniform grain size distribution through the core and the predomination (>50%) of the silt and clay fraction (Figure 4B). Whereas overbank deposition rates prior to 1850, the onset date of settlement and logging, are uniform, rates post-1850 show frequent, large variations as high as 2.59 g cm^{-2} yr^{-1}. As a comparison to data taken from larger basins, He and Walling (1996) and Walling *et al*. (1998) calculated overbank deposition rates of 0.010-0.554 g cm^{-2} yr^{-1} and 0.07-0.59 g cm^{-2} yr^{-1}. The peaks in overbank deposition occur soon after known disturbances to the basin. During 1700, a severe magnitude (~9) earthquake occurred north of the Mendocino Triple Junction (Grant *et al.*, 1995) and could explain the sudden increase in overbank deposition (0.389-0.560 g cm^{-2} yr^{-1}) between 1706 and 1764. Large peaks (≥1.30 g cm^{-2} yr^{-1}) occur soon after American settlement in 1850, deforestation in 1931 (Fig. 1A), and the third period of logging in the 1990's.

Pollen assemblage data confirm anthropogenic causes of increased overbank deposition after 1850. The relative abundance of *Sequoia* pollen declines from an average of 31.0% pre-1850 to 14.6% post-1850 (Figure 4C). *Alnus* (Alder), which is often an indicator of disturbance conditions (Davis, 1973), increases from 0.28% pre-1850 to 2.0% post-1850 (Figure 4D). To determine whether the average changes in pollen were significant for both species, the Mann-Whitney u-test ($\alpha = 0.01$) was used to test the null hypothesis that there was no significant difference between pollen abundance before and after 1850. In both cases, the null hypothesis was rejected based on a p-value of 0.0017 for *Sequoia* and of 0.0027 for *Alnus*. The significant changes in relative pollen abundance before and after 1850 serve as an independent test that the time-depth model (Figure 4A) constructed using Equation (1) is accurate and serve as evidence that the large increases in overbank deposition are related to logging events.

There are three potential causes for changes in overbank deposition: changes between the elevation of the channel bed and floodplain surface, changes in stream discharge, and changes in sediment loading. Changes in elevation difference would alter the amount of coarse suspended load deposited onto the floodplain (Walling *et al.*, 1997). We argue that the elevation difference between the channel bed and floodplain surface has remained essentially the same based on the uniform grain size distribution exhibited through the core (Figure 4B). During the time period investigated, changes in overbank deposition within the Flynn Creek basin can only be due to changes in stream discharge or sediment loading. The dominance of stream discharge and sediment loading in controlling overbank deposition rates is examined below.

Sediment Flux Relative to Natural Conditions

To better analyze the magnitude of changes in overbank deposition, the pre-1850 mean overbank deposition rate, hereafter the natural mean, was calculated based on the assumption that each of the pre-1850 measurements of overbank deposition could naturally occur at any time. The percent change of measured values from the natural mean (0.241 ±0.149 g cm^{-2} yr^{-1}) was then calculated (Figure 5). After the large magnitude earthquake of 1700, overbank deposition rates increased up to 132% of the natural mean and persisted 58 years before returning to near-normal conditions. Although there is evidence that seismic activity can affect pore-water pressure (Wang *et al.*, 2001), there is little evidence that earthquakes can induce long-term changes in hydrologic response. As a result, we believe the increase in overbank deposition at this time was due to an increase in sediment loading rather than stream discharge. Assuming a linear decrease in overbank deposition after the disturbance, sediment delivery to the floodplain decreased on the order of 0.005-0.006 g cm^{-2} yr^{-2} over the 58-year interval. Such a gradual decline suggests that loading to the stream network was chronic. A likely mechanism for chronic sediment loading is earthflow, which commonly occurs in northern coastal California (Nolan and Janda, 1990) and can provide a steady supply of sediment over many decades (Keefer and Johnson, 1983).

