Lake sediments as indicators of recent erosional events in an agricultural basin on the Canadian prairies

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Abstract Lake sediments provide an integrated record of the sediment dynamics of the contributing basin. In the research area on the prairies of western Canada, the earliest sediments in the larger lakes predate European settlement, allowing a direct evaluation of the erosional response of the basin to settlement. Lake sediment cores were collected from the Stony Creek research basin in eastern Saskatchewan. Pre- and post-settlement sediment in the central core were separated based on the increase in *Populus* pollen associated with the southward advance of the aspen parkland ecotone caused by fire suppression during agricultural settlement. A wet-chemical extraction procedure was used to separate the operationally defined organic fraction, the acid-soluble authigenic fraction, and biogenic silica from the clastic, non-carbonate, allogenic fraction of the lake sediment. Changes in the mineralogy and geochemistry of the clastic, allogenic fraction indicated that settlement resulted in an increased contribution of topsoil erosion to the sediment load of Stony Creek.

INTRODUCTION

Lake sediment characteristics reflect the combined effect of a large variety of processes occurring on the slopes of the contributing basin, within the lake water, and within the sediment after deposition. A number of studies have used the lake sediment record to evaluate the erosional history of the basin contributing water and sediment to the lake. Recent reviews of this approach have been published by Oldfield & Clark (1990) and Dearing (1991). Mackereth (1966) carried out one of the earliest investigations into the chemical stratigraphy of lake sediments, and used the Na, K, and Mg profiles as indicators of weathering and erosion intensity within the English Lakes basin. Since then, lake sediment chemistry has been used by a number of investigators to deduce the erosional history of the contributing basin. Early studies of lake sediment chemistry, however, were almost all based on bulk chemical analysis, even though lake sediment chemistry is controlled by process in the water column and within the deposited sediment, in addition to the processes on the slopes of the contributing basin.

To overcome the limitations posed by the bulk analysis method, Engstrom & Wright (1984) devised a fractionation procedure based on wet chemical extraction to separate the lake sediment into fractions according to origin. They distinguished the allogenic, authigenic, and biogenic fractions, whereby allogenic refers to that component derived from outside the lake; authigenic described those formed as a result of processes within the lake, either in the water column or in the sediment after deposition; and biogenic refers to the amorphous silica component which is primarily composed of diatom frustules. Note that the various fractions are operationally defined. The fractionation procedure described by Engstrom & Wright (1984) was subsequently used in various other studies, sometimes in slightly modified form (Engstrom & Hansen, 1985; Engstrom & Swain, 1986; Engstrom *et al.*, 1985; Heathwaite & O'Sullivan, 1991). The present study uses the fractionation procedure of Engstrom & Wright (1984) to evaluate the changing properties of the allogenic fraction resulting from settlement and subsequent changes in land use in a small, agricultural basin on the Canadian prairies.

STUDY SITE

The area selected for this study is located in the parkland/prairie region of eastern Saskatchewan, Canada (Fig. 1). The climate in the field area is humid continental or Dfb in the Köppen climate system. Kamsack, located 10 km north of the Stony Creek basin, has an average annual temperature of 0.9°C and an average annual precipitation of 386 mm with a summer maximum (Atmospheric Environment Service, 1982). On average 26% of the annual precipitation falls as snow.

Lake sediment cores were obtained from an unnamed lake, approximately 1 km long and 100 m wide, in the Stony Creek basin, a 110 km^2 agricultural basin. The lake occupies part of the valley floor, and Stony Creek flows into the lake from the southwest, and continue downstream from the lake to the east. The topography of the area is irregular and hummocky, with numerous closed depressions. Surface deposits in the research basin consist of till and glacial outwash, and of colluvium and alluvium directly adjacent to Stony Creek. Soils in the basin are medium and coarse textured, black soils, and medium textured, upland, grey podzol soils. Soils on the steep slopes adjacent to Stony Creek are classified as eroded, with a varied texture and thin, truncated profiles (Mitchell *et al.*, 1977).

