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On the Identification and Characterization of Drought and Aridity in Postglacial Paleoenvironmental Records from the Northern Great Plains

Identification et définition de la sécheresse et de l'aridité à partir des relevés paléoenvironnemenaux postglaciaires des Grandes Plaines du Nord

Identificación y caracterización de la sequía y la aridez en el registro de paleoambientes postglaciares de las grandes praderas de Norteamérica

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Article abstract

The Northern Great Plains region is especially sensitive to drought and is likely to be even more drought-prone under projected global warming. Drought has been invoked as an explanatory factor for changes seen in postglacial paleoenvironmental records. These proxy records may extend drought history derived from instrumental data. Moreover, in the last decade, some paleoenvironmental studies have been expressly undertaken for the examination of long-term drought history. Nevertheless, few such studies explicitly define drought. This makes it difficult to compare results or to understand what the results mean in terms of the operational drought definitions that are used in resource management. Operational drought is defined as usually short-term; longer sustained dry intervals reflect a shift to aridity. Therefore, high resolution paleoenvironmental proxies (annual or subdecadal) are best for the investigation of drought history. Such proxies include tree rings and some lake records. However, most lake-based records are sampled at lower resolution (decadal or subcentury) and are therefore providing aridity signals.

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ON THE IDENTIFICATION AND CHARACTERIZATION OF DROUGHT AND ARIDITY IN POSTGLACIAL PALEOENVIRONMENTAL RECORDS FROM THE NORTHERN GREAT PLAINS

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ABSTRACT The Northern Great Plains region is especially sensitive to drought and is likely to be even more drought-prone under projected global warming. Drought has been invoked as an explanatory factor for changes seen in postglacial paleoenvironmental records. These proxy records may extend drought history derived from instrumental data. Moreover, in the last decade, some paleoenvironmental studies have been expressly undertaken for the examination of long-term drought history. Nevertheless, few such studies explicitly define drought. This makes it difficult to compare results or to understand what the results mean in terms of the operational drought definitions that are used in resource management. Operational drought is defined as usually short-term; longer sustained dry intervals reflect a shift to aridity. Therefore, high resolution paleoenvironmental proxies (annual or subdecadal) are best for the investigation of drought history. Such proxies include tree rings and some lake records. However, most lake-based records are sampled at lower resolution (decadal or subcentury) and are therefore providing aridity signals.

RÉSUMÉ *Identification et définition de la sécheresse et de l'aridité à partir des relevés paléoenvironnemenaux postglaciaires des Grandes Plaines du Nord.* Les Grandes Plaines du Nord sont particulièrement sensibles à la sécheresse et seront vraisemblablement grandement touchées par le réchauffement climatique prévu. La sécheresse est un facteur qui peut expliquer les changements observés dans les relevés paléoenvironmentaux postglaciaires. Ces derniers permettent de comprendre, sur une plus longue période, l'évolution de la sécheresse révélée par les données climatiques modernes. Au cours de la dernière décennie, plusieurs études paléoenvironnementales ont été expressément entreprises dans ce but. Toutefois, peu d'entre elles présentent une définition précise de la sécheresse. Cela complique la comparaison et l'interprétation des résultats en ce qui a trait à la définition de la sécheresse en phase active. La sécheresse active n'est habituellement que de courte durée ; les épisodes secs plus longs reflètent un passage à l'aridité. Les indicateurs paléoenvironnementaux de haute résolution (annuels ou de moins d'une décennie) sont les meilleurs pour suivre l'évolution de la sécheresse. Ces indicateurs comprennent les cernes de croissance des arbres et certaines données lacustres. Cependant, les données lacustres d'une résolution inférieure (à l'échelle de la décennie ou de la fraction de siècle) tendent à donner des signaux d'aridité.

RESUMEN *Identificación y caracterización de la sequía y la aridez en el registro de paleoambientes postglaciares de las grandes praderas de Norteamérica.* La región de las grandes praderas de Norteamérica es particularmente sensible a la sequía y será sin duda afectada por el calentamiento global por venir. Se ha propuesto que la sequía puede ser el factor que explique los cambios observados en el registro de paleoambientes postglaciares. Dicho registro permite comprender la evolución de la sequía obtenida a partir de datos cuantitativos modernos, durante un periodo mas largo de tiempo. Mas aun, en la ultima década algunos estudios paleoambientales se han llevado a cabo expresamente para examinar la evolución de la sequía a largo plazo. Sin embargo, pocos son los estudios que definen explícitamente la sequía. Esto dificulta la interpretación y comparación de resultados en términos de una definición operacional de la sequía que permita su uso en el manejo de los recursos. La sequía operacional se define generalmente a corto plazo mientras que intervalos mas prolongados de sequías reflejan un paso a la aridez. Por consecuente, indicadores de alta resolución paleoambiental (anual o inferior a décadas) son mas adecuados para investigar la evolución de la sequía. Tales indicadores incluyen registros dendrocronológicos y datos lacustres. Aun cuando la mayor parte de registros basados en sedimentos lacustres son muestreados a baja resolución (décadas o fracciones de siglos) proporcionan también signos de aridez.

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INTRODUCTION

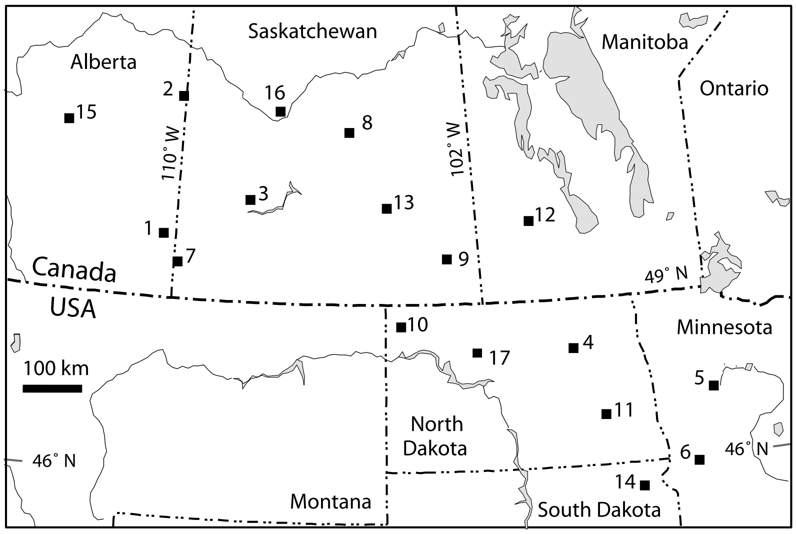
The Northern Great Plains (NGP) area (Fig. 1) is especially sensitive to droughts and yet remains important as a focus for regional economic development and agricultural production, especially in the Canadian portion. If projected global warming trends continue, the region's vulnerability to drought is likely to be enhanced (Lemmen *et al.,* 1997). Droughts have enormous economic and social impacts and so it is especially critical to understand their spatial and temporal occurrence. Instrumental climate records in this region are short, extending only to the late 19th century, and hence proxy postglacial paleoenvironmental records may be used to extend drought history (*e.g.*, Woodhouse and Overpeck, 1998). The hope is that, by examining the pattern of past droughts, a better understanding of the climate factors underlying drought may be gained and better predictive models for future drought may be developed.

In the last decade, many paleoenvironmental studies, especially in the Northern Great Plains, have been explicitly directed at the illumination of drought history (*e.g.*, Fritz *et al.*, 1994; Case and MacDonald, 1995; Laird *et al.*, 1996a, 2003; Clark *et al.*, 2002). Moreover, paleoenvironmental data are also used in climate modelling, especially for verification or "hindcasting" of conditions at critical intervals (*e.g.*, Vettoretti *et al.*, 1998; Kohfeld and Harrison, 2000; Peltier, 2000). Such climate models often have, as one objective, climate prediction (Kattenberg *et al.*, 1996). However, if information from paleoenvironmental studies is to be helpful for deriving drought histories, assessing the magnitude of contemporary droughts, verifying models, or assisting in drought prediction, then rigorous definitions of inferences from proxy indicators are required. In other words, it should be clear what "drought" inferred from a proxy indicator means. In particular, it needs to be clear whether these data can be translated into terms that mesh with operational definitions used by policy makers. This is especially important if the results from paleoenvironmental studies are to feed into drought forecasting or are to be useful for climate projections.

It is not always clear that drought identified from paleoenvironmental records has the same meaning as drought defined operationally (Table I). Indeed, many studies and reviews (*e.g.*, Woodhouse and Overpeck, 1998) do not include a definition of drought; the term is taken for granted. Certainly, paleoenvironmental records offer many proxy indicators that mainly reflect meteorological or hydrological drought (Table II). Not all of these indicators respond to dry conditions in the same way. Because of varying response times or record resolution, the measures of drought duration or intensity produced from different paleoenvironmental records may not be comparable. Moreover, it may be difficult to translate drought inferred from paleoenvironmental records to the operational definitions used in contemporary drought management. In the rest of this review, I will examine conceptual and operational definitions of drought, then consider the ways in which drought has been inferred from paleoenvironmental records, before suggesting terminology that may enhance communication between different disciplines concerned with drought.

