Signatures of high-magnitude 19th-century floods in *Quercus macrocarpa* tree rings along the Red River, Manitoba, Canada

Scott St. George*
Geological Survey of Canada, 360-1395 Ellice Avenue, Winnipeg, Manitoba R3G 3P2, Canada
Erik Nielsen
Manitoba Geological Survey, 360-1395 Ellice Avenue, Winnipeg, Manitoba R3G 3P2, Canada

ABSTRACT

Quercus macrocarpa **(Michx.) growing along the Red River, Manitoba, Canada, contain an anatomical signature related to high-magnitude 19th-century floods. Tree-ring samples were collected from 194 *Q. macrocarpa* over a 100 km transect along the Red River valley. The combined tree-ring record extends from A.D. 1463 to A.D. 1999; sample depth between 1463 and 1650 is limited and made up exclusively of subfossil logs derived from alluvial deposits. Thirteen trees from four sites contain annual rings with reduced earlywood-vessel transverse areas that reflect flooding during the tree's growing season. Flood rings in 1826 are present in 24% of *Q. macrocarpa* samples and are coincident with the largest flood observed in the Red River valley. Flood rings in 1852 are exhibited in 5.9% of samples and correspond with the second largest Red River flood. These results confirm that *Quercus* species adapt to prolonged inundation by reducing the transverse area of their earlywood vessels and suggest that anatomical signatures in riverbank trees may be used to identify and delineate high-magnitude paleofloods for low-gradient rivers.**

Keywords: Red River, paleofloods, dendrochronology, flood rings.

INTRODUCTION

A fundamental requirement of paleoflood hydrology is the identification and dating of flood events prior to instrumental and historical records. Previous research has demonstrated that tree-ring analysis of riverbank trees may be used to identify paleofloods over the past several hundred years with annual resolution. The most common dendrohydrological procedure associates recent flood events with dated tree scars (e.g., Sigafoos, 1964; McCord, 1996). Flood-scar chronologies have been used to provide a history of past flooding in several environments, particularly in the American Southwest, but analysis has so far largely been restricted to rivers flowing in narrow deep canyons with relatively steep gradients (e.g., Gottesfeld and Johnson Gottesfeld, 1990; McCord, 1996).

Whereas scars are external manifestations of the effects of floods on nearby trees, inundation during high water levels may also lead to internal changes in tree physiology. Working with *Fraxinus americanum* L. and *F. pennsylvanica* Marsh. on the Potomac River, Yanosky (1983) observed changes in wood anatomy present in flood-damaged (drowned) trees. These changes were restricted to those rings formed during and shortly after high-water events and were described as flood rings. While Potomac flood rings corresponded to local and regional discharge peaks, Yanosky's sampling concentrated on trees growing at the low-water limit in order to maximize the number of floods detected. These bottomland trees were regularly inundated and displayed a complex range of anatomical responses to floods of varying magnitudes (i.e., the mean annual flood and greater). Yanosky's flood-ring record was also largely confined to the 20th century, the majority of samples covering the period 1930–1979.

Forecasting for the purpose of flood mitigation is mainly concerned with high-magnitude, low-frequency events. It would therefore be useful to develop flood-ring chronologies that record only high-magnitude floods, because these events have the most significant potential as natural hazards. The Red River, Manitoba, Canada, like many rivers with broad flood plains, is surrounded by a riparian fringe that may extend for several hundred meters on both sides of the river. While the marginal trees on the upper terraces and adjacent prairie surface are protected from small frequent floods by distance and intermediate vegetation, they are inundated by large infrequent floods for several weeks. In this paper, we relate changes in tree-ring anatomy from *Quercus macrocarpa* (Michx.) (bur oak) to inundation during large 19th-century floods of the Red River.

SOCIAL, GEOLOGICAL, AND ECOLOGICAL SETTING

Flooding of the Red River is a significant recurring natural hazard in southern Manitoba, Canada. About 70% of Manitoba's 1.1 million citizens live in the Red River valley; consequently, the province is vulnerable to social and economic disruption during widespread flooding. During the "flood of the century" in 1997, costs for flood fighting and recovery were estimated at Cdn. $500 million; 28,000 people were evacuated from high-flood-risk areas (Manitoba Water Commission, 1998). Without a series of measures protecting the provincial capital of Winnipeg, losses due to flooding could have reached $5–$7 billion (Manitoba Water Commission, 1998).