Overbank deposition increased on the order of 440-970% of the natural mean after the logging events in 1850 and 1931. After each disturbance, the duration of increased overbank deposition is short, on the order of 2-4 years, and the linear decline in overbank deposition is 0.043-0.15 g cm^{-2} yr^{-2}. In an assessment of the hydrologic response to clear cutting and roads in small Pacific-Northwest basins much like the Flynn Creek catchment, Jones and Grant (1996) determined that average peak discharge increases up to 50% after logging and persists at least 25 years. The long-duration response in peak discharge suggests that increased flooding was not responsible for the short-duration peaks in overbank deposition. Thus, we argue that logging within the Flynn Creek catchment generated rapid, short-lived increases in sediment loading that resembled sediment pulses. Empirical data (Pitlick, 1990) and stochastic modeling (Benda and Dunne, 1997) of sediment transport in the Pacific Northwest provide evidence that sediment pulses travel rapidly through small drainages and may further explain the short duration of increased overbank deposition. Florsheim and others (1991) found similar evidence for rapid transport of sediment generated by disturbance events in a small watershed of southern California.

After logging activities subsided, overbank deposition rates decreased to values 60-70% less than the natural mean and the extremely low rates persisted for 45 after the first logging event and 64 years after the second. The depressed deposition rates were likely a result of how logging impacted the nature of sediment sources. Of the various sources, landslides have been identified as the primary source of sediment in the Flynn Creek region (US EPA, 2000). The magnitude and frequency of landslides, which generate sediment pulses (Benda and Dunne, 1997), increase after logging events (Pitlick, 1990; Montgomery *et al.*, 2000). As the volume of material stored in some hollows is reduced due to landsliding (Montgomery and Dietrich, 1994), the volume of material available for transport within the system is reduced, generating depressed overbank deposition rates. The major source of sediment between logging periods becomes sediment stored upstream from culverts or bridges that is gradually reworked into the system (Constantine *et al.*, 2003) until the next logging disturbance destabilizes and empties new hollows. The legacy of logging on the subsequent interdecadal recovery period is to significantly reduce sediment flux associated with more frequent natural processes, although the immediate impact is to initiate extreme events that dramatically increase sediment loading.

Reconciling Palynological Results with Previous Findings

In Constantine *et al*. (2003), we described the inability of the Flynn Creek study site to record the effects of anthropogenically-derived sediment pulses using only ^{14}C data. We attributed the inability to the damming effects of culverts and in-channel large woody debris. Using the palynological approach, however, we now find that the study site is indeed capable of recording sediment pulses. The most obvious reason for the contrasting results is that the palynological technique allows us to determine overbank deposition rates at a much finer temporal resolution. The contrasting results illustrate the ability of the palynological approach to tease out short-lived fluctuations from long-term averaged sedimentation rates. This paper suggests that although sources of sediment are being released chronically due to land-use change (Constantine *et al*., 2003), the Flynn Creek basin is also highly sensitive to land-use perturbations and can rapidly release significant quantities of sediment as a result.

CONCLUSIONS

Using a palynological approach originally adapted for calculating sedimentation in lake and estuarine environments, we calculated overbank deposition rates in a wetland floodplain of the California Coast Range. The deposition record we produced was of sufficient temporal resolution and extent to determine the effects of logging on sediment flux. Overbank deposition rates increased over 400% after logging events and the increased rates persisted for less than 4 years. In each case, after logging-induced deposition peaked, overbank deposition rates decreased over 60% relative to the pre-logging values. The decreased deposition rates persisted for over 40 years. Our study suggests that although logging immediately increases sediment loading, the majority of the subsequent interdecadal recovery period experiences reduced sediment loading to the stream network. The results of this study could not have been generated with any other known empirical technique, neither monitoring-based nor isotope-based. As such, we advocate use of the palynological approach as a major tool of watershed assessment throughout logging-impacted regions to determine the scope of degraded watershed environments.