VERNACULAR AND CONCEPTUAL DEFINITIONS OF DROUGHT

At its simplest in common parlance, drought is defined as "continuous dry weather" or "absence of rain" (Sykes, 1976: 318). Walker (1999: 358) defines drought as "a marked deficiency of rain compared to that usually occurring at the place and season under consideration". Steila (1983: 194) considers drought as "a temporary negative deviation of an environment's moisture-status from its expected amount". These definitions



1 Chappice Lake (Vance *et al.*, 1993)
2 Chauvin Lake (Laird *et al.*, 2003)
3 Clearwater Lake (Leavitt *et al.*, 1999)
4 Devils Lake (Fritz *et al.*, 1994)
5 Elk Lake (Clearwater Co.) (Sanger and Hay, 1993)
6 Elk Lake (Grant Co.) (Smith *et al.*, 2002)
7 Harris Lake (Sauchyn and Sauchyn, 1991)
8 Humboldt Lake (Laird *et al.*, 2003)
9 Kenosee Lake (Vance *et al.*, 1997)
10 Kettle Lake (Clark *et al.,* 2002)
11 Moon Lake (Laird *et al.*, 1996b)
12 Nora Lake (Laird *et al.*, 2003)
13 Pasqua Lake (Hall *et al.*, 1999)
14 Pickerel Lake (Dean and Schwalb, 2000)
15 Pine Lake (Campbell, 1998)
16 Redberry Lake (Van Stempvoort *et al.*, 1993)
17 Rice Lake (Yu and Ito, 1999)

FIGURE 1. Lakes and locations on the northern Great Plains mentioned in the text.

Lacs et sites des Grandes Plaines du Nord signalés dans le texte.

TABLE I

Operational definitions of drought

Type	Defined by	Example of indices
Meteorological drought	Long-term lack of precipitation	Percent of Normal Deciles Palmer Drought Severity Index (PDSI) Crop Moisture Index (CMI) Standardized Precipitation Index (SPI)
Hydrological drought	Reduced surface run-off, decreased streamflow, and reduced groundwater levels	Palmer Hydrological Drought Index (PHDI) Surface Water Supply Index (SWSI) Reclamation Drought Index (RDI)
Agricultural drought	Reduced crop yields, insufficient soil moisture reserves to support crop growth	Crop yields Livestock sales Soil Moisture Drought Index (SMDI) Crop-specific Drought Index (CSDI)
Socioeconomic drought	Reduced supply of some economic resource Famine	Income reduction Farm and business bankrupties Crop insurance claims Out migration Human mortality

Table based on Wilhite and Glantz (1985), Maybank *et al.* (1995), Byun and Wilhite (1999), Hayes *et al.* (1999), and Hayes (2002).

TABLE II

Some proxy indicators used for investigation of aridity and drought in the Northern Great Plains

Proxy indicator	Aridity or drought inferred by	Examples
Charcoal	Increased charcoal abundance -> increased fire frequency related to drier conditions or Decreased charcoal abundance -> reduced fuel availability	Clark (1993), Clark *et al.* (2002)
Diatoms	Assemblage changes reflecting salinity changes	Fritz *et al.* (1991, 1994), Laird *et al.* (1996a, b, 2003), Leavitt *et al.* (nda, ndb, ndc)
Ostracodes	Assemblage changes relating to salinity changes	Vance *et al.* (1997), Smith *et al.* (1997)
Ostracodes	Changes in element ratios (Mg/Ca, Sr/Ca) in shells reflecting water temperature and salinity changes	Engstrom and Nelson (1991), Fritz *et al.* (1994), Haskell *et al.* (1996), Yu and Ito (1999)
Plant macroremains	Assemblage changes reflecting lake level fluctuations (*e.g.*, increased salinity -> increased *Ruppia*) and shoreline shifts	Vance *et al.* (1992, 1993)

TABLE II (suite)

Some proxy indicators used for investigation of aridity and drought in the Northern Great Plains

Proxy indicator	Aridity or drought inferred by	Examples
Pollen (local)	Assemblage changes reflecting lake level fluctuations, shoreline shifts, and salinity changes	Vance *et al.* (1992, 1993), Laird *et al.* (1996b)
Pollen (regional)	Assemblage changes reflecting change in composition of regional (terrestrial, upland) vegetation	Clark *et al.* (2002)
Sediment geochemistry	Changes in element ratios from carbonates reflecting salinity changes of lake water	Fritz *et al.* (1994), Haskell *et al.* (1996)
Sedimentary pigments	Concentration changes reflecting productivity	Van Stempvoort *et al.* (1993)
Sediment mineralogy and geochemistry	Change in mineral species deposited reflecting water chemistry	Vance *et al.* (1993), Clark *et al.* (2002)
Sediment particle size distribution	Change from coarser -> finer grained sediments, implying low flow regime	Campbell (1998)
Sediment type	Clastic -> organic, implying falling lake levels and terrestrialization	Beierle and Smith (1998)
Stable isotopes	Changes in isotopic ratios (O or C) -> increased water temperature. Isotopes preserved in deposited aragonite or calcite	Van Stempvoort *et al.* (1993), Valero-Garcés *et al.* (1997), Dean and Schwalb (2000)
Tree rings	Narrow rings compared to adjacent rings in standardized record. Calibrated against instrumental climate data. Used to reconstruct precipitation	Stockton and Meko (1983), Meko (1992), Case and MacDonald (1995), Meko *et al.* (1995), Sauchyn and Beaudoin (1998), Watson and Luckman (2001), Sauchyn *et al.* (2003)
Tree rings	Narrow rings compared to adjacent rings in standardized record. Calibrated against instrumentally-derived data. Used to reconstruct PHDI	Cook *et al.* (1996, 1999)
Tree rings	Narrow rings compared to adjacent rings in standardized record. Calibrated against instrumental streamflow data	Case and MacDonald (2003)

highlight two characteristics of drought that pervade both meteorological and paleoenvironmental studies: it is a reflection of conditions compared to some measure of normal or expected conditions and it is defined in relation to a particular place. The consequences are that drought does not have an absolute value, but can vary through time at the same place and across space at the same time. Drought is a relative term.

Drought is one of the extreme climate events that severely affect economic activity and cause large financial losses (Kunkel *et al.*, 1999). The early 20th century drought (1930s) on the Great Plains, which Henson *et al.* (1999) characterized as number one in the "Top Ten" weather events of that century in the United States, stimulated research into better forecasting methods, in an effort to mitigate the effects of future droughts (Hecht, 1983). Wilhite and Glantz (1985: 116) remark that "the ultimate significance to society of drought lies in its impacts". These impacts depend on what activities are being carried out in the affected area; some activities are going to be more sensitive to moisture deficiencies than others. Drought also depends on the perception of the viewer (Diggs, 1991; Dagel, 1997): a farmer's drought is a holidaymaker's fine vacation weather. This implies that a drought may not be perceived as a drought unless it has a measurable or apparent impact on some aspect of human activity. Indeed, Hare (1987: 4) defined drought as an interval of precipitation deficiency "over a period long enough for it to hurt". Steila (1983: 192) argued that, from a millennial perspective, intervals of reduced water availability are to be expected, so that "extremes are normal and anomalies do not exist". In his view, drought is a perceptual term, used when available water is insufficient to meet human needs. For human systems as well as ecosystems, drought therefore has a demand component and is not simply related to moisture inputs. To encompass these aspects, Glantz and Katz (1977) suggest that drought needs a social as well as a physical definition. Clearly, these social impacts are not directly measurable through paleoenvironmental studies, though scholars have used drought as one of the explanatory factors for societal collapse identified through the archeological record in many areas of the world (*e.g.*, Abbott *et al.*, 1997; Stahle *et al.*, 1998; Hodell *et al.*, 2001; Weiss and Bradley, 2001).

OPERATIONAL DEFINITIONS OF DROUGHT

In practical terms, drought is more than simply dry weather. In land and resource management, drought is defined operationally depending on the application (Table I). Four types of drought are widely recognized: meteorological, agricultural, hydrological, and socioeconomic drought (Dracup *et al.*, 1980; Hayes, 2002). Meteorological and hydrological droughts are related primarily to water supply, whereas agricultural and socioeconomic droughts reflect demand for water. Meteorological and hydrological drought can often be described by indices that have quantitative definitions and are usually based on instrumental measures or monitoring. The most widely known of these is the Palmer Drought Severity Index (PDSI), computed from precipitation and temperature data and an estimate of soil moisture (Palmer, 1965; Alley, 1984; Akinremi *et al.*, 1996). All meaningful indices recognize that drought is a function not only of moisture inputs, but also of losses through potential evapotranspiration and environmental demand for water. These indices may be used to set up threshold values that trigger crop insurance programs, mitigation measures, or disaster relief, as documented for the United States by Wilhite (1983). All indices have problems in sensitivity, definition, and computation that limit their usefulness (Alley, 1984; Byun and Wilhite, 1999). Therefore, as Wilhite and Glantz (1985: 113) note, it is unlikely that a universally acceptable definition of drought can be formulated.