Along the Red River valley, the underlying bedrock is buried beneath late Pleistocene glacial sediments capped with a clay-rich veneer of glaciolacustrine sediments (Teller and Bluemle, 1983). This landscape contains a limited number of large natural water-storage sites (International Red River Basin Task Force, 1997), leaving the Red River valley with insufficient capacity to contain the higher flows carried by the river. Under extreme flows, caused primarily by snowmelt and heavy spring precipitation (International Red River Basin Task Force, 1997), the Red River forms a broad, shallow flood zone from Winnipeg to the Canada–United States border. During the flood of 1997, floodwaters occupied approximately 2000 km^2 and formed a temporary lake up to 40 km wide (Manitoba Water Commission, 1998).

Vegetation in south-central Manitoba is almost exclusively tall- and mixed-grass prairie; however, high water tables protect riverbank trees from prairie moisture deficits and allow the development of deciduous forest belts typically 100–200 m wide (Scott, 1995). The uppermost prairie surface surrounding the Red River is colonized by *Quercus macrocarpa*, a species with moderate tolerance to flood conditions (Tang and Kozlowski, 1982). While their high elevation relative to the valley bottom protects *Q. macrocarpa* from flooding during small to moderate flows, large flows that spill over onto the prairie surface may inundate the trees for several weeks in spring

*E-mail: sstgeorg@nrcan.gc.ca.

and early summer. In effect, *Q. macrocarpa*'s position on the prairie level acts as a filter that enhances the tree-ring signal related to large floods and omits the "noise" of smaller floods.

TREE-RING NETWORK

Samples from 194 *Q. macrocarpa* were collected from 11 living tree sites, nine historical buildings, and exposures in the alluvium along the Red River (Table 1). The sampling locations extend over 100 km along the Red River from Emerson to the North Kildonan area of Winnipeg (Fig. 1). Cores from living trees were extracted using a 16-inch increment borer (one core per tree), and cross-sectional disks were collected from historical and alluvial samples, as well as from trees removed through forest management. Ring dates for live trees were assigned by counting backward from the outermost ring, formed during the year of collection. Each tree-ring sample was dated independently and then cross-dated (Cook and Kairiukstis, 1990) across all sites as a final confirmation of correct age. Once dates for living trees were confirmed, the same procedure was used to date historical and subfossil samples.

The combined *Q. macrocarpa* record, including living, subfossil and historical samples, extends for 536 yr, from A.D. 1463 to A.D. 1999. The majority of living trees along the Red River started growing between 1860 and 1880, reflecting extensive clear-cutting by European-Canadian settlers during the early and middle 19th century. Samples collected from historic buildings and Red River alluvium maintain good sample depth back to 1650. Between 1463 and 1650, sample depth is less than nine trees and is made up exclusively of subfossil logs derived from alluvial deposits.

FLOOD SIGNATURES

Quercus macrocarpa is a ring-porous species that forms annual rings with distinct anatomical features related to spring and summer growth. Spring growth, or earlywood, includes large vessels, which appear circular in cross section, used for vertical conduction of water. The latewood part of the annual ring, formed during the summer, contains vessels that are smaller or absent. Large vessels are formed during the early part of the growing season to conduct large amounts of water to the leaves, while the smaller latewood vessels reflect a reduction in water demand and availability later in the year (Carlquist, 1975).

TABLE 1. SITE INFORMATION FOR THE RED RIVER *Quercus macrocarpa* NETWORK

Site	Type	No. of trees	Span (A.D.)
Kildonan Park	Living	2	1796 - 1990
Barber House	Historical	34	1648 - 1864
Various buildings, Winnipeg	Historical	14	1644 - 1872
Winnipeg	Living	17	1822 - 1994
St. Vital Park	Living	12	1830 - 1998
St. Norbert	Living	10	1855 - 1998
La Barriere Park	Living	11	1895 - 1998
Rat River House	Historical	6	1659 - 1859
Ste. Agathe	Living	11	1856 - 1998
Parker Farm	Living	12	1889 - 1998
St. Jean Baptiste Park	Living	10	1883 - 1997
Remus Farm	Living	10	1875 - 1998
Marais River	Living	11	1850 - 1999
Fort Dufferin	Living	9	1866 - 1997
Fort Dufferin	Historical	2	1723 - 1872
Various locations	Alluvial	23	1463 - 1997