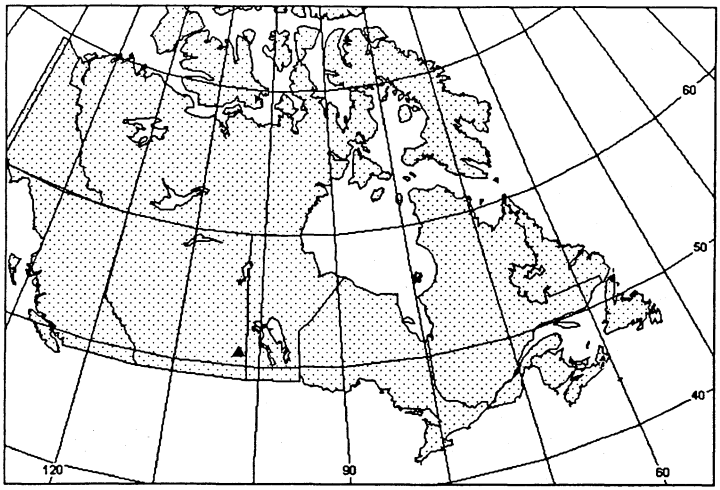

Fig. 1 Map of Canada showing the general location of the Stony Creek field area in Saskatchewan (solid triangle).

LAND USE HISTORY AND VEGETATIONAL CHANGE

Agricultural settlement in the region started in the 1880s with the establishment of the first homesteads in the area (Anonymous, 1967). In 1903 the Canadian Northern Railway expanded into the region, leading to an increased influx of settlers, and by 1905 the area was well settled (Anonymous, 1967). Census data for 1916 show that 24% of the area in the three municipalities in which the Stony Creek basin is located was under field crop, mainly wheat, barley, and oats. By 1971, this percentage had increased to 42%.

At present, the study site lies within the aspen parkland ecotone (Archibold & Wilson, 1980) which is the transition between the grasslands of the Great Plains and the boreal forest. The aspen parkland typically consists of groves of aspen (*Populus tremuloides*) in the wetter locations in the landscape such as hollows and north-facing slopes, combined with grass land (fescue prairie) on the drier ridges and south-facing slopes. In the recent past, the vegetation of the study area has changed in response to changing land use practices. Most authors report the expansion of aspen groves and replacement of grassland by aspen parkland since agricultural settlement as a result of fire suppression (Archibold & Wilson, 1980; Thorpe, 1993). Bird (1961) presented maps of the extent of the aspen parkland in 1905 and 1956 which show the expansion of the aspen parkland southward.

METHODS

Coring

Lake sediment cores were collected in February 1992 from the ice cover. Twenty one cores were taken along two parallel transects running the length of the lake. Cores where spaced 100 m apart in the upstream part of the lake, and 50 m apart in the downstream part of the lake. The coring device used was a modified version of the Reasoner (1986) lightweight percussion corer. The corer collected a 3 inch diameter core in a PVC tube which was capped for transport.

Laboratory analyses

In the laboratory the cores were split lengthwise for visual inspection of the sediment structure. Directly after splitting the colour of the moist sediment was described using Munsell Soil Color Charts, and the core was sectioned into 1 cm slices which were used for further analysis. Core 13 was selected for further detailed analysis because of its central location and undisturbed appearance upon visual inspection. Core 13 had an overall length of 95 cm. Loss on ignition (LOI) at 550°C was determined using standard methods. Subsamples from selected depths were prepared for pollen analysis using standard methods. For each subsample approximately 300 grains were counted. A wet chemical extraction procedure as described by Engstrom & Wright (1984) was used to separate the operationally defined allogenic, authigenic, and biogenic fractions. The extractants were analysed by ICP spectrometry. After the wet extraction sequence, the remaining residue underwent a multi-acid digestion ($HF/HNO_3/HClO_4$) prior to analysis by ICP spectrometry.

RESULTS

Sediment colour, LOI, and palynology

Based on sediment colour, core 13 consists of two strikingly different layers: from 15 to 42 cm the sediment is black (10YR2/1), changing gradually to very dark grey (10YR3/1) at the bottom of the layer. A sharp boundary at 42 cm separates this material from the underlying greyish brown sediment, which on the basis of slight differences in colour can be further subdivided (Fig. 2). The change in colour coincides with a fairly sharp change in LOI, which varies over a depth of about 5 cm from values in excess of 40% in the upper, black layer, to values less than 10% in the lower, lighter coloured material (Fig. 2).

Pollen analysis was used as a dating tool, and samples from various depths were selected to establish whether changes in the visual appearance of the sediment corresponded to palynological changes. The pollen diagrams show a marked increase in the percentage of tree pollen, from 36% at 45 cm to 52.7% at 29 cm (Fig. 3). A breakdown into individual species shows that the increase in tree pollen is mainly due to *populus* sp., with concurrent increases in *Picea* sp. and *Pinus* sp.. The latter two species, however, are most likely not local. The increase in tree pollen is almost entirely at the expense of shrub pollen, especially *Juniperus* sp. The percentage of herb pollen remains relatively constant throughout the core.