Nevertheless, these operational definitions share common characteristics. The drought indices all compare conditions to some concept of normality for the particular place under consideration (Wilhite and Glantz, 1985; Maybank *et al.*, 1995). The basis for comparison may be the climate normals (*i.e.*, thirty years of record) or longer (Dracup *et al.*, 1980). For example, Agriculture and Agri-Food Canada (nd) defines drought based on growing season precipitation (April 1-August 31) compared to data from 1961-1990. Depending when precipitation occurs, therefore, it is possible to have an agricultural drought in a year when neither meteorological nor hydrological drought occurs. Droughts are, however, usually reported on an annual basis although multiyear droughts are recognized.

Current conditions therefore feed into the averages that form the basis for comparison. If droughts persist for many years, then the long term normals will also shift towards a drier scale. At some point, the dry conditions are no longer a deviation from normal or extreme. Merely, the climate has shifted to a drier modality. Therefore, what is recognized as a drought may change over time at a particular place. Specifically, a low precipitation amount may be characterized as a drought if it occurs in a generally moist interval, whereas if the climate shifts towards aridity it would not meet the criterion for drought. When aridity is persistent and extreme, drought does not occur (Steila, 1983). As Hare (1987: 4) remarked, "Drought is a meaningless term when rain is a rare event".

It also follows that the recognition of drought is highly sensitive to the conditions that are chosen as the basis for comparison. Selection of an appropriate comparative data set, both on a spatial and temporal basis, is critical. Consider, for instance, that the 1990s have seen many warm and dry summers on the NGP. Therefore, the temperature normals for the 1971-2000 interval are likely to be higher than those for the previous normal intervals. This suggests higher potential evapotranspiration rates. At Medicine Hat, for example, the mean annual temperature increased between the 1951-1980 and 1971-2000 normals, and the total annual precipitation decreased (Table III). Using normals from a warmer and drier interval will give an apparent reduction in the number of identified droughts, whereas more droughts will be identified if normals from a cooler and moister interval are used as the basis for comparison (Table IV). This factor becomes especially critical when choosing a comparative data set and interval for long proxy records, as discussed more fully below.

Indeed, the comparative interval may be specifically chosen so as emphasize the prevalence of drought. For example, Mock (1991: 28) chose the 1951-1980 interval in his study of 19th century instrumental data for drought history on the Great Plains because it "excludes the droughts of the 1930s and the

TABLE III

Climate normals for Medicine Hat and Maple Creek

	1951-1980	1961-1990	1971-2000
Medicine Hat A, AB			
Mean annual temperature (°C)	5.1	5.5	5.7
Precipitation (mm)	347.9	322.6	333.8
Maple Creek North, SK			
Mean annual temperature (°C)	5	5.3	5.4
Precipitation (mm)	394.4	375.3	379.3

Sources: 1951-1980 normals from Atmospheric Environment Service (1982), 1961-1990 and 1971-2000 normals from Environment Canada (2002)

TABLE IV

Computation of drought years for Medicine Hat (1895 - 1999)[1]

Years used for comparison	Years of available data	Mean ppt (mm)	SD (mm)	Drought years[2]	Severe drought years[3]
1951-1980	29	410.7	88.4	27	7
1961-1990	28	382.4	83.6	24	3
1971-1999	27	390.7	89.2	25	2

1 Mean and sd values are computed from the annual precipitation values and therefore vary from the normals shown in Table III which are based on daily data. The 1 sd cut-off was chosen following Steila (1983). Sources: Medicine Hat data (1895 - 1999) obtained from Historical Canadian Climate Database, Environment Canada, see Mekis (2000).

2 More than 1 sd below mean.

3 More than 2 sd below mean.

1980s, which may present *misleading representations of climatic normals*" (my italics). Droughts (either spring/summer or fall/winter) were defined when precipitation was equal or less than 80 % of that of the normal interval (Mock, 1991: 35-36). By selecting normals from a moister interval as a basis for comparison, he obtained a higher apparent incidence of drought in the historic data. Because drought is a recurrent feature of prairie climate, characterising a comparative (normal) interval that includes drought as "misleading" suggests an implicit assumption that drought is "abnormal".

Not all droughts are the same; droughts also vary in severity or intensity (Wilhite and Glantz, 1985). Numerical drought indices, such as the Palmer Drought Severity Index (PDSI), usually measure drought severity in terms of departure from some standardized conditions. These take into account the degree of dryness or moisture deficit and the duration of dry conditions. Drought severity has spatial and temporal components. Maybank *et al.* (1995: 204) point out that "drought can be severe because it covers a wider area ... for one growing season or ... because it affects an area for several years".

Drought has a time limit; even on a subcontinental scale multiyear droughts are usually sub-decadal (see Diaz, 1983). Moreover, most droughts last for a year or less; droughts that persist for two years or more are comparatively rare (Fig. 2) though the effects of these infrequent high intensity droughts may be highly devastating. Even within decades characterized as droughty, conditions are variable. Karl and Heim (1990) noted that the 1930s in the United States contained at least four distinct drought episodes, separated by intervals when conditions were less severe. Dry conditions that persist for many years (decades or centuries) cannot be considered drought under these operational definitions. Merely, desiccation has set in as the climate shifted to greater aridity (Hare, 1987). The consequences of this shift to aridity may be profound and

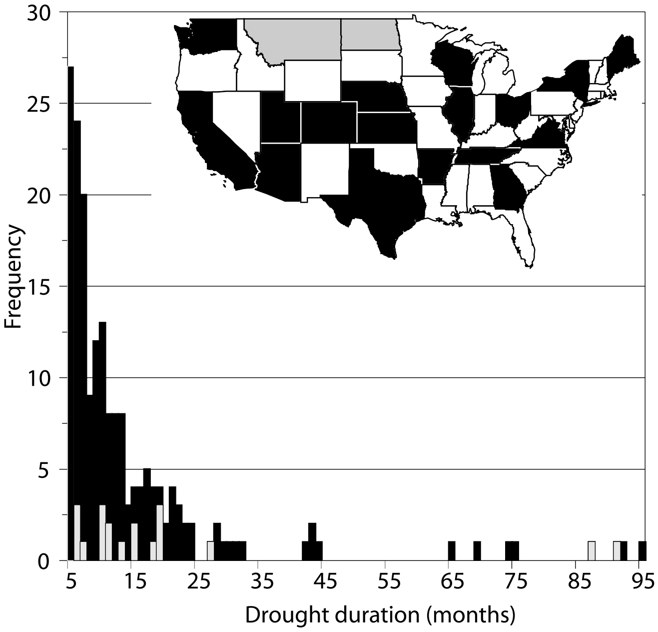


FIGURE 2. Dry interval frequency, based on Table I in Diaz (1983). This table shows dry period duration based on climate data from 1895-1981 for nineteen states (inset map highlights states in analysis). Data for Northern Great Plains states (Montana and North Dakota) in grey. Dry intervals or drought sequences were defined as three or more consecutive months with a PDSI ≤ -2.0.

Fréquence des périodes sèches d'après le tableau de Diaz (1983). Celui-ci montre la durée des périodes de sécheresse selon les données climatiques de 1895 à 1981 issues de 19 États américains (désignés dans le carton). Les États des Grandes Plaines du Nord (Montana et Dakota du Nord) sont en gris. On considère qu'une période de sécheresse s'étend sur au moins trois mois consécutifs (indice de Palmer ≤ -2.0).

the landscape effects may be long-lasting. However, I can find no definitions of exactly when this transition between a multiyear drought and shift to a more arid climate occurs. The closest is the remark by Hare (1987: 6) that desiccation is "a prolonged period in which drought slowly and intermittently intensifies", characterized by "two or three decades of progressively decreasing rainfall". My reading of the available literature suggests that droughts usually last less than five years (and mostly less than two), whereas persistent dry conditions lasting more than a decade reflect a shift to aridity.

It is here that the greatest disconnect between paleoenvironmental investigations and operational definitions occurs. In a recent review, for instance, Woodhouse and Overpeck (1998) refer to multidecadal droughts inferred from paleoenvironmental studies (see also Forman *et al.*, 2001). Weiss and Bradley (2001) refer to a *ca.* 200 year drought in the Middle East. According to the operational definitions discussed here, these arid intervals could not (and should not) be characterized as droughts. Moreover, it is important to distinguish between these two concepts (drought and aridity), because the landscape, biological, and social consequences of each may be quite different. Additionally, from an operational or socioeconomic perspective, it is the comparison with present conditions, the short-term view, that is of greatest relevance. From this viewpoint, dry conditions in the past need to be characterized as to whether they would be considered drought using the present drought definition for that region. Unless paleoenvironmental records can offer data in these terms, their value to the wider community will not be appreciated.

CONSIDERATIONS IN THE INVESTIGATION OF ARIDITY AND DROUGHT HISTORY THROUGH PALEOENVIRONMENTAL RECORDS

The interpretation of drought or aridity from paleoenvironmental records, especially when these are derived from lake cores, depends on whether they can be investigated at a resolution that enables a distinction between them. This is at least partly dependent on the chronologic control available. Few NGP lake records are annually laminated (varved). The Moon Lake record, for example, is relatively well-constrained by fourteen AMS dates (Valero-Garcés *et al.*, 1997), a level of chronologic control that is beyond the reach of most research projects. Many NGP lake records (Fig. 1) have few "pinning points" to offer chronologic control. Moreover, the usual assumption of constant sedimentation rate between dated levels (whether linear or some other form of interpolation) may give a particularly misleading picture in NGP landscapes where variable and episodic deposition is likely.

