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Resolving the chronology of recent lake sediments: an example from Devils Lake, North Dakota

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Abstract

Devils Lake is a closed, saline lake in North Dakota; it is typical of lake basins in the Great Plains Region, where windy conditions and fluctuating water-levels disturb sediment and confound chronostratigraphy. Pollen analysis and ^{210}Pb dating of two cores collected from bathymetrically contrasting embayments demonstrate (1) how certain agriculture-related pollen types differ in their value as chronostratigraphic markers, (2) how pollen and ^{210}Pb stratigraphies can be reconciled to determine the approximate depth of sediment mixing, and (3) the importance of coring-site selection, especially in lakes with unstable sedimentary conditions.

Introduction

A reliable chronology is essential when lake sediments are used to study environmental history of a region or locality. As the time period of interest becomes shorter, dating accuracy and precision must increase. The most common radiometric method used for dating lake sediments younger than 150 years old is ^{210}Pb. This technique usually assumes a constant supply of ^{210}Pb to the sediments as well as lack of mixing of sediments after deposition; both are reasonable assumptions in many lakes.

However, many lake basins located in the prairie region of the midwestern United States, including North and South Dakota and parts of Minnesota, present problems. Typically these lakes are shallow (less than 10 m deep), and wind-driven currents can resuspend and move sediment particles. Most lakes in this region are in topographically closed basins and thus are sensitive to climatic change. Fluctuating lake levels can also have significant effects on the rate of supply of both sediment and ^{210}Pb to a coring site.

Careful site selection can help minimize these problems (Jacobson & Bradshaw, 1981). Unfortunately, many sites in the Dakota region have dried on one or more occasions during the past 10 000 years (some as recently as the 1930's), leaving hiatuses in the stratigraphic record. Chronostratigraphies based on ^{210}Pb dating of lake sediments of this region must therefore be evaluated carefully and checked by independent means. Pollen analysis, for example, reveals the well-documented history of Euro-American settlement and the introduction of both cultivars and the non-native weed *Salsola iberica* Senn. & Pau. (Russian Thistle), the chronostratigraphic significance of which has not been described previously in the literature.

Here we present an example from Devils Lake, North Dakota, demonstrating how a chronology based on ^{210}Pb can be checked with pollen analysis, historical accounts, and lake-level records. The importance of sampling technique, pollen production and transport, and accuracy of historical records in chronostratigraphy is demonstrated. Results derived from two bays with distinctive bathymetry illustrate the importance of coring-site location. ^{210}Pb and pollen chronologies from an open, wind-stressed bay disagree, while those from a narrow, more protected site correspond well.

Study site

Devils Lake lies on the Drift Prairie (Simpson, 1929) of northeastern North Dakota (48°05′N, 98°56′W). The major portion of the lake is the circular Main Bay (50 km^2); Creel Bay (5 km^2) is a narrow appendage on the northeast corner of Main Bay (Fig. 1).

Surficial deposits in the area consist of glacial drift containing fragments of Pierre Shale. Late-glacial lacustrine deposits are also present. The

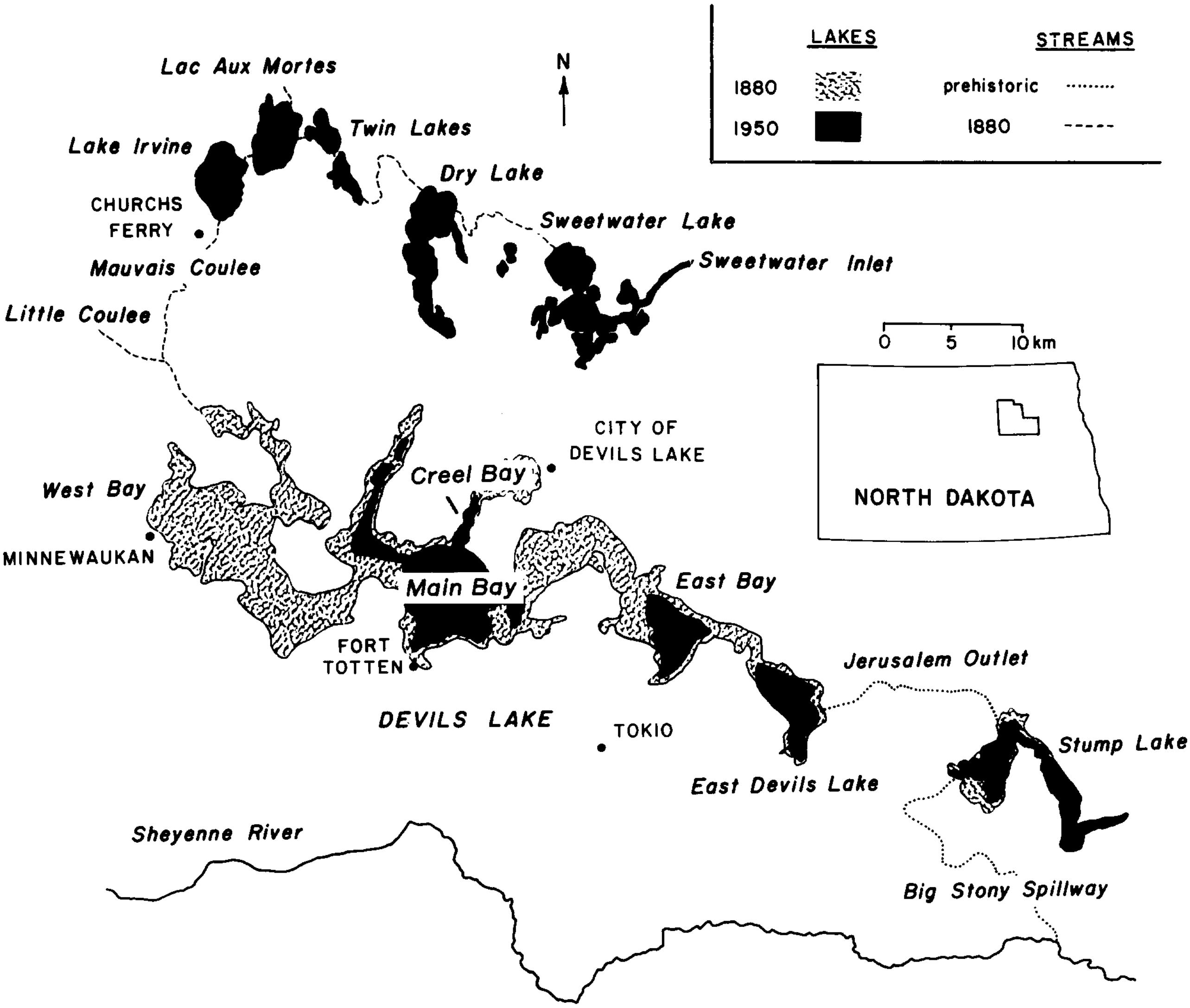


Fig. 1. Map of Devils Lake showing some recent and historical changes in basin morphometry and hydrology (after Aronow, 1957).

lake is bounded on the south by the North Viking morainal complex, which is characterized by 'knob and kettle' topography. The poorly developed Sweetwater moraine is 10 km to the northeast. Gently rolling topography of washboard moraine occurs northwest of Devils Lake (Callendar, 1968).

During the Late Wisconsin glaciation, meltwater flowed from Devils Lake through the Jersusalem Outlet to Stump Lake and then through the Big Stoney Spillway to the Sheyenne River (Aronow, 1957) (Fig. 1). Through-drainage terminated after iceretreat, and lakes formed in the individual basins. Until AD 1889, Devils Lake was supplied by water from Mauvaise Coulee, which drained the Sweetwater group of lakes as well as the waters of the Sweetwater Inlet and Little Coulee to the north. Since 1889 Mauvais Coulee has had a dry bed, except during spring thaws (Simpson, 1912; Aronow, 1957). As a result, by 1965 the surface area of the lake had decreased from about 20000 to 4800 ha (Stoermer *et al.*, 1971).