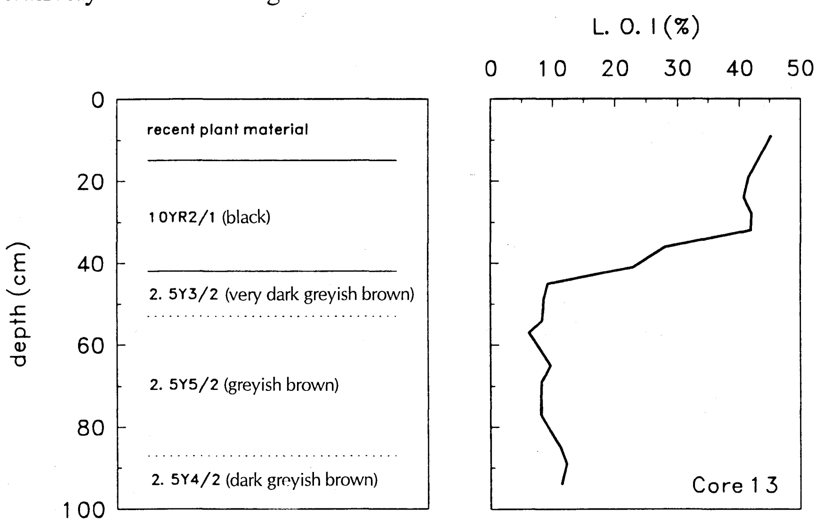

Fig. 2 Lake sediment stratigraphy and loss on ignition (LOI) of Stony Creek core 13.

Geochemistry

Figure 4 illustrates the results of the geochemical analyses for Al, Ca, Mg, Fe, and P. To describe the geochemical profiles, it is necessary to distinguish the bulk chemical composition, i.e. the composition of the authigenic fraction, of the allogenic fraction, and of the sum of these two fractions expressed per gram of dry sediment (Fig. 4, left-hand side for each element), from the composition of the allogenic fraction (Fig. 4,