Furthermore, where the chronologic control is provided by radiocarbon dates, the analytical error on the dates is such that the records may not be resolved at an interval sufficient to detect drought. It is worth noting that most chronologic models based on radiocarbon dates derived for lake records assume single numerical values for the dated levels and infer dates for other levels based on interpolation. In other words, the chronologic models do not include error or interval analysis ("fuzzy" mathematics) in their computations. This may be a particular concern when regional drought syntheses are being attempted based on integration of data from many records (*e.g.*, Fritz *et al.*, 2000; Laird *et al.*, 2003) or when the data are being used to extract cyclicity or periodicities, as from the Kettle Lake (Clark *et al.*, 2002), Pickerel Lake (Dean and Schwalb, 2000), and Rice Lake (Yu and Ito, 1999) records.

Because of dewatering and sediment compaction, the time interval represented by even closely based samples can vary from the base to the top of a sediment core. Hence, a greater time interval may be represented by each sampling interval in older compared to younger sediments, as noted in the two core segments from Kettle Lake (Clark *et al.*, 2002) and at Pine Lake (Campbell, 1998). Therefore, it may be more difficult to achieve subdecadal resolution data for early mid-Holocene intervals. Ironically, it is precisely these intervals that are often considered an analogue for conditions under continued global warming (Beaudoin, 1999).

The investigation of drought history may also be limited by practical considerations, such as how many samples can be analysed. Potentially, many lake-based records could yield drought histories if they were sampled at closely-spaced or contiguous intervals. Multiproxy studies are also more likely to provide a comprehensive picture, especially if independent proxies are investigated. However, the exigencies of research funding and time constraints may make this unfeasible. One practical alternative is to perform nested or hierarchical sampling, with critical intervals sampled at much finer resolution, as in Dean's (1997) work at Elk Lake.

Many studies of drought are site specific. However, drought has a high degree of spatial variability and so generalizing from a single site to a broader region may be problematic. In the summer of 2002, for example, southern Alberta had "extremely high" precipitation (90-100 percentile class) with some parts experiencing "record wet" conditions, while central Alberta was experiencing "extremely low" precipitation with some parts suffering "record dry" conditions (Agriculture and Agri-Food Canada, 2002). Conversely, during the growing season of 2000, the Milk River area experienced extreme dry conditions (<40 % average precipitation) while most of southern Saskatchewan was experiencing well above average (150-200 %) precipitation (Beaudoin, 2003). Tree ring studies (*e.g.*, Meko, 1992) have attempted to explore this regional variability, although the spatial distribution of tree ring records across the NGP is sparse. In a recent comparison of diatom-inferred salinity from three lakes in North Dakota, Fritz *et al.* (2000) identified broad coherence in the overall pattern of salinity fluctuations over the last 2000 years. Nevertheless, there are some differences between these records which may reflect very local site specific differences or perhaps chronological inconsistencies. A wider study, including proxy data (diatom studies) from six lakes across the NGP (Laird *et al.*, 2003) also showed regional patterning in the timing of inferred aridity intervals. Differences at the regional scale were attributed to different climate characteristics of the sites, such as dominant airmass types and position in relation to jet stream, fronts, and storm tracks. Operational drought conditions are strongly related to these synoptic factors. It is perhaps here that the greatest challenge for paleoenvironmental studies lies.

Operational drought definitions, especially agricultural or crop-specific definitions (Table I), often require dry conditions to be identified on the basis of the growing season, that is, a sub-annual resolution. For these purposes, it is not so much the total annual precipitation that is important, but its timing and distribution with respect to the growing season. Although many paleoenvironmental proxies do reflect growing season conditions, this level of resolution is unlikely to be attainable by most records.

The regional understanding of drought history is also compromised by the spatial unevenness of the available paleoenvironmental records. I identified 149 paleoenvironment records, mainly from lakes or wetlands, in a recent compilation for the NGP, comprising southern Alberta, Saskatchewan and Manitoba, and adjacent areas of the northern United States (Beaudoin, 2001). Of these, the majority were from Alberta, Saskatchewan, and Minnesota, with only two from Montana, and none for eastern Montana and western North and South Dakota. Paleoenvironmental records tend to be derived from the periphery of the NGP, with sparse coverage for many areas (Fig. 1).

INFERRING DROUGHT FROM PROXY PALEOENVIRONMENTAL INDICATORS

Many different types of paleoenvironmental indicators in the NGP have been used to investigate aridity or drought (Table II). In some paleoenvironmental studies (*e.g.*, Fritz *et al.*, 2000; Clark *et al.*, 2002; Smith *et al.*, 2002) drought is the explicit focus of the research. Nevertheless, drought is rarely defined in these studies. Drought is inferred through its impact on a proxy indicator. To provide data comparable to operational drought definitions, the proxy indicator needs to have a low buffering capacity, a rapid response, and yield an annual to seasonal record. Few proxy indicators meet these criteria. Moreover, technical constraints (*e.g.*, sampling in lake sediments) may preclude extraction of an annual signal. In the following section, I review some of the types of proxy indicators that have been used to infer drought history on the NGP. My concern here is primarily methodological, that is, how drought or aridity has been inferred from the indicators.

A) HIGH-RESOLUTION OR ANNUALLY RESOLVED RECORDS FROM TREE RING DATA

Tree rings record information at annual resolution and so they offer the best hope for producing drought histories that may be comparable to those derived from instrumental records. Trees around the margin of the NGP grasslands are likely to be especially sensitive to moisture deficiencies and have been used to infer drought history (*e.g.*, Stockton and Meko, 1983; Meko, 1992; Case and MacDonald, 1995; Meko *et al.*, 1995; Sauchyn and Beaudoin, 1998; Watson and Luckman, 2001; St. George and Nielsen, 2002) and also streamflow histories (*e.g.*, Case and MacDonald, 2003; see also Meko and Graybill, 1995). Because tree rings reflect growing season conditions, they may also provide a reasonable proxy for assessing agricultural drought. Tree ring records are usually calibrated using instrumental climate data (Table II). These records therefore offer the best hope of rapprochement between the paleoenvironmental and meteorological approaches to drought investigation.

However, there is not a standard way of inferring drought from tree ring records; the degree of data abstraction varies between studies. Sauchyn and Beaudoin (1998), for example, inferred droughts when reconstructed precipitation values were distinctly less than the mean of the whole record (Fig. 3A), assessed by visual inspection. Case and MacDonald (1995: 274) defined drought years as those when inferred "precipitation is more than one standard deviation less than the average of the complete series". This approach builds on earlier work by Stockton and Meko (1983), who identified drought years when reconstructed percent normal precipitation values were more than one standard deviation below the 1933-1977 mean based on instrumental data. Years when the values deviated by more than two standard deviations were also identified. This procedure not only provided an indication of when droughts occurred, it also provided a relative indication of drought intensity. The one standard deviation cut-off is computationally and statistically attractive, yet it may not be meaningful for the trees or ecological systems. It would seem preferable to use threshold