Annual records of water level in Devils Lake (Fig. 2) show a steady decline between 1867 and 1940 and a subsequent rise to the present (Swenson & Colby, 1955). The maximum depth of the water in 1968 was about 3.5 m (Callendar, 1968), but today it is near 8.5 m. Stoermer *et al.* (1971) reported that the water column in Main Bay could be disturbed by the slightest wind, because of the shallow water depth and pan-like morphometry (Fig. 3).

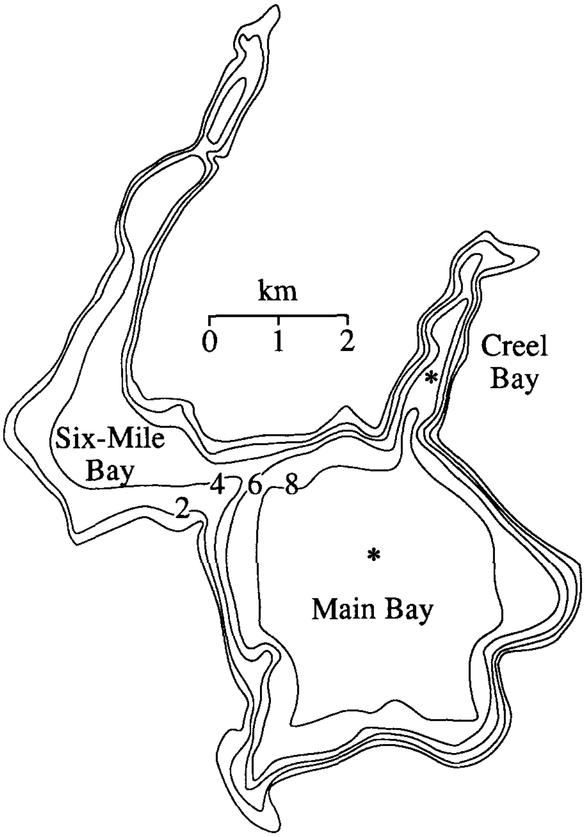


Fig. 3. Bathymetric map of Devils Lake with depth contours in meters. Asterisks denote coring sites.

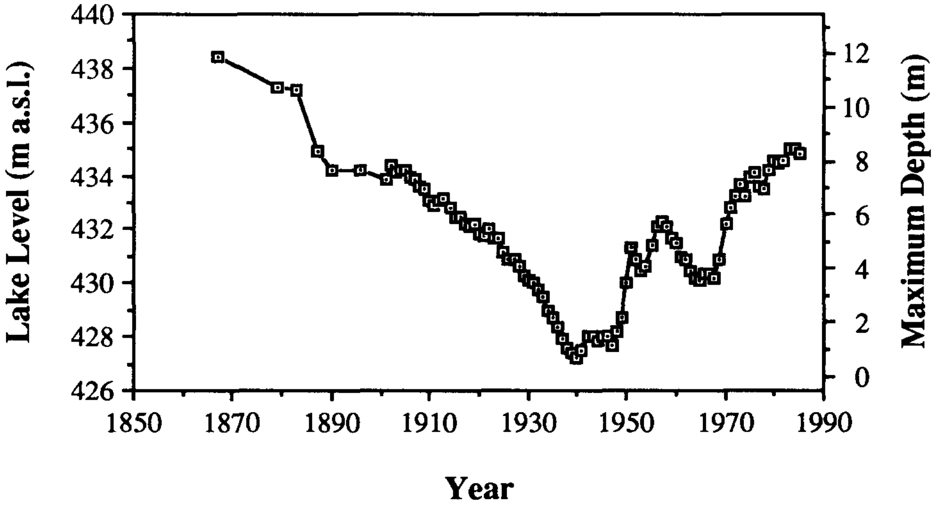


Fig. 2. Historical water level fluctuations in Devils Lake (compiled by the Army Corp of Engineers).

Settlement history

In 1859 the first farm was established in the Red River Valley. At that time a settlement of about 100 families of Chippewa Indians was located at Devils Lake. The Turtle Mountain region 100 km northwest of Devils Lake was settled by European farmers around 1870, when less than 100 acres were under cultivation in North Dakota (Lounsberry, 1919).

North Dakota was surveyed and divided into districts in 1872 and 1873, after which homesteading began, primarily on land along waterways. Homesteaders were alloted quarter-sections (160 acres), which were often shared by family members. Initially, only native prairie grasses were harvested in quantity for animal fodder. Within a few years settlers usually had acquired breaking plows and oxen, and were thus able to raise grains (H. R. Rutten, personal communication). For the first decade, however, homesteaders grew only enough crops to feed their families and trade with neighbors. Cash crops such as wheat (*Triticum*) were not grown until their rapid transport was made possible by construction of railroads (Drache, 1970), which were then the key to agricultural and economic expansion (Fig. 4).