Thirteen trees from four sites contain annual rings with anatomical anomalies that are interpreted to reflect inundation during high-magnitude 19th-century Red River floods. Red River flood rings are characterized by a marked reduction in the mean transverse area of earlywood vessels (Fig. 2). Samples containing most or all of the trees' cross-sectional area indicated that this reduction occurs uniformly around the entire annual ring. Astrade and Bégin (1997) observed similar vessel area reductions in *Quercus robur* L., caused by floods between 1969 and 1990 of the Saône River, France. This reduction is present in Red River *Q. macrocarpa* during the year of inundation only; vessel size returned to normal in the subsequent year. Reduced earlywood vessel areas have also been observed for woody species native to xerophytic environments, an adaptation that has been described as a survival mechanism to prevent water loss during periods of reduced water availability (Carlquist, 1975). Within normal nonflood rings, earlywood vessel areas in *Q. macrocarpa* along the Red River are relatively constant.

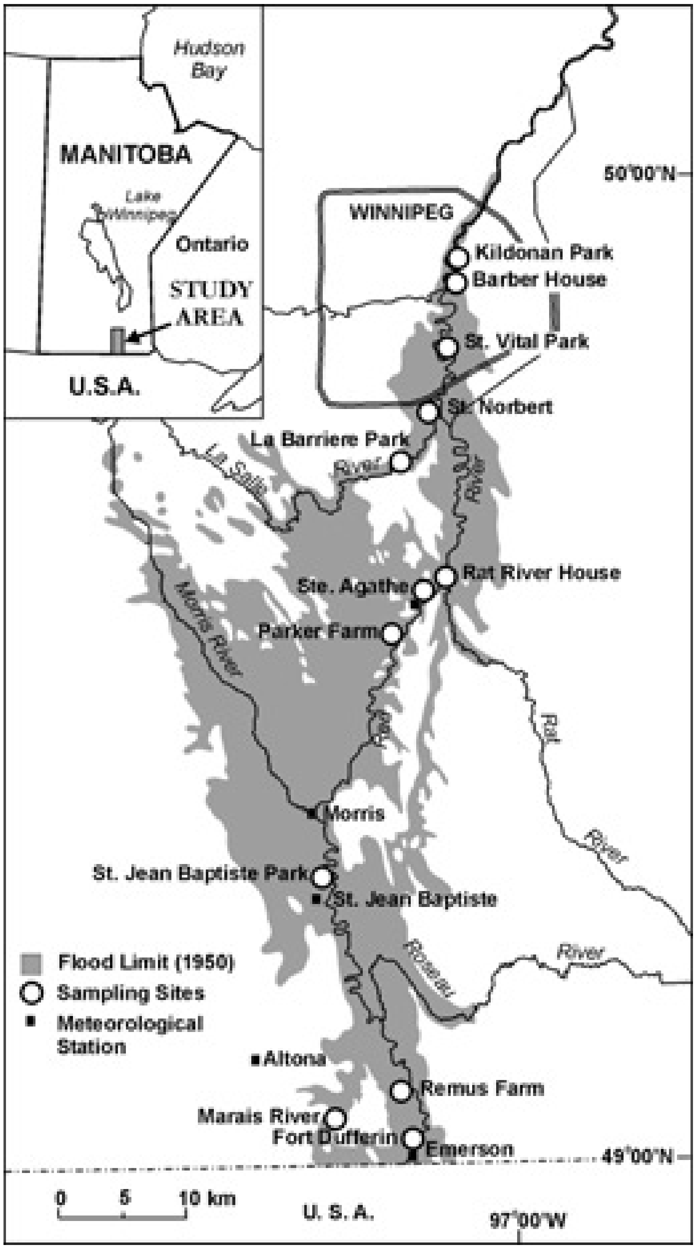

Figure 1. In this map of study area, shading shows limit of 1950 flood, last major flood in Red River prior to construction of major channel diversion protecting provincial capital of Winnipeg.

Flood rings are present for the years 1826 and 1852 (Table 2; Fig. 3). The most common flood ring is for 1826; it is present in 24% (12/50) of samples that contain a ring from that year. The 1826 flood ring is recorded in trees from three sites along the valley (Rat River House, Barber House, and Kildonan Park) over a distance of approximately 40 km. The 1826 flood ring is coincident with the largest observed flood in the Red River valley. Flow during the 1826 flood is estimated from historical records at ~6370 m^3/s in downtown Winnipeg (Canadian Department of Resources and Development, 1953), roughly 40% larger (by peak discharge) than the 1997 flood. The stage of the Red River in late May of 1826 was estimated from high-water marks at 11.3 m above datum at the Forks (the confluence of the Red and Assiniboine rivers; Canadian Department of Resources and Development, 1953). Flood rings for 1852 are exhibited by 5.9% (3/51) of *Q. macrocarpa* samples. The 1852 flood ring corresponds to the second largest Red River flood, which peaked at 4670 m^3/s. During the 1852 flood, which also occurred in the month of May, the Red River rose over its banks and flooded the valley, reaching a peak stage of ~10.7 m at the Forks (Canadian Department of Resources and Development, 1953).