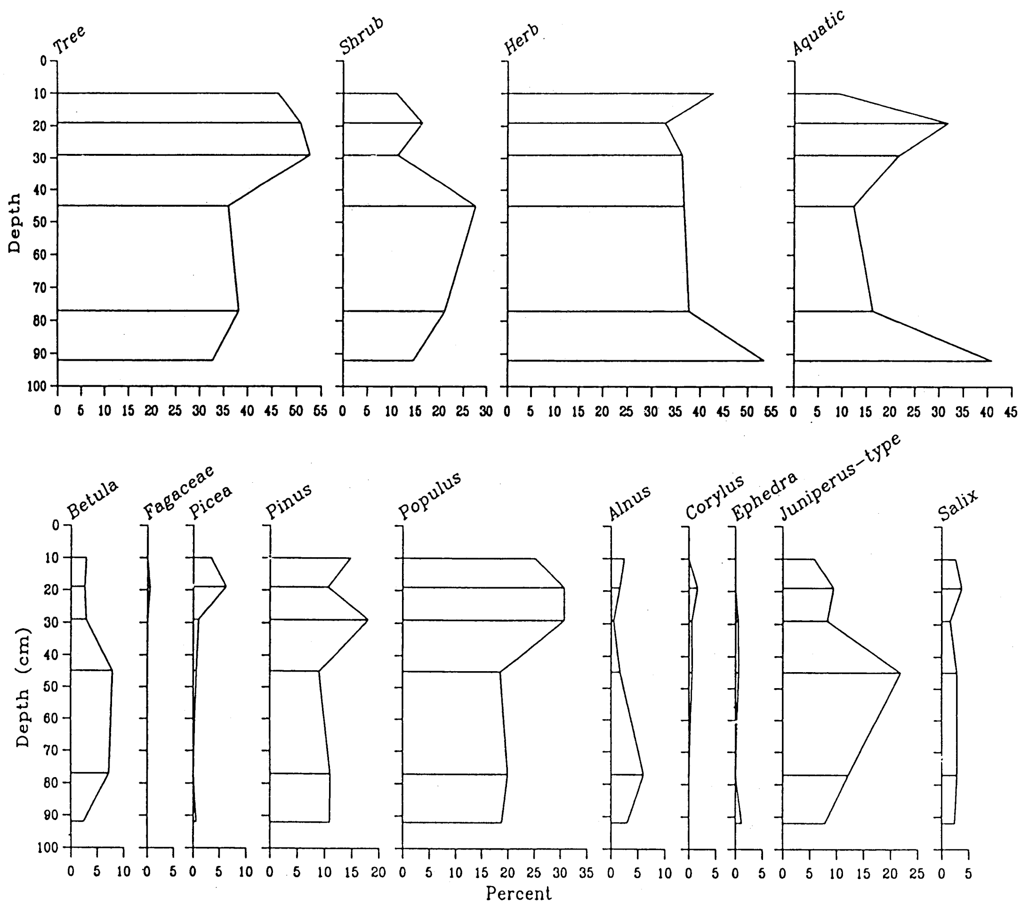

Fig. 3 Pollen profiles of Stony Creek core 13.

right-hand side for each element). It is worth noting that the bulk geochemical composition is for most part controlled by the composition of the allogenic fraction. The biogenic fraction for these elements was negligible and is not shown in Fig. 4.

The Al profile shows that at the base of the core total Al concentrations are relatively low, and increase sharply between 45 and 41 cm. This increase corresponds to the lower boundary (at 43 cm) of the black, organic rich layer. Highest Al concentrations are generally found between 19 and 32 cm. In the upper part of the core between 19 and 11 cm a sharp decrease in total concentration occurs, corresponding to the lower boundary of the recent plant material at 15 cm. Total Al concentrations in the upper, recent plant material layer are lower than the peak concentration in the black, organic-rich sediment, but higher than the concentrations in the bottom part of the core. Almost all Al in present in the allogenic fraction, although the authigenic fraction accounts for a small percentage of Al between 36 and 11 cm. The Al profile of the allogenic fraction is similar to the dry sediment profile for total Al. A number of elements display behaviour similar to that of Al (e.g. K and Fe).

The Ca profile is entirely different. At the base of the core, total concentrations are high and variable, and show a peak at 77 cm. Above this peak, total concentrations