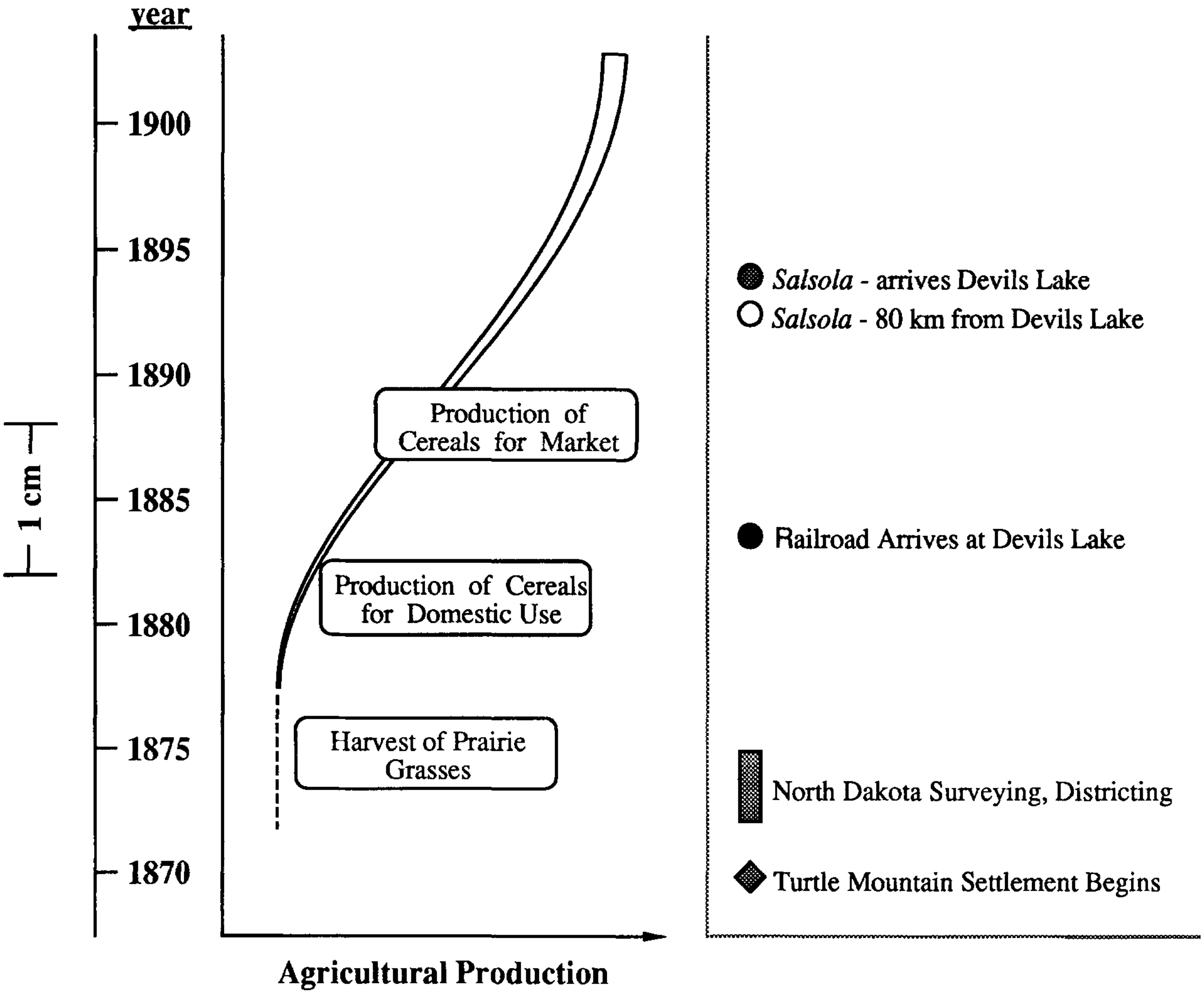


Fig. 4. Schematic representation of agricultural production and historical events in the Devils Lake area relative to their vertical expression in the core.

The Great Northern Railroad reached the town of Devils Lake in July of 1883. Already Devils Lake was a 'rapidly growing town' large enough to support establishment of other nearby towns (Severson, 1924). Wheat production escalated in the following years, until it became the primary crop in the region (Reitz, 1954).

The region suffered disastrous droughts in 1934 and 1936, and precipitation remained relatively low through 1939. Many farms were abandoned during those 'dust bowl' years (Robsinson, 1966).

Methods

Sampling

In July of 1983 a core of the uppermost sediment from the center of Main Bay of Devils Lake (Fig. 3) was obtained with a piston sampler in water 8.4 m deep. The core was 10 cm in diameter, about 1 m long, and watery on top but progressively firmer toward the bottom. While the tube was held vertically in the field, the upper 50 cm of the core was extruded and sampled at 1-cm intervals, and the lower 50 cm was cut into 2-cm segments. Each section was sealed in a marked Whirlpak. The samples were homogenized by hand and stored at 4 °C for 17 months. A core 1 m long from a depth of 7.5 m in Creel Bay was collected and subsampled in the same manner in January of 1986.

^{210}Pb dating

The two cores from Devils Lake were analyzed for excess ^{210}Pb activity to determine age and sediment-accumulation rates for the past 200 years. ^{210}Pb was measured at 32 depth intervals in each core through its grand-daughter product ^{210}Po, with ^{208}Po added as an internal yield tracer. The polonium isotopes were distilled from 1–3 g dry sediment at 550 °C following pretreatment with concentrated HCl and plated directly (without HNO_3 oxidation) onto silver planchettes from a 0.5 N HCl solution (modified from Eakins and Morrison, 1978). Activity was measured for $1–4 \times 10^5$ s with Si-depleted surface detectors and an Ortec Adcam^{TM} alpha spectroscopy system. Unsupported ^{210}Pb was calculated by subtracting supported activity from the total activity measured at each level; supported ^{210}Pb was estimated from the asymptotic activity at depth (the mean of the lowest 7 samples in Creel Bay, and 9 samples in Main Bay). Dates and sedimentation rates were determined according to the c.r.s. (constant rate of supply) model (Appleby & Oldfield, 1978), with confidence intervals calculated by first-order error analysis of counting uncertainty (Binford, 1988).

Pollen analysis

Subsamples of 1 cm^3 were processed for pollen analysis by standard chemical methods (Faegri & Iversen, 1975). A known volume of a microsphere suspension of known concentration was added to each subsample in order to determine pollen concentrations (Benninghoff, 1962).

Pollen counts were made with a Leitz Ortholux light microscope at 450 × and 900 × magnifications. At least 300 pollen grains were counted at each level. Identifications were aided by the reference collection of E. J. Cushing, reference texts (Faegri & Iversen, 1975; McAndrews *et al.*, 1973), and consultation with E. J. Cushing & E. C. Grimm. Poaceae pollen was separated into the Wild-Grass Group, *Hordeum* Group, *Avena/Triticum* Group, and *Secale* according to the characteristics described by Andersen (1979) & Beug (1961).

The important indicator genus *Salsola* was carefully distinguished from similar Chenopodiaceae taxa such as *Corispermum*. *Salsola* pollen is subpolyhedric and periporate. It usually has approximately 36 pores, which occur in deep depressions. The depressions are separated by broad ridges with striking scabrate elements (Faegri & Iversen, 1975). Two species of *Salsola* occur in the Great Plains, *S. iberica*, which was introduced in the 19th century, and *S. collina* Pall., which arrived as early as 1922 but went unrecognized until 1958 (Beadle, 1973; Brooks, 1986).

Diagrams of pollen percentages show all upland taxa in the pollen sum, including those of clearly local origin. Aquatic and wetland taxa are excluded from the sum, as are 'unknown' and 'indeterminable' grains (Cushing, 1967). Botanical nomenclature follows Great Plains Flora Association (1986).

Results and discussion

Lead-210

Lead-210 profiles are generally similar for the Creel and Main Bay cores (Fig. 5). Maximum unsupported activities in the uppermost sediments (< 6.5 pCi/g) are considerably lower than values commonly reported for lakes in forested regions (e.g. Davis *et al.*, 1984), reflecting in part dilution of ^{210}Pb by a high sediment flux. As a result, supported ^{210}Pb (derived from *in situ* decay of ^{226}Ra) represents a substantial portion of the total activity at all stratigraphic levels. Although such conditions can introduce substantial errors in older dates (Appleby & Oldfield, 1988), estimates of supported ^{210}Pb (from the asymptote of total activity) are highly precise and nearly identical for the two cores (0.78 ± 0.02 and 0.80 ± 0.03), lending confidence to our calculated values for unsupported ^{210}Pb.

In both cores unsupported activity decreases exponentially with depth (or its analog, cumulative dry weight), although close-interval dating shows the profiles to be non-monotonic. A major inflection occurs at 30–35 cm (7–9 g/cm^2 cumulative dry wt.) in the Creel Bay core, while the Main Bay profile is virtually flat between 24 and 34 cm (6–10 g/cm^2 cumulative dry wt.). The c.r.s. model treats these sections as periods of higher sediment flux as indicated by steep slopes on the age-depth