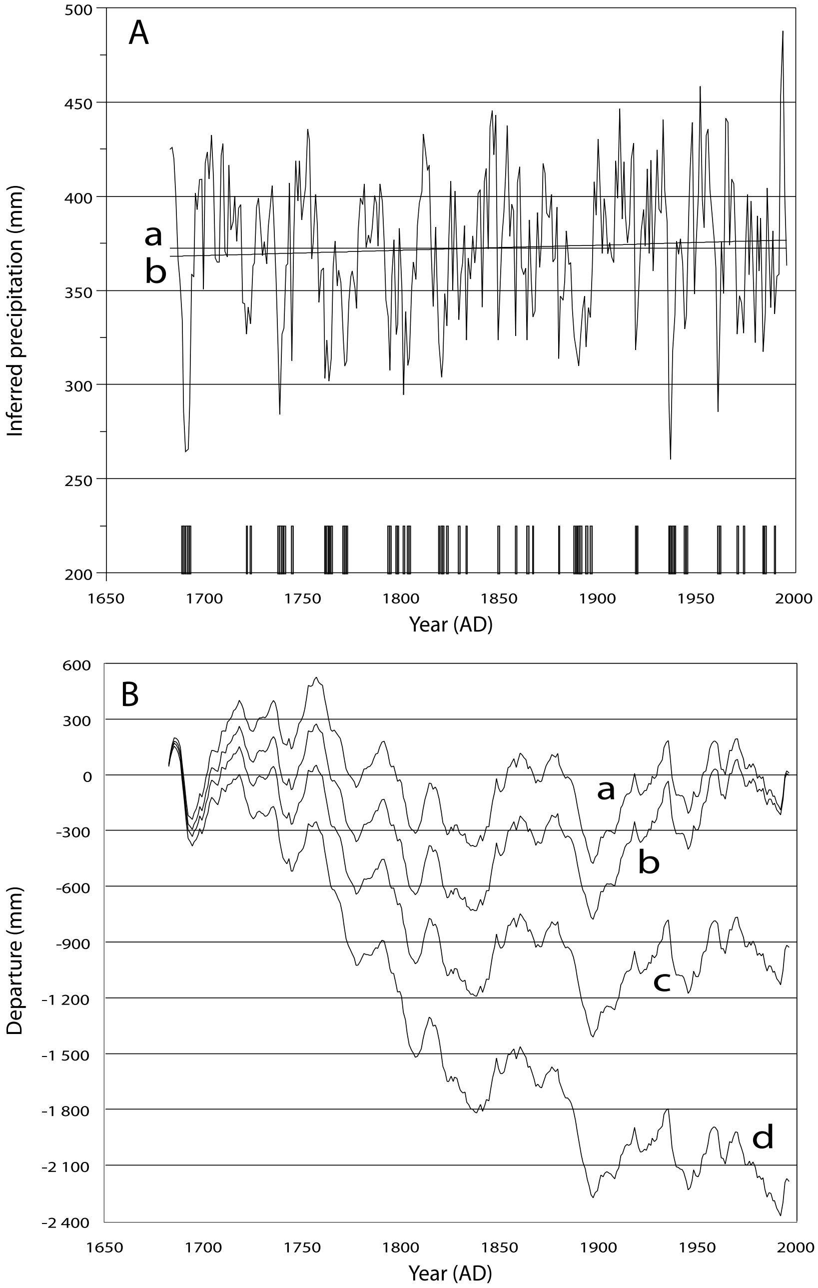


FIGURE 3. Examination of the tree ring record from the Cypress Hills: A) inferred precipitation for Maple Creek (1682-1996) based on *Picea glauca* ring widths (revised data set provided by D.J. Sauchyn, after Sauchyn and Beaudoin, 1998), line a) is the mean for the entire ring record (372.6 mm), line b) is a best fit linear trend through the data (368.03 + 0.027x, where x is the number of years incremented), bars mark drought years, defined following Stockton and Meko (1983) as those when absolute value of inferred precipitation is ≥1 standard deviation below the mean for the record as a whole; B) four reconstructions of antecedent conditions, computed as cumulative departures from the specified value: a) using the best fit linear trend, b) using the mean for the entire ring record (372.6 mm), c) using 375.3 mm, the normal for 1961-1990 for Maple Creek, d) using 379.3 mm, the normal for 1971-2000 for Maple Creek. Normals from Environment Canada (2002).

Examen des relevés dendrochronologiques des Cypress Hills : A) précipitations estimées pour Maple Creek (1682-1996) à partir de la largeur des cernes de croissance de Picea glauca *(données révisées de D.J. Sauchyn, d'après Sauchyn et Beaudoin, 1998). La ligne a) représente la moyenne du relevé complet (372,6 mm); la ligne b) est la régression linéaire qui représente le mieux les données (368,03 + 0,027x, où x représente le nombre d'années). Les barres identifient les années de sécheresse, définies d'après Stockton et Meko (1983) comme étant celles où la valeur absolue calculée des précipitations est à ≥1 écart type sous la moyenne du relevé complet ; B) quatre reconstitutions des conditions passées calculées à partir de la somme des déviations d'après une valeur donnée : a) la meilleure régression linéaire ; b) la moyenne des précipitations d'après le relevé dendrochronologique complet (372,6 mm) ; c) 375,3 mm, la normale de 1961 à 1990 pour Maple Creek ; d) 379,3 mm, la normale de 1971 à 2000 pour Maple Creek. Les normales proviennent d'Environnement Canada (2002).*

values that relate more clearly to tree growth or ecosystem functioning, although these are likely to be species or site specific.

From the eastern United States, Cleaveland and Stahle (1996) and Stahle *et al.* (1998) offer a further level of data abstraction by presenting estimated Palmer Hydrological Drought Index (PHDI) values based on ring width series; similar approaches have been developed for the Great Plains by Cook *et al.* (1996, 1999). Stahle *et al.* (1998) used instrumentally-derived July PHDI data for 1941-1984 as the calibration data set and reconstructed July PHDI values between AD 1185-1984. Droughts were inferred when the tree ring-derived July PHDI was below the zero value for the record as a whole.

In a recent study, Stahle *et al*. (2000) have used the term "megadrought". They examined tree-ring-derived drought records extending back to at least AD 1500 from 96 sites, predominantly in the western United States, with some in the southeast United States and Great Lakes region, and one near Banff. Drought was inferred from examination of derived PDSI values. These sites concur in showing severe and prolonged dry conditions in the 16th century AD. Persistent dry conditions seem to have developed first in Mexico in the 1540s, and then affected areas to the north and east during the latter part of the 16th century, showing a temporal and spatial transgression (Stahle *et al.*, 2000). Indeed this dry interval stands out as being the most severe in a two thousand year proxy precipitation record from New Mexico (Grissino-Mayer, 1996) and Stahle *et al*. (1998) implicate it in the failure of European settlement attempts along the United States eastern seaboard, such as the Jamestown colony. As used by Stahle *et al.* (2000), the term "megadrought" incorporates three ideas: a prolonged interval of intense aridity that was spatially extensive. This term was taken up by Forman *et al.* (2001: 22), who defined it as "the dominance of drought conditions for a decade or more with at least a 25 % deficit in growing season precipitation". Forman *et al.* (2001) relate these conditions to reactivation of dune systems on the Great Plains in the early Holocene and again in the last two millennia. Clearly, events of this magnitude and extent do not meet the criteria for drought considered here.

Prolonged or multiyear intervals of drought show up clearly in the tree ring records when growth is compromised for several years. Instrumental records show that drought years have a tendency to form runs or clusters and a similar pattern appears to extend into the past (Fig. 3A). Thus, rather than reflecting conditions in any one year, tree ring records may be reflecting the cumulative impact of several years' dry conditions affecting soil moisture reserves. To show this, and highlight the effect of antecedent conditions, Wolfe *et al.* (2001) redrafted the tree ring records of Case and MacDonald (1995) and Sauchyn and Beaudoin (1998) on the basis of cumulative departures from the mean for the complete set. This analytical approach is particularly sensitive to the choice of comparative conditions and to the starting point (Fig. 3B). Departures based on some average derived from the available proxy data do show closure, though the relative intensity of the events through the record can appear quite different depending on the type of mean used (compare curves a and b on Fig. 3B). Departures computed using normals from recent meteorological data do not show closure (as computationally expected) and give a more negative view of deficits (curves c and d on Fig. 3B). Yet there is no *a priori* reason for preferring any of the comparative values, all are equally valid, and, from the perspective of operational definitions of drought, the comparison with the present conditions may be most appropriate.

Several methodological and practical issues stand out from a close examination of these various studies; similar concerns apply to other paleoenvironmental proxies. First, it is often not clear what the spatial and topographic relationships may be between the tree ring sample sites and the instrumental record sites that are available for calibration. This is particularly the case for Stockton and Meko (1983) and Stahle *et al.* (1998). Because precipitation (and drought!) can be spatially highly variable, it is most desirable that the two sets of data should be from sites that are close and have similar characteristics for precipitation potential. Stahle *et al.* (1998), for instance, indicate that regional data were used for calibration. Presumably, some variance will be lost from regionally smoothed or abstracted data.

Second, it may be difficult to find instrumental data for calibration because the network of instrumental data stations across the NGP is fairly sparse and there are few stations yielding long records (see Mock, 1991). Even where stations do have records going back into the late 19th century, it is unlikely that the stations have remained in one spot for the entire length of recording. Moreover, stations that have remained fixed for long intervals may have data problems because of urban effects, which are likely to be more of an issue for temperature than precipitation data (Vincent and Gullett, 1999). It is only recently, for instance, that long time series of data corrected for these effects have become available for the Canadian prairies (Mekis, 2000; Zhang *et al.*, 2000; Vincent, 2001; Vincent *et al.*, 2002). For tree ring calibration, it may be a case of doing the best that you can with the limited instrumental data available.

Moreover, the selection of tree ring study sites may also influence reconstructed drought history. Generally, trees may be selected for study because they are growing in locales where they are likely to be moisture-stressed. However, there may be a higher probability for trees in highly stressed locales to die in severe drought, as found by Ogle *et al.* (2000) for Pinyon Pine in northern Arizona. Therefore, the potential number of archive trees may be reduced. Areas where droughts have been most severe or where aridity is persistent may lack tree ring archives altogether.