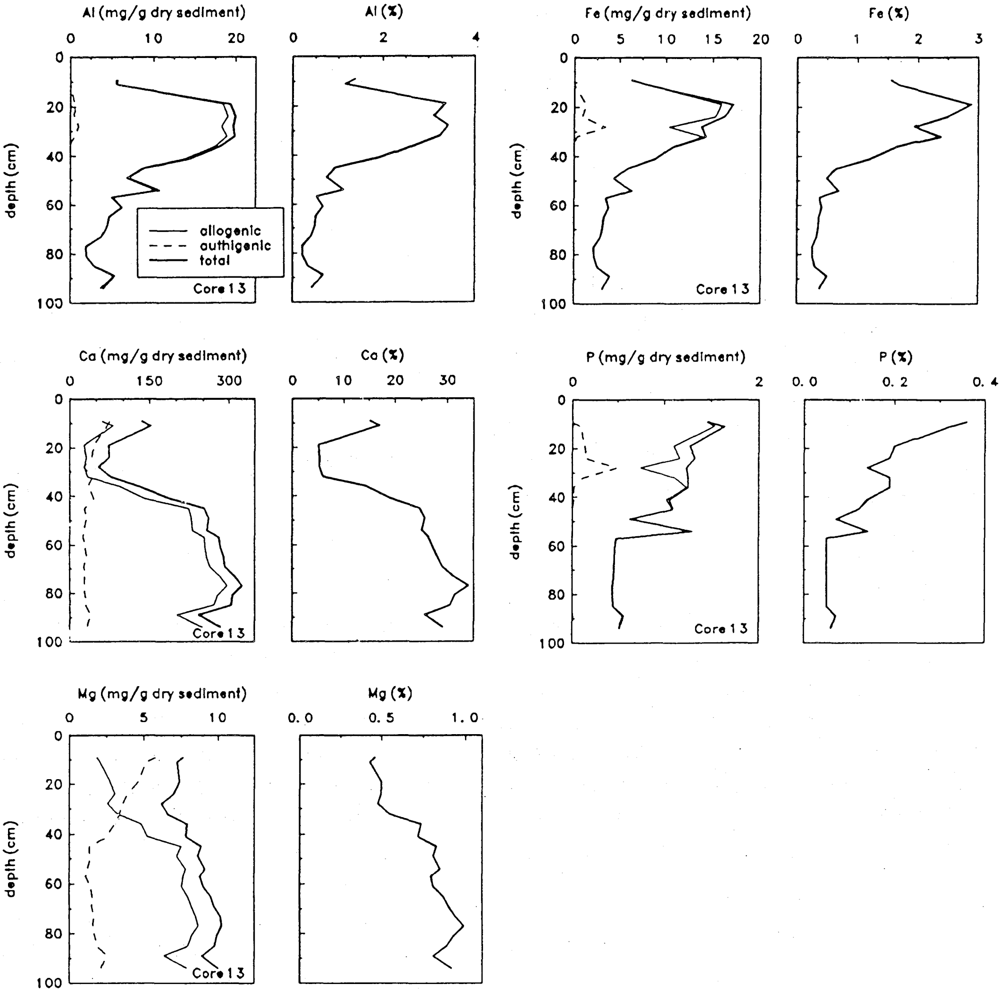

Fig. 4 Selected geochemical profiles of Stony Creek core 13. For each element, the contributions of the allogenic and authigenic fractions are shown on the left, whereas the composition of the allogenic fraction is shown on the right.

slightly decrease upwards but remain high. Above 45 cm, total concentrations decrease sharply to reach low values between 32 and 19 cm, and above 19 cm, total concentrations increase slightly again. Most Ca is present in the allogenic fraction, but there is a significant contribution from the authigenic fraction which is constant over most of the core and increases slightly upcore. The Ca profile of the allogenic fraction is similar to that of total Ca. The profile of Mg is very similar to that of Ca, except that total Mg concentrations between 45 and 19 cm do not decrease as sharply as for Ca. Like Ca, Mg shows a significant contribution of the authigenic fraction which increases towards the top of the core.

The P profile shows the lowest values of the total concentration in the lower part of the core. At 53 cm depth total concentrations start to increase and reach a peak value in the upper layer of sediment. Most P is found in the allogenic fraction, but the contribution of the authigenic fraction is significant between 45 and 11 cm. The profile for the composition of the allogenic fraction shows an increase in P starting at 49 cm, and peak values at the top of the core.

DISCUSSION

In core 13, a distinct boundary is found at 42 cm. This boundary separates the greyish brown sediment below from the overlying black sediment (Fig. 2). As the LOI (Fig. 2) and the geochemical profiles (Fig. 4) indicate, there actually is a transition zone within the upper black layer extending from 32 to 42 cm. In the pollen diagrams (Fig. 3), the 42 cm boundary corresponds to a marked increase in the percentage of *Populus* pollen. Based on the vegetational history of the region, this increase in *Populus* pollen indicates the start of agricultural settlement in the region, which resulted in the suppression of natural and human-made fires. The interpretation of the 42 cm boundary as the agricultural settlement boundary implies a date for that boundary in the 1880s, 1890s, or 1900s, depending on how rapidly settlement would have a noticeable impact on the vegetation cover.

The changes in sediment colour, LOI, and palynology at the 42 cm agricultural settlement boundary coincide with distinctive changes in sediment geochemistry (Fig. 4). Because the geochemical profiles are dominated by the composition of the allogenic fraction the following discussion will focus on the latter. The allogenic fraction initially shows an increase in Al, Fe, and P, and a decrease in Ca and Mg. This indicates that agricultural settlement resulted in an increased contribution of sediment from a sources rich in Al and Fe oxides and hydroxides, aluminosilicates, and mineral phosphorus, and is interpreted as an increase in topsoil erosion. Prior to settlement, the geochemistry of the allogenic fraction was dominated by Ca and Mg. This is interpreted as indicating that the predominant pre-settlement sediment source was the calcareous till exposed in the stream banks and bed. Preliminary XRD data show that the dominant minerals were (in order of importance) calcite, quartz, and aragonite in the brownish grey pre-settlement layer, and quartz and calcite in the black post-settlement layer. This raises the question whether the extraction procedure for the authigenic fraction has resulted in the dissolution of the entire carbonate fraction. The magnitude of the Ca concentrations of the allogenic fraction in the pre-settlement layer suggest that part of the Ca is still present as $CaCO_3$, in addition to that present in feldspars, micas, and other silicate minerals.