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Table 1. Results from the palynological approach to calculating sedimentation rates. R_i (g cm^{-2} yr^{-1}) is the sedimentation rate of interval i, $\bar{n}$ is the average number of pollen grains per unit area between dated horizons, n_i is the total number of pollen grains per unit area in interval i, $\bar{R}$ (cm yr^{-1}) is the average sedimentation rate based on horizon dates (ybp), and ρ_i is the sample bulk density within interval i (g cm^{-3}).

Depth (cm)	$\bar{R}$ (cm yr^{-1})	ρ_i (g cm^{-3})	$\bar{n}$	n_i	R_i (g cm^{-2} yr^{-1})
0-3	0.141	1.729	23060	9314	0.6036
3-6	0.141	1.407	23060	49440	0.09253
6-9	0.141	1.209	23060	1516	2.593
9-12	0.141	1.415	23060	69920	0.06580
12-15	0.141	1.305	23060	2890	1.468
15-18	0.141	1.225	23060	9146	0.4355
18-21	0.141	1.779	23060	4437	1.304
21-24	0.141	1.455	23060	37800	0.1252
24-27	0.094	1.912	36803	36817	0.1797
27-30	0.094	1.123	36803	19580	0.1984
33-36	0.094	1.746	36803	15510	0.3894
39-42	0.094	1.428	36803	8810	0.5607
51-54	0.094	2.037	36803	36846	0.1913
60-63	0.094	2.185	36803	36798	0.2054
75-78	0.094	1.411	36803	27460	0.1778
78-81	0.094	1.588	36803	126100	0.04357
84-87	0.094	1.534	36803	23310	0.2277

FIGURE CAPTIONS

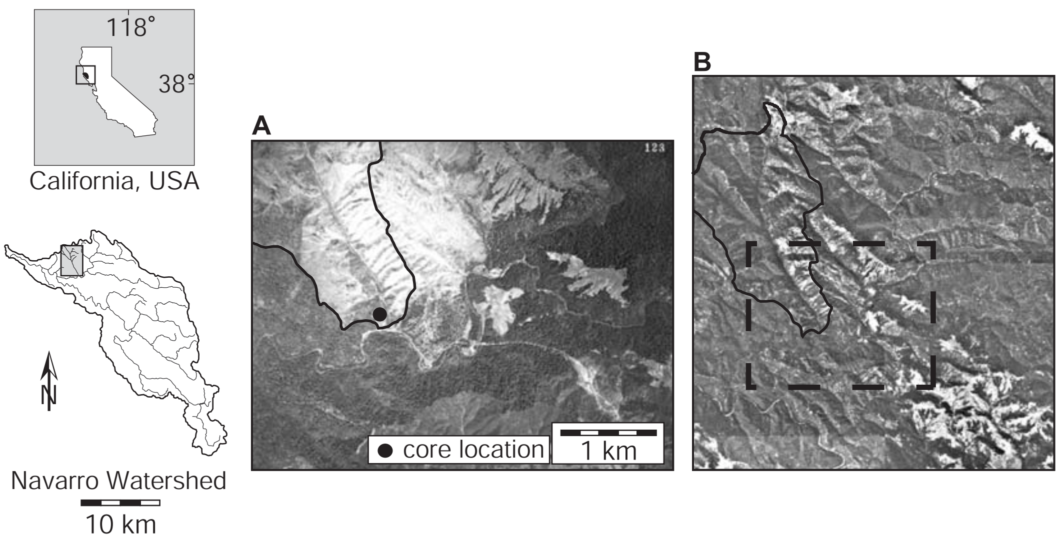
Figure 1. Flynn Creek Basin. A: Aerial photograph of the lower portion of Flynn Creek basin and surrounding region in 1936 after logging and a fire in 1931 removed much of the forest cover. The core location at the mouth of Flynn Creek is also shown. B: Satellite image of the basin and region in 1998. The hatched box is the viewing area in (A). The outline of the Flynn Creek basin is drawn into both images.