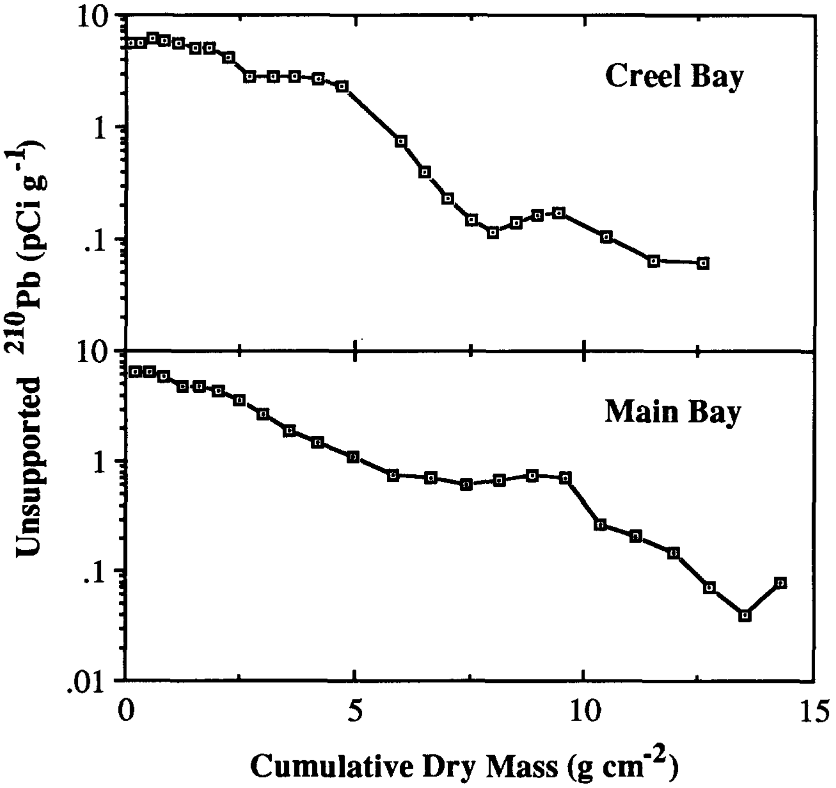


Fig. 5. Unsupported ^{210}Pb activity profiles from the Creel Bay and Main Bay cores; the error bars for counting precision (± 1 s.d.), if shown, would be generally smaller than the square symbols on the graph.

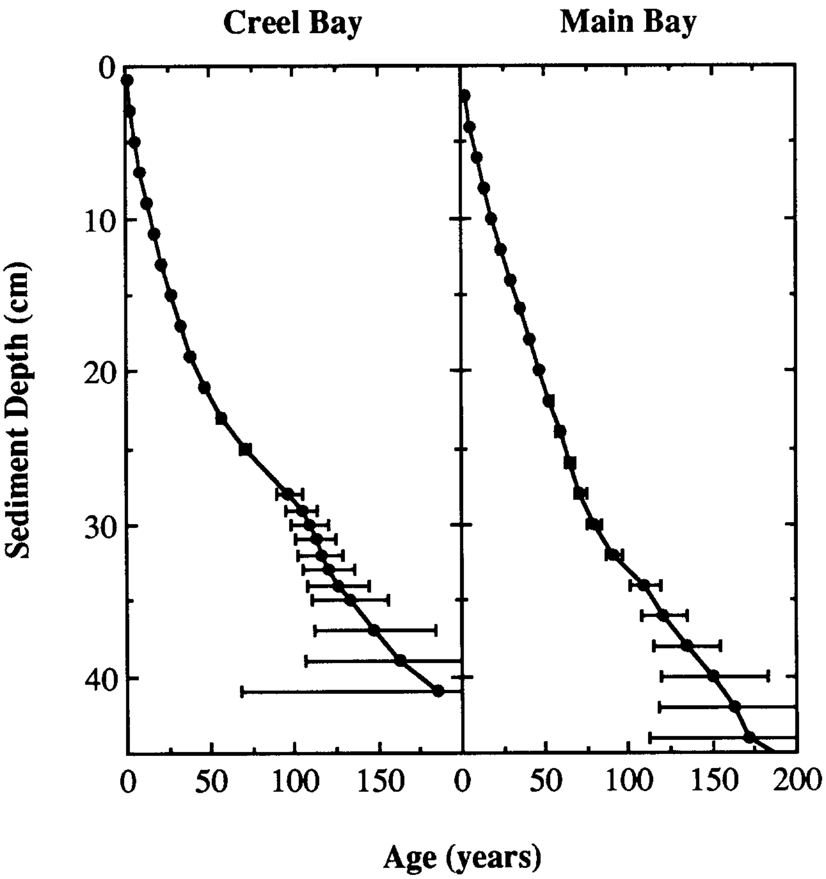


Fig. 6. ^{210}Pb-derived age/depth profiles from the Creel Bay and Main Bay cores; the error bars (± 1 s.d.) represent first-order propagation of counting precision.

profiles (Fig. 6). Average sediment accumulation is similar for the two basins, but it fluctuates asynchronously between 50 and 150 mg cm^{-2} yr^{-1} over the last 200 years (Fig. 7). These changes in accumulation are not correlated with any discernible shift in gross sediment composition (Fig. 8) that should normally accompany changes in material input to a lake (nutrients, clastics, etc.). The accumulation peaks more likely reflect shifts in sediment deposition pattern within the two basins, whereby more material was moved to the core-sites without changing its composition. Despite differences in sedimentary history, the flux of ^{210}Pb is very similar in Creel Bay and Main Bay (0.653 and 0.637 pCi cm^{-2} yr^{-1}, respectively), a condition that supports the use of the c.r.s. dating model.

Presettlement vegetation

Diagrams of pollen percentages (Fig. 9) from both Creel Bay and Main Bay of Devils Lake reveal that prior to disturbance by Europeans the prairie vegetation was similar to that of the North Dakota Plains described by McAndrews & Wright (1969). Pollen spectra are characterized by *Artemisia* (20–25%), Wild-Grass Group of Poaceae (10–20%), and *Ambrosia*-type (1–5%). Trees and shrubs such as *Acer negundo, Fraxinus pennsylvanica, Ulmus americana, Ostrya virginiana, Populus deltoides* var. *occidentalis, Corylus cornuta, Alnus* spp., and *Salix* spp. probably occurred in wet, shallow sloughs, which are abundant in the morainal topography surrounding Devils Lake, as well as along the lake shores, where they also

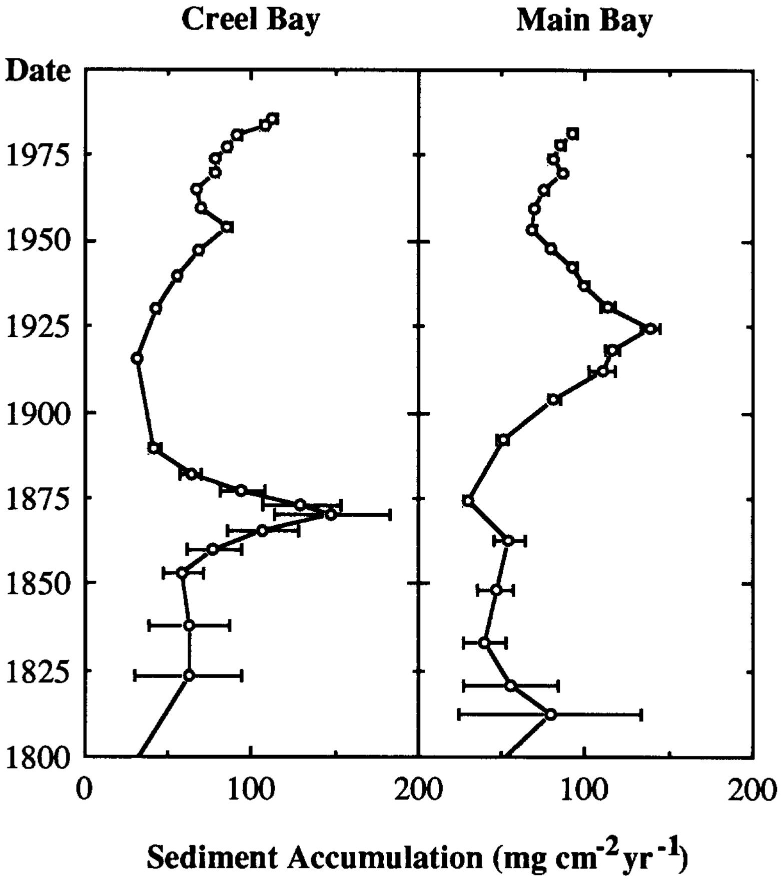


Fig. 7. ^{210}Pb-derived sediment accumulation rates for the Creel Bay and Main Bay cores; the error bars (± 1 s.d.) represent first-order propagation of counting precision.

grow today (Stevens, 1963; Fowells, 1965). *Quercus macrocarpa* probably occupied drier, more exposed sandy plains and west-facing slopes (Fowells, 1965).