B) MID-RESOLUTION (SUB-DECADAL OR DECADAL RESOLUTION) RECORDS FROM LAKE LEVEL STUDIES (INTERNAL PROXIES)

Reduced lake levels are commonly assumed to be an indicator of drought. Lake levels may fall through increased evapotranspiration or decreased moisture input from either meteoric or groundwater sources. Lake level changes are therefore most likely to reflect hydrologic drought. Small enclosed basins, such as the prairie potholes that dot the NGP, will generally have a more rapid response to decreased moisture inputs, and hence be the most sensitive to drought (Larson, 1995). Larger lakes may be less responsive and have a greater buffering capacity to short-term decreases in moisture inputs. Lake morphometry is also important with respect to water level changes (Smith *et al.,* 2002), with deeper lakes having a lower surface area/volume ratio being less sensitive and shallow lakes being more drought sensitive. However, the response of a lake basin depends on the balance between meteoric and groundwater inputs. Although several studies, including Smith *et al.* (1997), Birks and Remenda (1999), Saros *et al.* (2000), and Clark *et al.* (2002), have documented the importance of groundwater inputs to prairie lakes, this is by far the most poorly known component of most prairie lake hydrologic systems. Without knowledge of this component, it is difficult to assess the climatic sensitivity of any specific lake system.

Lake level changes can also result in a change in lake surface area, especially for shallow lakes with large littoral zones. Campbell *et al.* (1994) used lake area measurements from air photos to demonstrate that lakes in the grassland area of southern Alberta were highly sensitive to climatic moisture, with a sharp transition to lower sensitivity at the grassland-parkland boundary. For proxy data, this suggests that lake-level changes from sites in the semi-arid grasslands should provide a sensitive record of long-term moisture changes. Whether the proxy records of these changes provide details of drought or aridity, however, will depend on the lakes' sediment characteristics and the sampling interval used. Lakes with annually laminated sediments have the highest potential to provide drought records. Such lakes are likely to be rare; Last (1999) estimates that only 8 % of small lakes in the Canadian portion of the northern plains have depths greater than 3 m and hence have potential to yield laminated sediments.

Many proxy indicators have been used to infer falling lake levels in response to drought or aridity (Table II). These proxy indicators all reflect processes within the lake basin itself and are therefore related to limnological conditions. They include a broad spectrum of biotic and abiotic proxies (Table II). NGP lakes where drought or aridity has been a major focus of research include Devils Lake (Fritz *et al.*, 1994), Moon Lake (Laird *et al.*, 1996a, b; Valero-Garcés *et al.*, 1997), Chappice Lake (Vance *et al.*, 1992, 1993), and Elk Lake (Grant County) (Saros *et al.*, 2000; Donovan *et al.*, 2002; Smith *et al.*, 2002). Most studies use several proxies, albeit often closely related, for the understanding of lake history. However, different proxies may respond to changes within the lake in different ways. Hence, the magnitude and timing of hydrologic response may appear different depending on what proxy is examined.

Many biological indicators (such as ostracodes and diatoms) are related to lake salinity. Increased salinity is usually attributed to increased evapotranspiration or reduced meteoric input leading to falling lake levels and higher salt concentrations. For Devils Lake, North Dakota (Fig. 1), modern instrumental data on lake levels and salinity showed that the values followed a markedly inverse relationship, as expected (Fritz *et al.*, 1994: Fig. 3). At Moon Lake, North Dakota (Fig. 1), Laird *et al.* (1996b) compared diatom-inferred salinity with P-ET (precipitation-evapotranspiration, a measure of effective moisture) values computed from instrumental data. Therefore, in general, high salinity correlates with aridity, and lower salinity with moister conditions. There is, consequently, a two stage level of inference between the proxy and the inferred drought or aridity record.

Interpretation of salinity may not be straightforward because there may be a dilution effect from groundwater or other hydrologic changes (Smith *et al.*, 1997, 2002; Valero-Garcés *et al.*, 1997; Donovan *et al.*, 2002). For example, at Kenosee Lake, Saskatchewan, Vance *et al.* (1997) noted a salinity maximum, inferred from ostracodes and stable isotopes, at a time (*ca.* 2800-2300 yr BP) when the plant macroremains suggested increasing water depth. They suggested that an influx of saline groundwater, rather than increased evapotranspiration, explained this discrepancy. Furthermore, the sensitivity of the proxy indicator may vary depending on salinity levels. At Moon Lake, for example, Laird *et al.* (1996b) observed that diatom assemblages were not responsive to changing salinities in the hypersaline mid-Holocene interval. At Harris Lake (Fig. 1), Wilson and Smol (1999) noted a discrepancy between the biotic (diatoms and ostracodes) and abiotic (mineralogy) records in the early mid-Holocene, with the latter suggesting partial drying of the lake basin whereas the former provided no evidence for this. They commented that the low sensitivity of the diatom-inferred salinity record at this site was most likely a reflection of the relative dominance of groundwater inputs.

At Devils Lake, Fritz *et al.* (1994) used three proxies (diatom stratigraphy, element ratios [Mg/Ca and Sr/Ca] of ostracode shells, and sediment geochemistry) to deduce salinity changes from a short core spanning about a millennium. Examining the last 500 years of record, Fritz *et al.* (1994) identified an interval of high salinity between the 16th to the mid-19th centuries. They interpreted this signal as reflecting aridity and drought conditions as severe as those of the early 20th century. In this record, closely-spaced samples span about 1-5 years in the upper part and perhaps 10-15 years in the lower part of the record. Fritz *et al.* (1994) noted that, because of this variable resolution and because the hydrological response of the lake may be complex, it may be difficult to say whether the inferred high salinities are a reflection of a high frequency of severe drought years or a longer interval of sustained drought. Nevertheless, the pattern of this record suggests that it is picking up a signal with a temporal signature that would be indicative of drought, however that might be blurred through temporal integration from sampling.

In a similar high-resolution study at Moon Lake, North Dakota (Fig. 1), Laird *et al.* (1996a, 1998a) used diatom assemblages to infer salinity changes over a 2300 year record, with 427 samples providing a sub-decadal resolution. As at Devils Lake, the record here is noisy, but clear salinity trends were discerned, with high salinity intervals in the last 200 years correlated with known historic droughts (1890s and 1930s). Laird *et al.* (1996a) interpret a change in the pattern of salinity fluctuations before about AD 1200 as indicating greater drought frequency and intensity over this earlier portion of the record. However, based on the criteria discussed in this review, the record may also show a shift to greater overall climatic aridity prior to AD 1200, depending on which part of the record is used as the basis for comparison. The "extreme droughts" (using Laird *et al.*'s terminology) are extreme mainly in comparison to modern conditions. Indeed, Laird *et al.* (1996a: 553) conclude that the last "~750 years has been wetter/cooler than any of the preceding ~1,500 years" reflected in "a profound shift in mean salinity", thus implicitly recognising changes in overall climatic aridity.

Laird *et al.* (1996b) also reported a somewhat lower resolution diatom study of a long core (11.2 m) spanning 11 800 yr BP. Samples were taken at 4 to 8 cm intervals yielding a variable temporal resolution, depending on sediment accumulation rates, of about 50 to 200 years (Laird *et al.*, 1996b). This temporal separation of samples, therefore, is too great to resolve droughts. Other studies at Devils Lake (Fritz *et al.*, 1991; Haskell *et al.*, 1996) have examined proxies from a much longer core (24 m) spanning about 12 000 years. Beneath the 1 m level, this core was sampled at somewhat lower resolution than in the study by Fritz *et al.* (1994), that is, the samples are more widely spaced, and some may span greater core segments (*e.g.*, 8 cm core segments used for ostracode samples by Haskell *et al.*, 1996). Both the Moon Lake and Devils Lake records show four main postglacial salinity phases, although the length, timing, and intensity of the phases varies. At Devils Lake, each of these phases spanned a millennium or more and is characterized by different overall salinity levels, though each exhibits salinity fluctuations. Laird *et al.* (1996b; see also Valero-Garcés *et al.*, 1997) and Haskell *et al.* (1996) linked these phases with intervals of greater and lesser effective moisture or postglacial aridity respectively, an interpretation that is consistent with the drought/aridity distinction made in this review.

In these Devils Lake and Moon Lake studies, intervals of greater and lesser salinity have been identified mainly on the basis of peaks in the curves, rather than by numerical methods. A numerical approach has been taken in another series of drought history studies across the Canadian sector of the NGP, including work at Chauvin Lake, Nora Lake, and Humboldt Lake (Leavitt *et al.*, nda, ndb, ndc; Laird *et al.*, 2003). Short-cores, spanning about the last 2000 years, were recovered from these lakes and sampled at very fine intervals (2.5 mm); these samples were thought to represent 3-4 years, giving a subdecadal resolution. Here, the long-term trend was removed from diatom-inferred salinity records, by fitting a linear regression through the data, and extreme events (deviations from the trend) were examined. Drought was assumed when inferred salinity values were greater than those recorded at Moon Lake in the 1988-1989 drought (*e.g.*, Leavitt *et al.*, nda; Leavitt, nd). The basis for comparison, therefore, is a recent well-documented event. Because this recent drought can also be characterized in terms of operational drought definitions, this paleoenvironmental record may be translated to operational terms. This paleoenvironmental study is rare in having a clearly-stated quantifiable definition of drought.

In this series of lake records, periodicity was examined by looking at the time between events, using flood frequency analysis as an analogy. These data were then used to assess probability of drought occurrence and hence developed as a predictive tool for risk analysis of future droughts (Leavitt, nd). For Chauvin Lake, for example, Leavitt *et al.* (nda) determined that conditions similar to or more extreme than the 1988-1989 drought lasted about 12 years on average and occurred at intervals of about 60 years, with 25 such events in the 2000 year record, the longest lasting around 45 years (see also Laird *et al.*, 2003). However, because the basis of comparison is a recent drought, this analytical approach may exaggerate the magnitude and length of events in the past if they occur in an interval of greater aridity, despite removal of the impact of an overall moistening trend (salinity reduction).