DISCUSSION

The detection of anatomically distinct tree rings coincident with the two largest floods in the Red River demonstrates that *Q. macrocarpa* record signatures from high-magnitude flooding. Unfortunately, we are not certain about the duration of inundation necessary to produce a flood ring, because information on the 1826 and 1852 floods is limited. The best available account of the 1826 flood is the composite Red River stage heights record at the Forks reconstructed from observations made by Hudson Bay Company employees (A.A. Warkentin, 2000, personal commun.). Only two trees in growth position, sample W9109 from Kildonan Park in northern Winnipeg and W9097 from central Winnipeg, span 1826. Sample W9109 from Kildonan Park contains a flood ring for 1826. Because the approximate elevation for this tree is 227.7 m, comparison with the 1826 flood stage (roughly 5 km upstream from Kildonan Park) suggests that the tree was inundated for about 40 days, from May 4 to June 12. Sample W9007, located 4.5 km west of the Forks near the banks of the Assiniboine River, has an elevation of 234.1 m and would not have been under water during 1826. An equivalent reconstructed flood stage for the 1852 flood is not available.

TABLE 2. PLOT OF FLOOD RINGS ACROSS THE RED RIVER NETWORK

Location	Sample	Record length	1826	1852
Kildonan Park	W9109	1796 - 1990	■	
Barber House	B9804	1649 - 1863	■	
	B9809	1723 - 1861	■	
	B9810	1737 - 1863	■	
	B9814	1684 - 1860	■	
	B9825	1733 - 1859	■	
	B9826	1735 - 1864	■	
	Roz1	1732 - 1860	■	■
	Roz18	1651 - 1862	■	
	Roz27	1657 - 1861	■	■
Rat River House	T9702	1663 - 1857	■	
	T9703	1667 - 1860	■	
Marais River	I9903	1850 - 1999		■

The presence or absence of flood rings for 1826 and 1852 in any given sample is most likely related to the tree's growth position relative to the Red River. This suggests that trees containing flood rings could be used to provide estimates of the minimum peak flood stage and flood extent. Unfortunately, only two sites contain trees in growth position with flood rings: Kildonan Park (1826) and Marais River (1852). Therefore, conclusions regarding the spatial response of trees to flooding are limited by the small number of sites containing flood rings, as well as the predominance of pre-1860 historical and alluvial samples, which may have been moved from their growth location. Downstream transport distances for alluvial logs are unknown; however, the abundance of *Q. macrocarpa* trees suitable for construction along the river suggests that settlers harvested wood within a few kilometers (upstream or downstream) of their building site. Expanding the living tree-ring network and sampling a greater number of historical samples along the Red River may allow past flood events to be better defined spatially. Moreover, as the majority of flood signatures for the 1826 and 1852

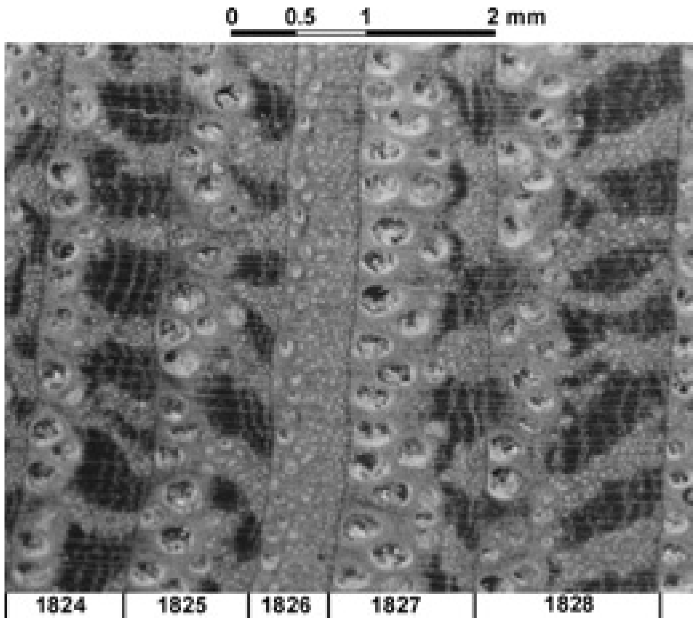

Figure 2. Flood ring of 1826 in *Quercus macrocarpa* from central Winnipeg. Vessels appear as light-colored circles in left-most part of each annual ring. Flood ring is distinguished by reduced area of its earlywood vessels.