Cultural chronostratigraphic indicators in the pollen record

As the population of homesteaders increased in the region surrounding Devils Lake, more and more land was converted from native mixed-prairie to cultivated fields. Evidence of those changes in land use are preserved in the fossil-pollen stratigraphy as the initial appearance of pollen types from imported cultivars, such as wheat (*Triticum*), rye (*Secale*), and oats (*Avena*), and by increases in pollen of native weedy plants such as *Ambrosia*, *Chenopodium*-type, and *Iva xanthifolia*, which proliferate when prairie vegetation is disturbed. Other anthropogenic indicators include deliberately or inadvertently introduced weeds such as *Brassica* and *Salsola iberica* (formerly *Salsola kali* L. var. *tenuifolia* Tausch and *S. pestifer* A. Nels.), natives of eastern Europe and western Asia.

The chronostratigraphic value of individual anthropogenic indicators depends upon several factors, including pollen production and transport relative to the size of the collecting basin, historical documentation of events affecting the taxon, sampling interval relative to sedimentation rate, and the number of grains counted per level relative to the vegetation type. These taxa can be separated into three ecological groups: native weeds, cultivars, and introduced weeds.

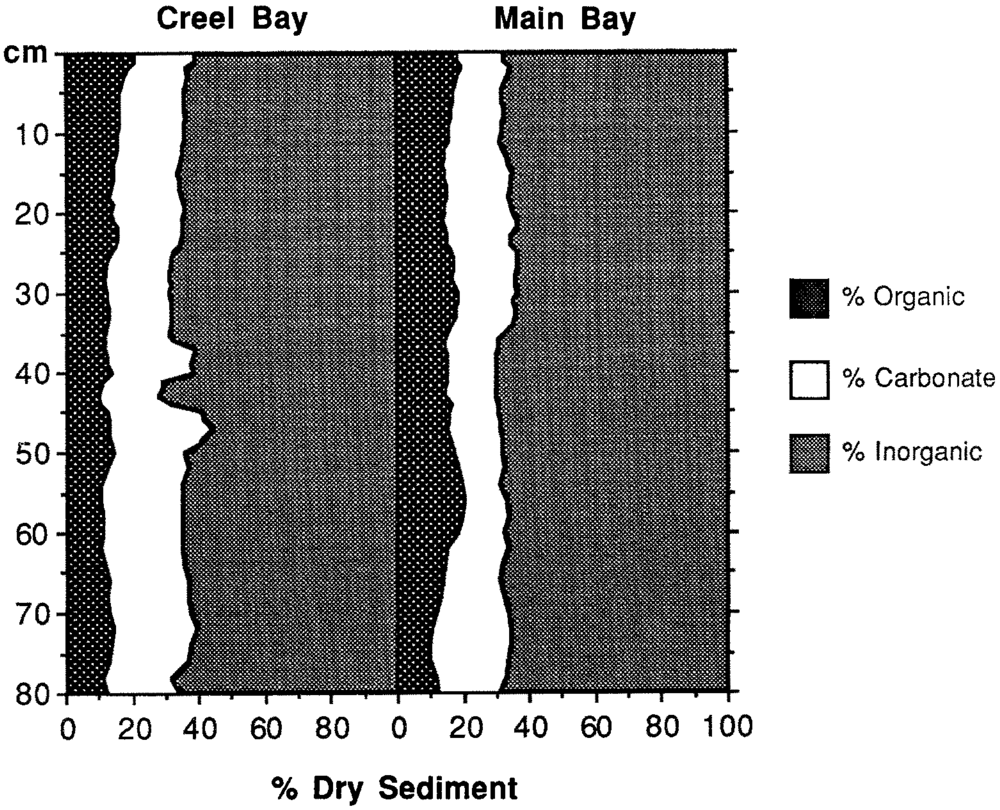


Fig. 8. Sediment composition of Creel and Main Bay sediments as determined by loss-on-ignition.

Native weeds

In the Creel Bay core *Ambrosia* pollen rises initially from 5% to 10% between 35 and 33 cm, and again from 10% to 15% between 29 and 27 cm. *Chenopodium*-type also increases from less than 10% to over 15% at 27 cm, after which both taxa remain relatively abundant to the top of the core. There is also a slight increase in *Iva xanthifolia* at this time.

A marked increase in *Ambrosia* pollen is considered a reliable indicator of regional and local land clearance and agricultural disturbance across eastern North America (Bradbury & Waddington, 1973; Brugam, 1978). Discrepancies between radiocarbon dates for the *Ambrosia*-rise and dates of historically recorded disturbance have often been used to correct radiocarbon dates of long cores (Grimm, 1983; Waddington, 1969).

Chenopodium-type pollen can increase in response to both land disturbance and climatic warming, especially when lake levels are lowered and mud flats become exposed (Wright *et al.*, 1963; Watts & Winter, 1966). Lake-level records since the late 1860's show that between 1880 and 1890, just at the beginning of local agricultural expansion, the water depth at Devils Lake decreased by ca. 3 m (Fig. 2). It is likely that this occurred in other lakes of the region as well. In a gently sloping basin like Devils Lake, a 3 m drop in water level would result in aerial exposure of a considerable area of lake bottom suitable for colonization by taxa in the family Chenopodiaceae (Fig. 3).

Both *Ambrosia* and Chenopodiaceae taxa produce large quantities of pollen, which is dispersed over long distances. They compete effectively for water and do well during dry periods. If the collecting basin is large as at Devils Lake, agricultural disturbance and warm or dry climatic events should be detected at some distance.