Fluctuating lake levels and varying evapotranspiration rates may also affect the isotopic balance and chemical composition of water, especially in closed lake basins. Engstrom and Nelson (1991) and Yu and Ito (1999) examined composition of ostracode shells (Sr/Ca and Mg/Ca), taking increased ratios as an indicator of drought. At Rice Lake, Yu and Ito (1999) sampled 5.5 m core length in contiguous 2.5 cm slices. Because of a high sedimentation rate (the core length represented about 2100 years of accumulation), each sample integrated a decade. Mg/Ca molar ratios suggested 25 distinct prolonged dry intervals, compared to the mean of the record as a whole. Yu and Ito (1999) used spectral analysis to explore periodicities in these data, and detected similar patterns to solar activity, in particular 400, 200, 130 and 100 year periodicities. From this, they suggested solar forcing as an underlying mechanism for "century-scale drought frequency" (Yu and Ito, 1999: 266). In this study, century-scale drier intervals (= increased aridity) are apparent, with finer-scale fluctuations (of smaller amplitude) probably representing shorter drought episodes.

Some other biological indicators (such as pigments) reflect lake productivity (Table II). Studies of pigments have been carried out at several NGP lakes including Redberry Lake (Van Stempvoort *et al.*, 1993), Clearwater Lake (Leavitt *et al.*, 1999), and Elk Lake, Clearwater County (Sanger and Hay, 1993). Higher lake productivity may be linked with overall warmer waters, which may correlate with higher evaporation rates and lower lake levels. However, the causes of lake productivity fluctuations, especially in the recent past, may be considerably more complex than this. For example, Hall *et al.* (1999) noted that productivity changes in the naturally-eutrophic Pasqua Lake, Saskatchewan (Fig. 1), were related to nutrient loading of the system from agricultural run-off and urbanization.

Most pollen preserved in lake sediments comes from the regional vegetation. However, some is produced from littoral or aquatic vegetation, and therefore can be considered an internal (to the limnological system) proxy. Increases in pollen from plants characteristic of saline sloughs or mudflats, such as *Sarcobatus*, have been used to infer more extensive littoral or disturbed areas, as in the Harris Lake record (Sauchyn and Sauchyn, 1991). One pollen and macrofossil taxon that has been used particularly to track salinity changes is *Ruppia*. This plant is associated with hypersaline waters (Husband and Hickman, 1985; Kantrud, 1991). At Moon Lake, for example, the appearance of *Ruppia* pollen was taken to indicate shallow highly-saline conditions under arid climate (Laird *et al.*, 1996b; Valero-Garcés *et al.*, 1997). However, drought investigation has not been the focus of most pollen records so far available from the NGP, which are often sampled at a coarser (subcentury) resolution.

At Chappice Lake, Alberta (Fig. 1), a transect of cores showed changes in plant macrofossil and pollen assemblages that were related to distance from shoreline, extent of exposed littoral area and hence fluctuating lake levels (Vance *et al.*, 1992, 1993). These changes were calibrated by modern assemblages (pollen and plant macroremains) obtained from transects across the shoreline zone (Vance and Mathewes, 1994). In the paleoenvironmental record, pollen and macrofossil assemblages, together with geochemical and lithological data, were used to detect intervals of greater and lesser salinity with lower and higher lake levels through a 7300 year record at a sub-century resolution. Vance *et al.* (1992) noted considerable variability during a generally low lake level-high salinity phase (7300-4400 yr BP). The extreme events were attributed to frequent and severe droughts. Fluctuations in the last millennium, tracked especially by fluctuations in the percentage of *Ruppia* pollen, were correlated with the Medieval Warm Period and Little Ice Age (Vance *et al.*, 1993).

Non-biological indicators (especially sediment geochemistry) have also been used to track water chemistry and lake-level changes across the NGP (Table II). There are many studies that explore brine composition and sediment geochemistry in saline lakes (see Last (1999) and references therein) but few of these studies have been concerned with the explication of drought history. Brine composition has been examined through changes in ostracode (Smith *et al.*, 1997) and diatom assemblages (Saros *et al.*, 2000) at Elk Lake (Grant County). Stable isotopes ($\delta^{18}O$ or $\delta^{13}C$) have been examined in carbonate minerals (calcite and aragonite) at Moon Lake (Valero-Garcés *et al.*, 1997), Pickerel Lake (Dean and Schwalb, 2000), and Redberry Lake (Van Stempvoort *et al.*, 1993). It is assumed that variations of stable isotopes may reflect changes in hydrology, which are partly a response to climate. As with other lake core studies, the inferences that can be made from these records are highly dependent on the sampling interval and resolution.

At Kettle Lake, North Dakota (Fig. 1), Clark *et al.* (2002) looked at aragonite precipitation in two 50 cm core segments sampled at 1 cm intervals, comparing one core segment from the mid-Holocene with one from the late Holocene. The younger core segment spanned 2950-2700 calendar yr BP, giving a resolution of 5 years per sample. In contrast, the older core segment spanned 8500-7900 calendar yr BP, so that each sample represented 32 years. Samples therefore each covered an interval equivalent to an instrumental climatic normal, and could potentially integrate data over several drought events. In this lake system, aragonite production was related to solutes from groundwater and therefore was greatest when groundwater inflow is high. Clark *et al.* (2002) used the ratio of aragonite (endogenic) and quartz (detrital) to distinguish between moister (greater amounts of aragonite precipitation, lower amounts of detrital quartz) and drier intervals. For the mid-Holocene interval, the data showed pronounced fluctuations between inferred moist and dry conditions, with five distinct dry intervals identified. Clark *et al.* (2002) used spectral analysis to detect a drought recurrence periodicity of around 100-130 years and they considered that their data were reflecting decade-scale droughts.

Interestingly, these signals were not reflected as well in other internal proxies from Kettle Lake, specifically diatom abundances. In particular, diatoms associated with high salinity are almost absent until around 8000 calendar yr BP (Clark *et al.*, 2002: Fig. 1). This re-emphasizes the point that different proxies may react in quite different ways to perturbation and that, to fully capture the drought and aridity signals, several proxies may need to be examined.

C) MID-RESOLUTION (SUB-DECADAL OR DECADAL RESOLUTION) RECORDS FROM PROXY INDICATORS PRESERVED IN LAKE SEDIMENTS (EXTERNAL PROXIES)

Lakes act as sediment sinks and therefore preserve proxy indicators that provide information on processes occurring in the watershed or region around the lake (Table II). Some of these processes, such as vegetation change or sediment yield, may reflect or respond to drought events. These terrestrial proxies include pollen (*e.g.*, Clark *et al.*, 2001, 2002) and clastic or detrital sediment influx (*e.g.*, Keen and Shane, 1990; Dean, 1993, 1997; Campbell, 1998; Dean and Schwalb, 2000). However, because these proxy indicators may be integrated over a wide area (as in the regional pollen rain), it may be more difficult to link them directly to drought events, even when the lake sediments are sampled at very high resolution (see Campbell, 1998; Campbell *et al.,* 1998).

The interpretation of pollen records preserved in lake sediments may be complicated by lake level fluctuations that affect the littoral zone. The records integrate information from the local pollen rain, produced by aquatic or nearshore plants, with the regional pollen rain derived from the surrounding vegetation. Disentangling these two sources may not be straightforward. For example, at Moon Lake, Laird *et al.* (1996b) noted an increase in *Picea* pollen around 6600-6300 yr BP, coincident with rapid sediment deposition. Laird *et al.* (1996b: 895) suggested that this reflected erosion and redeposition of nearshore sediment when lake levels fell during a short arid episode. Additional evidence for this was given by the abundance of *Ruppia* pollen and *Iva annua* pollen. The latter plant would have been growing on lake muds exposed by falling water levels.

Depending on site characteristics, the regional pollen rain integrates information from a broad area around the collecting site (Jacobson and Bradshaw, 1981). However, the vulnerability of upland plants to drought varies. Some vegetation may have a certain “buffering capacity” or resiliency and therefore be less responsive to short term events. Hence, the regional pollen signal may be a less sensitive indicator of short-term severe local or spatially discontinuous events or disturbances, such as those resulting from drought. For example, Laird *et al.* (1998b) noted differences between the pollen and diatom records from Moon Lake, which they attributed to the lower sensitivity of the regional vegetation to short-term fluctuations. Nevertheless, several studies have shown interesting patterns in terrestrial pollen signals that may be correlated with dry conditions.