Figure 2. Location map and topographic contours of the coring site. Topographic data used to construct the 25 m contours were obtained from the USGS National Elevation Dataset. Channel centerlines are shown for Flynn Creek and North Fork Navarro. The core location near the mouth of Flynn Creek allows the study site to more fully integrate upstream geomorphic processes as overbank deposition.

Figure 3. Diagram illustrating the palynological approach to calculating overbank deposition rates. In the diagram, the floodplain surface receives sediment through overbank flows at a rate (R_t). The floodplain surface also receives pollen grains (n) from the atmosphere through time interval (Δt). In the palynological approach, the number of pollen grains landing on the surface of the floodplain through time ($n/\Delta t$) is considered constant through the time interval (K_t). Between two determined time horizons, there is an average sedimentation rate ($\overline{R}$) and an average number of pollen grains ($\overline{n}$). Within a sample interval, the palynological approach calculates a sedimentation rate (R_i) using the bulk density of the sample interval, $\overline{R}$, $\overline{n}$, and the number of grains within the sample interval (n_i).

Figure 4. A: Overbank deposition rates through time plotted as midpoints; the time-depth model used to construct the time axis is located as an inset. B: Grain size fraction as determined through time. C: Relative abundance of *Sequoia* pollen through time. D: Relative abundance of *Alnus* pollen through time. Hatched line (1) marks the occurrence of a large magnitude earthquake in the region. Hatched lines (2), (3), and (4) mark logging events in the watershed.

Figure 5. Percent magnitude of change in overbank deposition rates from the natural mean through time. Shaded region defines the range of possible natural overbank deposition rates as determined by the standard deviation from the natural mean. Hatched line (1) marks the occurrence of a large magnitude earthquake in the region, whereas hatched lines (2), (3), and (4) mark logging events.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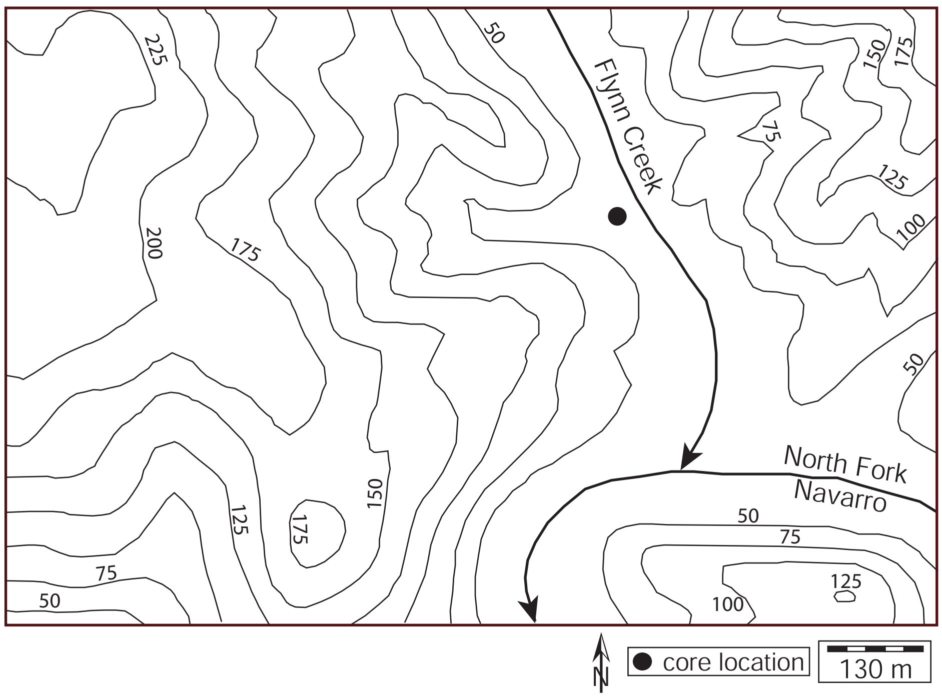