Iva xanthifolia occurs in rich soils of abandoned

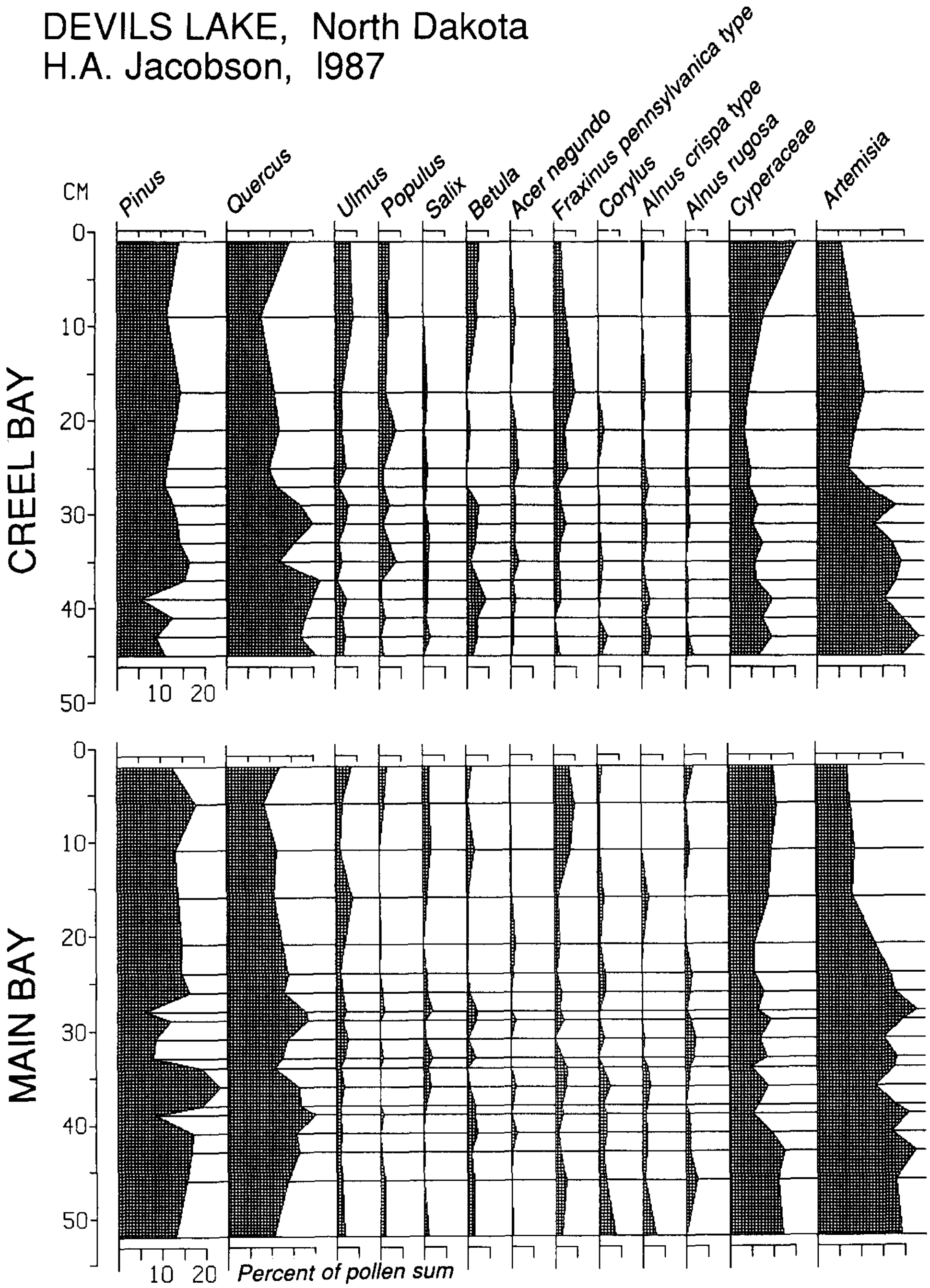
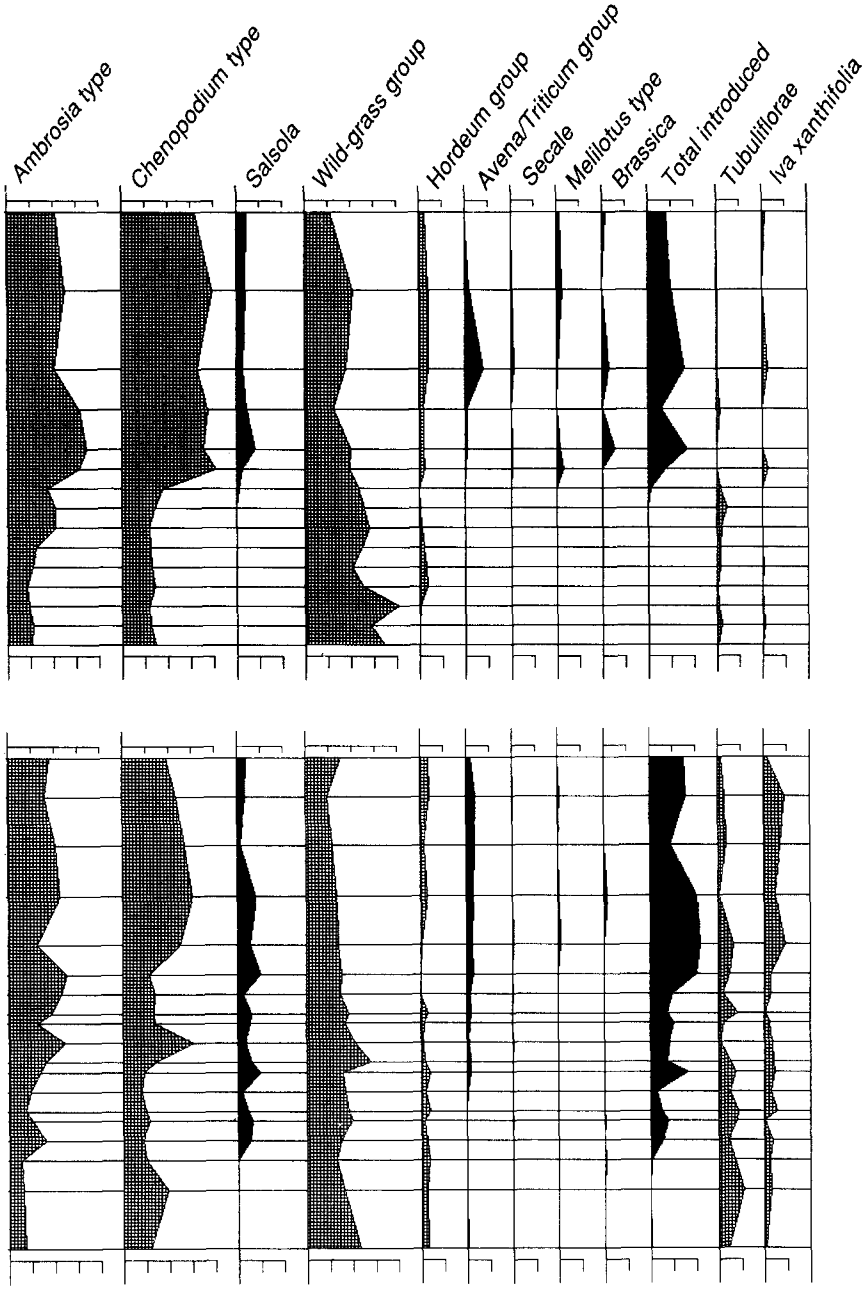


Fig. 9. Diagrams of pollen percentages of selected pollen types from Main Bay and Creel Bay.


Ambrosia type
Chenopodium type
Salsola
Wild-grass group
Hordeum group
Avena/Triticum group
Secale
Melilotus type
Brassica
Total introduced
Tubuliflorae
Iva xanthifolia

fields and waste places. Its native range in 1847 was from northeast Wisconsin to New Mexico, but by 1894 it had spread from farm to farm into all parts of North Dakota (Pammel, 1894). Its historical appearance at Devils Lake is undocumented.

The fact that *Chenopodium*-type and *Iva xanthifolia* pollen increase together with *Ambrosia* at 29–27 cm in Creel Bay suggests that this depth corresponds to the time of land disturbance that was either more intense or more local than that represented by the first rise in *Ambrosia* (35–33 cm), which may correspond to agricultural expansion in the Turtle Mountain region (1870) or to small-scale, local homesteading immediately following the formation of districts in 1873. The second *Ambrosia* rise probably corresponds to local agricultural expansion related to the opening of new markets by the railroad after 1883.

Cultivars

Cereals including *Avena, Triticum*, and *Secale* have large pollen grains that are not widely dispersed. *Avena* and *Triticum* are autogamous (self-fertilizing) species; much of their pollen remains in the chaff and is poorly dispersed except during thrashing (Behre, 1981; Vuorela, 1973). *Secale* is an allogamous (wind-pollinated) species with high pollen productivity. Although the pollen grain is large and rather poorly dispersed (Vuorela, 1973), it does occur in low concentrations in local lake sediments and is considered by Behre (1981) to be among the most reliable indicators of local cultivation.

Thus although the presence of cereal pollen in the sediments is a good indication of local presence of the taxon, its absence does not necessarily indicate local absence of the taxon (Behre, 1981). Historical records at Devils Lake reveal that cereals were grown nearby as early as 1875. However, pollen concentrations in the sediments probably would not have been high enough to be detected at the pollen levels counted in this study (ca. 300 grains counted per level) until after 1883, when crop production began to increase for export by railroad.