Hitherto, most pollen records from NGP lakes have been sampled at relatively coarse intervals, because they have been used primarily to explore vegetation history, and thus at a resolution insufficient to detect drought signals. At Harris Lake (Sauchyn and Sauchyn, 1991), for example, a core spanning

9120 years was sampled at 8 cm intervals. Therefore, each sample integrates information for about a decade with about 67 years between samples. Nonetheless, most NGP records do detect long-term moisture-aridity signals through terrestrial pollen assemblage changes (see MacDonald and Case, 2000). For instance, many NGP records, including Chappice Lake (Vance *et al.*, 1992, 1993) and Harris Lake (Sauchyn and Sauchyn, 1991), show drier conditions in the early mid-Holocene that are correlated with the climatic aridity of the Hypsithermal (see Vance *et al.*, 1995 for detailed discussion). Similar long-term trends are found in records from the periphery of the NGP, including Lofty Lake (Lichti-Federovich, 1970), Toboggan Lake (MacDonald, 1989) and Wabamun Lake (Hickman *et al.*, 1984) in Alberta and records from the eastern margin (Clark *et al.*, 2001).

In a higher-resolution study at Kettle Lake, Clark *et al.* (2002) noted that grass (Poaceae) and Ragweed (*Ambrosia*) pollen percentages showed fluctuations in the mid-Holocene that were correlated with the drier and moister intervals inferred from sedimentology. In this case, the record was sampled at sufficiently high resolution that decadal-scale data were derived. Poaceae pollen percentages were higher during inferred moister intervals and lower in drier intervals, with *Ambrosia* showing the opposite pattern in a more pronounced fashion. Clark *et al.* (2002) interpreted the reduced grass pollen percentages in dry intervals as reflecting reduced grass cover, while increased Ragweed pollen percentages were taken as an indicator of increased abundance of weedy taxa (see also Grimm, 2001).

D) EPISODIC OR LOWER-RESOLUTION (DECADAL TO CENTURY) RECORDS FROM PROXY INDICATORS OF LANDSCAPE-LEVEL PROCESSES

Fires are inherently episodic but increased fire frequency can be correlated with climate dryness. Johnson and Wowchuk (1993) have shown that fires are related to episodes of "fire weather", which are hot dry conditions in early spring or summer. Hence, when all else is equal, a generally warmer climate should lead to a greater number of fires. In northeast Alberta, Larsen and MacDonald (1995) detected a relationship between area burned and climate suggesting that warmer and drier conditions also lead to larger areas burned. However, Campbell and Flannigan (2000) note that fire activity may decrease if climate change results in fire-prone taxa (*e.g.*, conifers) being replaced by less fire-prone taxa, such as aspen. In the NGP, such climate-driven vegetation changes are likely to be less dramatic. Moreover, vegetation response in grassland areas differs markedly from the forest areas where most fire research has been carried out.

Fire histories can be derived from charcoal preserved in lake sediments (*e.g.*, Clark, 1993; Campbell and Campbell, 2000; Clark *et al.*, 2001). But the connection between this and drought or aridity is not direct, requiring at least a two stage process of inference, first extracting a fire frequency record from the sediments and then relating it to a climate signal. Moreover, fire signals are best preserved in forested areas, that is, around the margins of the NGP. These areas may be far removed from the drought-prone grasslands that have so far been the main focus of drought research.

Fire is not only a reflection of climate conditions, but also of fuel availability. At Kettle Lake, surrounded at present by mixed prairie, the charcoal abundance increased in inferred moister intervals in the mid-Holocene, which Clark *et al.* (2002) interpreted as reflecting greater fuel availability. Conversely, charcoal amounts are low during inferred drier intervals, reflecting lack of fuel associated with reduced vegetation cover (Clark *et al.*, 2002). It is notable, however, that the charcoal signal in this record does not show such a marked pattern as the other proxies (pollen, sediment geochemistry) examined in their study.

Beierle and Smith (1998) used lithostratigraphic changes, including marl and peat occurrence, and macrofossil types to track postglacial hydrologic changes in six lakes from southwest Alberta (Table II). These changes imply long intervals of lower moisture levels which Beierle and Smith (1998) estimated to occur between about 9400-6800 yr BP. Hence, these records are indicating prolonged early Holocene aridity.

Sand dunes are widespread throughout the NGP and postglacial sand dune activity has been a significant research focus (*e.g.*, Muhs *et al.*, 1997a, b; David *et al.*, 1999; Muhs and Wolfe, 1999). Keen and Shane (1990) examined eolian sediment input to lake deposits through the Holocene as an indicator of dune activation episodes. For the late Holocene, Wolfe *et al.* (2001) have explored the linkages between sand dune activation and dry intervals. They concluded that activation of dunes in the Great Sand Hills, Saskatchewan, beginning in the late 18th century, was a response to a prolonged interval of climatic aridity which greatly depleted soil moisture reserves. A noteworthy conclusion from their analysis is that drought alone is not necessarily sufficient to cause dune activation. Although a severe drought may be the ultimate trigger, antecedent conditions are important for mediating drought impact. Hence, increased aridity, rather than drought, may predispose dunes to movement. Wolfe *et al.* (2001) note that the early 20th century droughts did not result in widespread dune reactivation. Therefore sand dunes on the NGP, although they may react to climatic aridity and severe drought, do not in themselves constitute a sensitive drought monitoring system.

THE CASE FOR MORE RIGOROUS TERMINOLOGY

It is clear that the "droughts" discussed by different paleoenvironmental studies are not comparable in terms of scale or magnitude. Nor is drought precisely defined in many such studies. The term "drought" has been used to describe events that span a few years, a decade or more, several decades, or even a century or more. Most proxy paleoenvironmental records, because they integrate data over many years or over a wide area, provide details of aridity rather than drought.

Because droughts are short term events, proxy records need to be resolvable at an annual level to be able to detect them. Of the available indicators, tree rings have the greatest potential to yield drought records. Biotic, geochemical or sedimentological proxies from annually-laminated lake sediments also have a high potential to yield drought records. However, few lake records are sampled at annual resolution. More usually, sediments are not annually laminated or highly-resolved or are sampled at wider intervals. Sampling interval will be critical for drought detection in lake records. This is not a problem unique to the detection of drought. Other short-term or episodic events, such as fires, may also be difficult to detect. Generally, given the sampling resolution usually employed in paleoenvironmental studies, indicators from lake sediments have a better potential to provide indications of aridity rather than drought.

Based on this analysis, I recommend restricting the term drought to studies in which drought can clearly be detected. That is, the term should only be applied in situations where highly responsive proxies are investigated at an annual (at best) or subdecadal (at worst) resolution. Where resolution is less than this, or where the inferred drier conditions persist for decades or centuries, I suggest using the broader term aridity.

Moreover, when the term drought is used for past conditions, the basis for that definition should be stated, whether drought is defined in relation to present conditions in that area or with the concurrent conditions in that area. Only droughts that are defined with respect to the prevailing concurrent conditions can be considered drought in operational terms. When dry events are defined in relation to present conditions, then this should be clearly stated. That is, it should be explicit that these events represent conditions similar to those that are presently considered drought in that area. The distinction is important because of the influence of comparative conditions in operational drought definitions.

WHY DOES A CLEAR DEFINITION OF DROUGHT MATTER?

The clear definition of drought matters because of the need for unambiguous communication between disciplines concerned with investigation of past climate proxies. This is particularly important when the results of different studies based on different proxies are compared. Quite apart from the need for clarity in scholarly communication, however, is the more pragmatic concern for unambiguous communication with practitioners from other disciplines and with the public. Increasingly, we are being required to communicate the results of our studies to policy makers and the wider community who have a direct need for this information. If there is confusion over what the term drought means, then this will inevitably reduce the credibility of paleoenvironmental research in the eyes of decision makers (and funding agencies).

Paleoenvironmental studies should not promise more than they can deliver. For land managers and agricultural producers, operational drought definitions are the ones that matter. Paleoenvironmental studies would have more impact and would better communicate to these people and the wider public if their results were re-stated in operational terms. Thus, while "prolonged century-scale aridity" may be academically correct, it conveys little meaning to other practioners, whereas "conditions similar to those presently defined as drought in this region lasted for several centuries" conveys a more vivid and immediate mental image. In this regard, paleoenvironmental studies are vital for providing the long-term context within which to evaluate recent events, as Sauchyn *et al.* (2003) show for the 1999-2001 drought.

One specific example illustrates the communication gap well. The study that has made the best attempt to tie proxy paleoenvironmental records to operational drought definitions is the work by Leavitt (nd) and his research group. This study was driven by the need to make the work relevant to a "user sector" that included representatives from the agricultural sector and crop insurance agencies. Even with these efforts, however, the attempt was only partly successful. In a newspaper article, one user sector representative commented that the study "falls short on specifics and therefore isn't a reliable tool for long-term drought forecasting" partly because "their definition of drought is more general than a specific agricultural drought" (Teel, 2002). A representative from a crop insurance agency noted that their insurance rates are based on a 25-year interval and so the study would be unlikely to affect their policies (Teel, 2002).

This example can stand as a cautionary tale. Even with the best intentions, and the utmost rigour, the data generated from paleoenvironmental work may be seen by the wider community as not useful or as too generalized. This may seem a trivial or irrelevant issue to some researchers. However, drought will remain a public concern and a continual factor in the lives of people living on the plains. Developing precise and unambiguous terminology will ensure that paleoenvironmental data can play a role in efforts to understand and mitigate the effects of drought on the Northern Great Plains.

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