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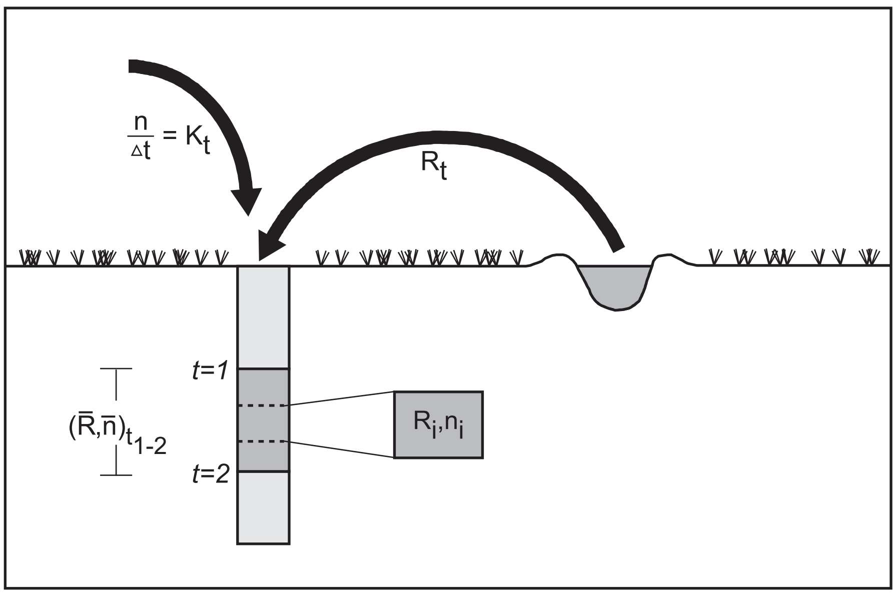
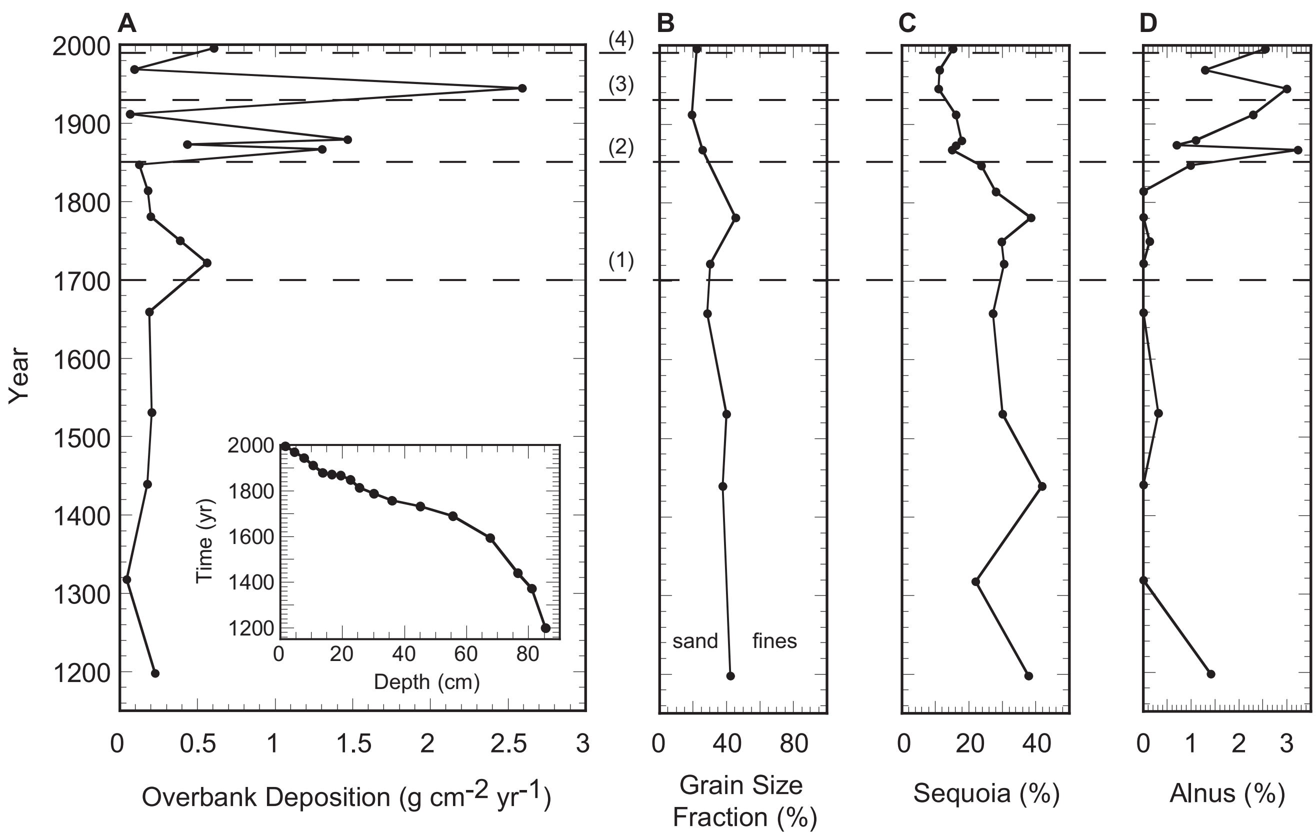