Melilotus albus, M. officinalis, Trifolium pratense, and *T. repens* make up the *Melilotus*-type (clover) group. Clover is a forage crop grown for livestock feed and was probably not abundant until after the railroads began transporting farm animals to the Devils Lake area. Thus the appearance of *Melilotus*-type pollen in the Creel Bay core at 25 cm also probably corresponds to sometime after 1883.

Introduced weeds

Brassica spp. (wild mustards) are weedy inhabitants of disturbed ground. Although many taxa are known to have been introduced from Eurasia (Rollins, 1981), the locations of introduction and the timing of dispersal are not well documented. *Brassica* pollen (ca. 3%) appears in the Creel Bay diagram for the first time at 25 cm; the plants were probably locally present at that time. Unfortunately, the arrival of *Brassica* can be constrained only to sometime after 1873.

Unlike *Brassica*, extensive documentation of the introduction and spread of *Salsola iberica* allows for a precise estimation of its time of arrival at Devils Lake (1894–1895). *Salsola* seeds from Russia were introduced to North America near the town of Scotland, Bom Homme Co., South Dakota, in 1873 (Dewey, 1893). The seeds were sown with the imported flaxseed (*Linum*), of which they were a contaminant.

Salsola iberica is an annual that does well during dry spells. It is capable of taking over cultivated fields to the virtual exclusion of the intended crop, and it can be a serious impediment to farm equipment. Significant reductions in wheat production in Russia and in the Dakotas have been attributed to this weed.

The young *Salsola* plants are succulent and digestible by livestock, but as they mature they form sharp spines and hard tissues. The mature plants have broad, light, hemispherical forms up to 2 m in diameter, which are held in place by a small, delicate, root system. The small root breaks under the force of the wind, setting the plant off rolling as a tumbleweed, scattering thousands of seeds in its path. The dried corolla remains attached to the seed and acts like a sail, allowing the seed itself to be carried short distances by the wind.

In this manner individual *Salsola iberica* plants can advance 8 to 15 km over flat open areas in one season, primarily in the direction of prevailing winds. The spread of seeds is substantially hindered only by streams, hollows, or fences. By 1892 the distribution of the plant was bounded on the west by the Missouri River and on the east by several smaller north-south waterways. Such barriers were overcome, however, as seeds were carried by railroads and in the flaxseed they transported (Dewey, 1893). *Salsola*'s ability to spread is well illustrated in Mack's (1986) discussion of plant invasion in the intermountain West.

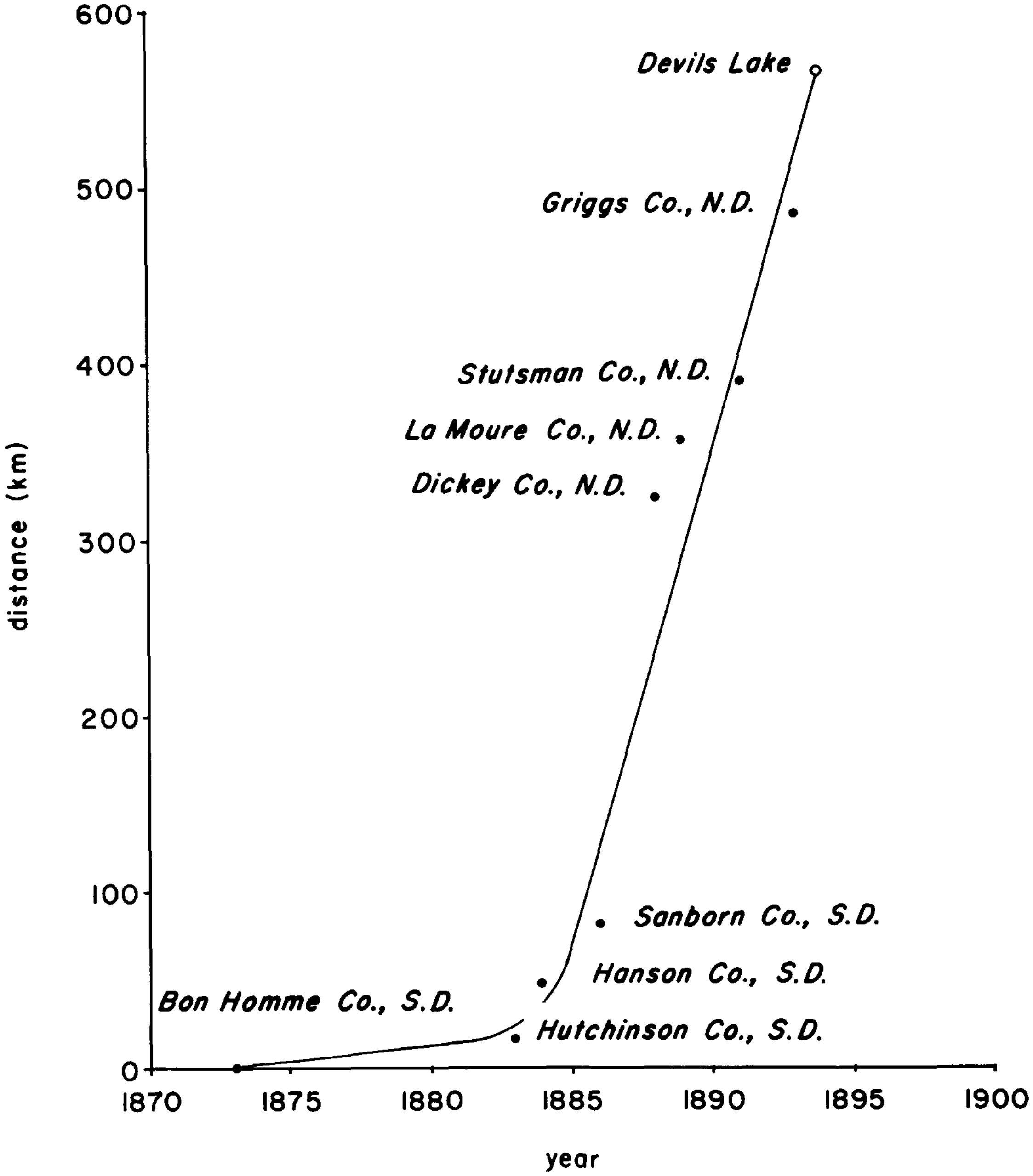


Fig. 10. Migration of *Salsola iberica* in South Dakota and North Dakota with projected arrival at Devils Lake (after Dewey, 1894).

The U.S. Department of Agriculture (Dewey, 1893, 1894, 1895) carefully recorded the expansion of *Salsola iberica* from county to county in South Dakota and into North Dakota as far as Griggs Co., where it arrived in 1893, about 80 km south of Devils Lake. Figure 10 shows the migration sequence, which includes a lag in the first decade and rapid migration (about 55 km/yr) in the next decade. If that rate was maintained between 1893 and 1894, as models of rates of spread predict (Roughgarden, 1986), *Salsola iberica* would have been present locally at Devils Lake by 1894 or 1895.

Like other taxa of the Chenopodiaceae, *Salsola* produces large quantities of easily dispersed pollen. *Salsola* pollen could therefore occur in low abundance in sediments of lakes several km or even tens of km from the source plants. In this case, however, the rate of migration (ca. 55 km/yr) was such that only two years prior to the arrival of this species at Devils Lake the population would have been too far away (> 100 km) for pollen to be detected with the pollen sum used. Assuming a sedimentation rate of 0.125–0.250 cm/yr, sediment deposited when the plants were locally present would have been less than one cm above that deposited when the source plants arrived within the range of pollen transport.