The change in composition of the allogenic fraction as a result of changing sediment sources upon agricultural settlement is quite distinct from the findings reported in the admittedly small number of other studies. Engstrom *et al.* (1985) investigated the geochemistry of a lake core in Vermont covering a record from 1000 years BP to the present, and found that the elemental composition of the allogenic fraction was virtually constant through the core, despite major changes in land use, vegetation cover and erosion rates. Similar findings were reported by Engstrom & Hansen (1985) for a lake sediment record of 10 500 years from Labrador.

CONCLUSIONS

Since the late nineteenth century, the introduction and expansion of agriculture on the

Canadian prairies has resulted in extensive changes in land use and vegetation. These changes were greatest during the period of actual agricultural settlement, and resulted in an advance of the aspen parkland ecotone at the expense of prairie grassland. The introduction of agriculture to the prairies also resulted in increased soil erosion, as grassland was brought under cultivation. Lake sediment geochemistry in the Stony Creek basin indicates that during this period the balance between the various sediment sources in the contributing basin changed owing to the increased contribution of topsoil erosion. At present, research is in progress to evaluate the changes in sediment source contribution since agricultural settlement.

Acknowledgements The author thanks Doug Anderson and Sherril Koroluk for assistance in the field and the laboratory, Jo-Anne Hirst for the XRD work, and Mary Sauchyn and Steve Porter for the pollen analysis. This project was funded by grants from NSERC, the University of Saskatchewan President's NSERC Fund, and the College of Arts and Sciences of the University of Saskatchewan.

REFERENCES

Anonymous (1967) *Kamsack, 1867-1967: Garden of Saskatchewan.* Chamber of Commerce, Kamsack, Saskatchewan.

Atmospheric Environment Service (1982) *Canadian Climate Normals 1951-80. Prairie Provinces.* Atmospheric Environment Service, Downsview, Ontario.

Archibold, O. W. & Wilson, M. R. (1980) The natural vegetation of Saskatchewan prior to agricultural settlement. *Can. J. Bot.* **58**, 2031-2042.

Bird, R. D. (1961) *Ecology of the Aspen Parkland of Western Canada.* Publ. no. 1066, Research Branch, Canada Department of Agriculture, Ottawa.

Dearing, J. A. (1991) Lake sediment records of erosional processes. *Hydrobiologia* **214,** 99-106.

Engstrom, D. R. & Wright, H. E. (1984) Chemical stratigraphy of lake sediments as a record of environmental change. In: *Lake Sediments and Environmental History* (ed. by E. Y. Haworth & J. W. G. Lund), 11-67. Leicester University Press, Leicester.

Engstrom, D. R. & Hansen, B. C. S. (1985) Postglacial vegetational change and soil development in southeastern Labrador as inferred from pollen and chemical stratigraphy. *Can. J. Bot.* **63,** 543-561.

Engstrom, D. R. & Swain E. B. (1986) The chemistry of lake sediments in time and space. *Hydrobiologia* **143,** 37-44.

Engstrom, D. R., Swain, E. B. & Kingston, J. C. (1985) A palaeolimnological record of human disturbance from Harvey's Lake, Vermont: geochemistry, pigments, and diatoms. *Freshwater Biol.* **15,** 261-288.

Heathwaite, A. L. & O'Sullivan P. E. (1991) Sequential inorganic chemical analysis of a core from Slapton Ley, Devon, UK. *Hydrobiologia* **214,** 125-135.

Mackereth, F. J. H. (1966) Some chemical observations on post-glacial lake sediment. *Phil. Trans. R. Soc. Lond.*, ser. B **250,** 165-213.

Mitchell, J., Moss, H. C. & Clayton, J. S. (1977) *Soil Survey of Southern Saskatchewan from Township 1 to 48 inclusive* (4th printing). Soil Survey Report no. 12, University of Saskatchewan, College of Agriculture, Saskatoon, Saskatchewan.

Oldfield, F. & Clark R. L. (1990) Lake sediment-based studies of soil erosion. In: *Soil Erosion on Agricultural Land* (ed. by J. Boardman, I. D. L. Foster, & J. A. Dearing), 201-228. Wiley, Chichester, UK.

Reasoner, M. A. (1986) An inexpensive, lightweight percussion core sampling system. *Géographie Phys. et Quaternaire* **40**, 217-219.

Thorpe, J. (1993) The life: vegetation and life zones. In: *Three Hundred Prairie Years – Henry Kelsey's "Inland Country of Good Report"* (ed. by H. Epp), 11-16. Canadian Plains Research Centre, Regina.