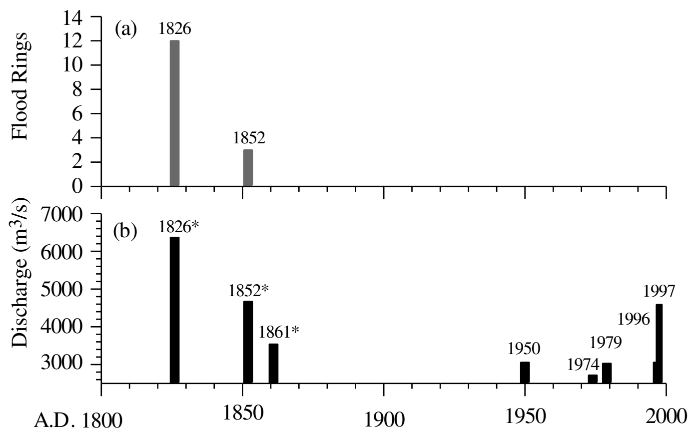

Figure 3. Frequency of *Quercus macrocarpa* flood rings (a) compared to high-magnitude Red River floods (b). Instrument records of floods in Winnipeg begin in 1912. Asterisks denote flood discharges estimated from historical records (Rannie, 1998).

events are contained in samples from Barber House, the composite flood-ring record may best reflect flood conditions in central Winnipeg and be somewhat less sensitive to flooding along the southern part of the network.

The flood-ring record for the Red River also suggests that the frequency of flood-ring formation may correspond to flood magnitude. Yanosky (1983) argued that an increase in flood magnitude would inundate a larger area and thereby increase the percentage of trees containing flood rings. This conclusion is supported by comparisons between flood-ring frequency and flood discharge for the Red River valley. The largest Red River flood in the historical record (1826) has the greatest number of flood rings. The second largest historical flood (1852) is the only other previously known event to leave a tree-ring signature. However, flood rings have not been detected for the flood of 1997, the discharge of which was just slightly less than that of 1852.

The absence of 1997 flood rings is difficult to attribute to a specific cause. Extrapolation from nearby gauging stations suggests that the Remus Farm site was under water for the longest period in 1997, from April 15 to May 29. This period is approximately equivalent to that estimated for the Kildonan Park site in 1826; thus, inundation during the first two weeks of June may be the critical factor determining flood-ring formation in *Q. macrocarpa*. The timing of flooding therefore appears to be more important to flood-ring development than the duration of inundation.

However, since estimates of the 1826 flood from historical records may contain considerable uncertainties (A.A. Warkentin, 2000, personal commun.), comparisons between stand elevation and reconstructed stage heights for 1826 may underestimate the true length of inundation at Kildonan Park. Furthermore, it is unclear why variation in the timing of spring floods of approximately two weeks should limit the ability of *Q. macrocarpa* to record flood signatures. Observations of *Q. robur* in England suggest that earlywood development begins in early March (Varley and Gradwell, 1962). Similar data are not yet available for *Q. macrocarpa* in Manitoba, but floods in April and May, such as the 1997 event, may occur prior to cambial activity.

The evidence presented above makes it difficult to identify the duration and timing of inundation necessary to form a flood ring. Flood tolerance experiments with *Q. macrocarpa* have used seedlings exclusively; because immature trees lack woody structure, the response of saplings to inundation, including the formation of hypertrophied lenticels and inhibited growth (Tang and Kozlowski, 1982), is markedly dissimilar to that of adult trees. Until the relationship between timing and length of inundation and flood-ring formation is more clearly defined, we can conclude only that floodwaters occupied the prairie level in northern and central Winnipeg and upstream of the Rat River in 1826 and central Winnipeg and the Marais River site in 1852 until the middle of June.

CONCLUSIONS

Results presented by Astrade and Bégin (1997) and in this paper suggest that *Quercus* species adjacent to flood-prone rivers adapt to prolonged inundation by reducing the mean transverse area of the earlywood vessels in their annual rings. Vessel reductions are confined to the year of inundation; tree anatomy returned to normal in subsequent nonflood years.