$\frac{n}{\Delta t} = K_t$
R_t
$t=1$
$(\bar{R},\bar{n})_{t_{1\text{-}2}}$
R_i, n_i
$t=2$



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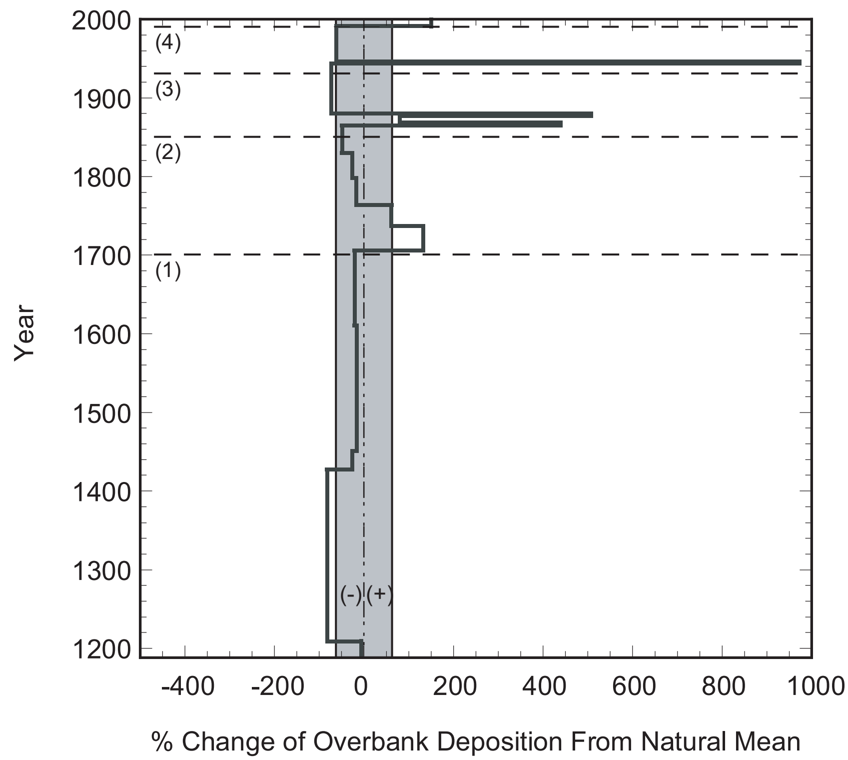
2.5
3
Overbank Deposition (g cm-2 yr-1)
0
40
80
Grain Size Fraction (%)
0
20
40
Sequoia (%)
0
1
2
3
Alnus (%)



2000
1900
1800
1700
1600
1500
1400
1300
1200
Year
(4)
(3)
(2)
(1)
(-)
(+)
-400
-200
0
200
400
600
800
1000
% Change of Overbank Deposition From Natural Mean