Comparison between Main Bay and Creel Bay

At the settlement horizon represented in both pollen diagrams (Fig. 9), *Artemisia* pollen decreases, *Ambrosia* and *Chenopodium*-type pollen increase, and *Avena/Triticum, Secale, Melilotus*-type, *Brassica*, and *Salsola* pollen appear. *Syringa vulgaris* (lilac) pollen also appears in Creel Bay samples.

It is doubtful that there are any significant differences in the history of the vegetation surrounding Main Bay and Creel Bay. However, the evidence in the cores of the events listed above differs considerably between the bays. In Creel Bay, all of the changes mentioned are relatively synchronous, occurring between 27–29 cm. In Main Bay, *Avena/Triticum* appears first at 53 cm but not again until 37 cm; *Brassica* first appears at 44 cm, *Salsola* at 41 cm, *Secale* at 40 cm, and *Melitous*-type at 17 cm.

The timing of the arrival of *Salsola iberica* provides the best check on the reliability of the Main Bay stratigraphy. *Salsola* appears for the first time at 41 cm in the Main Bay core; it may occur as low as 42 cm, which was not analyzed for pollen. Sediments at 41 cm corresponds to ca. 1825 by ^{210}Pb dating, 60 years earlier than the arrival of the species. The pollen and ^{210}Pb chronostratigraphies in Main Bay cannot be reconciled. Nor can it be assumed that the pollen record is necessarily accurate and the ^{210}Pb measurements faulty.

Historical records indicate that most of the palynological changes related to settlement should occur during the decade following 1883, when the railroad reached Devils Lake, including 1894, when *Salsola* arrived. (Before that time farming occurred at a rather small scale; little in the way of cultivars, livestock, weeds, or ornamentals such as *Syringa* had been imported.) The period of agricultural expansion would be represented within approximately 2–3 cm in the stratigraphic record (Fig. 4), rather than 10–20 cm as is suggested in the Main Bay diagram (Fig. 9).

In the Creel Bay core the correspondence between pollen and ^{210}Pb chronologies could not be better. The ^{210}Pb date at 28 cm is 1889 ± 7 years (± 1 s.d.); the settlement horizon at 27–29 cm in the pollen record dates to 1889 ± 5 years. Such good results are somewhat surprising for Devils Lake in the light of the large hydrologic fluctuations of the last 100 years, which easily could have altered sedimentary conditions in the basin.

By contrast, dating of the Main Bay could hardly be more ambiguous. Lead-210 gives an explicit date of 1892 ± 5 years (± 1 s.d.) at 32 cm, but abundant agricultural pollen occurs well below this level. While there is nothing in the ^{210}Pb stratigraphy to indicate violation of the c.r.s. dating model, the fact that the pollen stratigraphy is so highly smeared suggests that sediment redeposition may have occurred. A large, shallow, flat-bottomed basin such as the Main Bay of Devils Lake presents a nearly ideal site for advective transport of fine-grained sediments. Sediment and ^{210}Pb accumulation might have been episodic, shifting about the basin as a complex result of lake level and wind-induced turbulence.

If ^{210}Pb accumulation varied with the flux of redeposited sediment, the assumption of a constant ^{210}Pb supply to the coring site would be invalid. However, the nearly identical unsupported ^{210}Pb burdens in the Creel and Main Bay cores (20.46 and 20.97 pCi cm^{-2}, respectively) argue against this hypothesis. A highly variable ^{210}Pb flux is unlikely to produce a similar inventory of unsupported ^{210}Pb at two such dissimilar core sites. Instead the dating discrepancy might have been caused by severe mixing of the upper sediment column.

The presence of anthropogenic pollen well below the lead-dated settlement horizon in the Main Bay core could be explained by the ^{210}Pb date being too old. However, sediment mixing has exactly the opposite affect on ^{210}Pb dating; mixing enriches older sediments with ^{210}Pb, making them appear younger, not older. Alternatively the source of error might reside in the pollen stratigraphy itself. The direction of error in pollen dating would be the same as that for ^{210}Pb; new pollen taxa would be displaced down core, the settlement horizon would be incorrectly placed at greater depth, and ages extrapolated from this marker would be too young.

Because pollen markers are much more strongly affected by mixing than ^{210}Pb dates, it is possible for mixing to produce the dating discrepancy found in the Main Bay core, though causing both dating methods to err in the same direction. According to the c.r.s. model, the true ^{210}Pb age t of sediments at core depth i in the presence of rapid steady-state mixing is given by

$$t_i = 1/k \ln A_o/(A_i + WC_i) + W/R_i$$

where A_o is the unsupported ^{210}Pb burden for the entire core, A_i is the integrated unsupported activity below depth i, k is the ^{210}Pb decay constant (0.03114 yr^{-1}), W is the cumulative dry mass of the mixed layer, C_i is the unsupported ^{210}Pb concentration at depth i, and R_i is the sediment accumulation rate (Oldfield & Appleby, 1984). If we assume that the zone of mixing in the Main Bay core is represented by the discrepancy between the cultural-pollen horizon at 40 cm and the ^{210}Pb date of 1889, iteration of the above model yields a value of ca. 10 cm (3.8 g cm^{-2} cumulative dry mass) for the thickness of the mixed layer. Note that this value is greater than the 8 cm difference between pollen and ^{210}Pb dates assuming no mixing, and that 3.8 g cm^{-2} represents a modern mixed depth of 18 cm (density corrected).

This amount of sediment is clearly unrealistic, although less severe mixing could still contribute to some of the discrepancy observed between pollen and lead-based chronologies. The downward displacement of sufficient exotic pollen to ensure the detection of a few grains in precultural sediments would require far less vigorous mixing than that envisioned in the above example. A mixed depth of 10–12 cm and only partial homogenization might suffice. The strongest evidence for altered pollen stratigraphy in the Main Bay core is the gradual and asynchronous appearance of the introduced pollen taxa.

The marked contrast in sediment chronology between two contiguous basins of Devils lake clearly demonstrates the importance of site selection in high-resolution stratigraphic studies on lakes of the Great Plains. Generally shallow depths, strong winds, and little shoreline protection create a high-energy sedimentary environment in most basins. Many of these lakes also exhibit marked fluctuations in depth and surface area in response to hydrologic change. Combined with wind-induced turbulence, changing lake levels can alter sediment deposition patterns in unpredictable ways, obscuring stratigraphy and any subsequent effort to date it.

Dating success in Creel Bay and failure in Main Bay is probably linked to basin morphometry. While the two basins are nearly equal in depth, Creel Bay is narrow (ca. 1 km) in the direction of prevailing winds, while Main Bay is roughly circular and more than 8 km across. Wind stress mixes the water column of Main Bay throughout the year except during periods of ice cover, and with its pan-like morphometry it is not hard to imagine the active resuspension and transport of sediments, particularly at low lake stage.

In contrast, the sharp resolution of the Creel Bay pollen record and its precise correspondence to independent dating by ^{210}Pb argues against significant disturbance of sediment stratigraphy by mixing or episodic events. Clearly defined features in diatom and ostracode stratigraphy in the upper sediments (unpublished data) provide further evidence against substantial mixing in this core. A temporal resolution of 5 years in Creel Bay is probably nearly optimal for pollen dating and is only possible where stratigraphy is well preserved and vegetational change is both rapid and well documented. Because of unstable sedimentary conditions and a high flux of clastic sediments, lakes of the Great Plains are not ideal sites for ^{210}Pb dating. It is precisely under such conditions that independent dating techniques are required to resolve reliably the chronology of recent lake sediments.

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