The present flood record of the Red River, which combines instrumental and historical data, spans the entire 20th century as well as a part of the 19th century (Rannie, 1998). The strong relationship between flood-ring formation and large 19th-century Red River floods suggests that tree rings containing shrunken vessels may be used to identify and date paleofloods with annual resolution. Cross-comparison techniques used in tree-ring analysis combined with good sample depth allow tree rings to be dated independently of the criteria used to identify flood signatures. Flood rings may be used to identify high-magnitude, pre-instrumental flood events in low-gradient rivers and may provide an accurate proxy record of high-magnitude floods in the Red River. Such a record will provide the primary data necessary to determine how the frequency and magnitude of Red River floods have varied in response to long-term changes in climatological and geological conditions over the past several centuries.

ACKNOWLEDGMENTS

We received financial support from the Red River Flood Protection Program; Nielsen also received support from the Manitoba Hydro Forest Enhancement Program. We thank Greg Brooks and Alfred Warkentin for comments on earlier drafts of the paper; Alfred Warkentin for permission to include stage data for the 1826 flood; Bonnie Lenton and Gaywood Matile for assistance in the preparation of figures; and Gordon Jacoby and Greg Wiles for providing editorial comments on the manuscript.

REFERENCES CITED

Astrade, L., and Bégin, Y., 1997, Tree-ring response of *Populus tremula* L. and *Quercus robur* L. to recent spring floods of the Saône River, France: Ecoscience, v. 4, p. 232–239.

Canadian Department of Resources and Development, 1953, Report of investigations into measures for the reduction of the flood hazard in the greater Winnipeg area, appendix C, flood runoff analysis: Red River Basin investigation: Winnipeg, Canadian Department of Resources and Development, 142 p.

Carlquist, S., 1975, Ecological strategies of xylem evolution: Berkeley, University of California, 259 p.

Cook, E.R., and Kairiukstis, L.A., editors, 1990, Methods of dendrochronology: Applications in the environmental sciences: Dordrecht, Netherlands, Kluwer, 394 p.

Gottesfeld, A.S., and Johnson Gottesfeld, L.M.J., 1990, Flood-plain dynamics of a wandering river: Dendrochronology of the Maurice River, British Columbia, Canada: Geomorphology, v. 3, p. 159–179.

International Red River Basin Task Force, 1997, Red River flooding: Short-term measures: Ottawa, International Joint Commission, 65 p.

Manitoba Water Commission, 1998, An independent review of actions taken during the 1997 Red River flood: A report to the Honourable J. Glen Cummings, Minister of Natural Resources: Winnipeg, Manitoba Natural Resources, 105 p.

McCord, V.A., 1996, Fluvial process dendrogeomorphology: Reconstruction of flood events from the southwestern United States using flood-scarred trees, *in* Dean, J.S., et al., eds., Tree-rings, environment and humanity: Radiocarbon Special Issue, p. 689–699.

Rannie, W.F., 1998, A survey of hydroclimate, flooding, and runoff in the Red River basin prior to 1870: Geological Survey of Canada Open File 3705, 189 p.

Scott, G.A.J., 1995, Canada's vegetation: A world perspective: Montreal, McGill-Queen's, 361 p.

Sigafoos, R.S., 1964, Botanical evidence of floods and flood-plain deposition: U.S. Geological Survey Professional Paper 485-A, 35 p.

Tang, Z.C., and Kozlowski, T.T., 1982, Some physiological and morphological responses of *Quercus macrocarpa* seedlings to flooding: Canadian Journal of Forest Research, v. 12, p. 196–202.

Teller, J.T., and Bluemle, J.P., 1983, Geological setting of the Lake Agassiz region, *in* Teller, J.T., and Clayton, L., eds., Glacial Lake Agassiz: Geological Association of Canada Special Paper 26, p. 5–20.

Varley, G.C., and Gradwell, G.R., 1962, The effect of partial defoliation by caterpillars on the timber production of oak trees in England: Internationaler Kongress für Entomologie, XI, Wien 1960: Sonderdruck aus den Verhandlungen, Bd. II, p. 211–214.

Yanosky, T.M., 1983, Evidence of floods on the Potomac River from anatomical abnormalities in the wood of flood-plain trees: U.S. Geological Survey Professional Paper, v. 1296, 42 p.

Manuscript received April 5, 2000
Revised manuscript received July 5, 2000
Manuscript accepted July 19, 2000