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THE CANADIAN ARCHAEOLOGICAL RADIOCARBON DATABASE (CARD): ARCHAEOLOGICAL ^{14}C DATES IN NORTH AMERICA AND THEIR PALEO-ENVIRONMENTAL CONTEXT

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ABSTRACT. Databases of accumulated paleoecological and archaeological records provide a means for large-scale syntheses of environmental and cultural histories. We describe the current status of the Canadian Archaeological Radiocarbon Database (CARD), a searchable collection of more than 36,000 ^{14}C dates from archaeological and paleontological sites from across North America. CARD, built by the late Dr Richard Morlan of the Canadian Museum of Civilization, consists of uncalibrated ^{14}C data as well as information about the material dated, the cultural association of the date (e.g. Paleoindian, Archaic, Woodland), and its geographic location. The database can be used to study questions relating to prehistoric demography, migrations, human vulnerability to environmental change, and human impact on the landscape, but biases relating to sampling intensity and taphonomy must first be accounted for. Currently, Canada and the northern United States are well represented in the database, while the southern United States is underrepresented. The frequency of ^{14}C dates associated with archaeological sites increases through time from 15,000 cal yr BP until European contact, which likely reflects, among other factors, both the destruction of older cultural carbon due to erosion and dissolution and increasing population numbers through time. An exploratory analysis of the dates reveals their distribution in both time and space, and suggests that the database is sufficiently complete to enable quantitative analysis of general demographic trends.

INTRODUCTION

The study of the late Quaternary provides information about scales of environmental change, the possible states and dynamics of the environment, and the impact of human activities on the environment. In the past few decades, a critical mass of paleoecological data has been organized into searchable, publicly available databases, which has permitted the analysis and mapping of past climates and ecosystems (Gajewski 2008).

The analysis of such databases is a critical activity that can be used to summarize existing knowledge, provide a description of the evolution of ecosystems during the late Quaternary, and guide the formation of new, testable hypotheses concerning the causes of environmental change. However, although versions of databases such as the Global Pollen Database (GPD; Grimm et al. 2007), the Global Charcoal Database (GCD; Power et al. 2008) and FAUNMAP (Graham and Lundelius 1994) have been available for several decades, comprehensive databases of archaeological information have only recently emerged. This has limited our ability to tackle broad-scale questions pertaining to topics such as prehistoric demography, migration, and other issues that require spatially extensive data sets.

The emergence of both paleoecological and archaeological databases has also permitted an improved assessment of the environmental context in which to interpret archaeological data. At local to regional scales, analysis of spatiotemporal patterns in archaeological data is greatly enhanced by developing an understanding of the vegetation and climatic changes that may have influenced human activities, as well as how human land-use, such as agriculture, may have influenced vegetation structure and distribution, and potentially climate (e.g. Denevan 1992; Ruddiman 2003; Pongratz et al. 2008; Kaplan et al. 2009). There is an interest in expanding this approach from regional to continental scales, to examine whether general patterns emerge between the migration

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and settlement of human populations, subsistence activities such as hunting and farming, and the dynamics of animal and plant populations in relation to past environmental changes.

In this paper, we document the structure of a database composed of archaeological radiocarbon dates, and present approaches to analyze these data in a paleoenvironmental context. The Canadian Archaeological Radiocarbon Database (CARD; http://www.canadianarchaeology.ca/; Morlan 2005) is a repository of over 35,000 ^{14}C dates derived from archaeological and paleontological materials from Canada, the continental United States, Alaska, and easternmost Russia (Peros et al. 2010). Originally conceived and created by the late Dr Richard Morlan of the Canadian Museum of Civilization (CMC), the database is maintained by the CMC, where it continues to grow as more dates are added. It is the largest set of ^{14}C dates available for North America, and has been used to study regional- to continental-scale changes in prehistoric demography, migration, and culture (e.g. McGhee 2000; Buchanan et al. 2008; Munoz and Gajewski 2010; Munoz et al. 2010; Peros et al. 2010; Steele 2010). To facilitate the growth, continued use, and application of CARD, we document the history of its creation and the sampling methods utilized in its formation and describe the spatiotemporal structure of the data (excluding the data from easternmost Russia). The paper concludes with an overview of several recent applications of the CARD data set, which have included studies investigating human demographic trends, migration, and the relationship between humans and changing environments.

This paper is a tribute to Dr Richard Morlan, whose foresight and dedication has permitted the analyses we outline in the paper. He is listed here as a coauthor posthumously, both because of the tremendous effort he applied to creating the database, but also because his unpublished writing is used in sections describing the creation of the data set.

THE CANADIAN ARCHAEOLOGICAL RADIOCARBON DATABASE (CARD)

The development of CARD has a history spanning more than 20 yr (Morlan 1987, 1999). In 1987, Richard Morlan, a curator at the Canadian Museum of Civilization (CMC) in Gatineau, Québec, participated in a workshop at Yale University to plan the scope and content of the International Radiocarbon Database (Kra 1988a,b). Roger McNeely, director of the Geological Survey of Canada (GSC) Radiocarbon Laboratory, also attended the workshop, and both he and Morlan quickly realized the potential for collaborating to produce a common database of paleontological, geological, and archaeological ^{14}C dates.

Initially, the database grew organically, based on the regional research interests of Morlan. The first set of compiled dates came from a (Late) Woodland period site, Avonlea, in Saskatchewan (Morlan 1988). This was followed by a compilation of Saskatchewan archaeological ^{14}C dates, which was eventually published in a regional journal (Morlan 1993). With the help of Brian Schreiner, McNeely augmented the list to include non-archaeological dates from Saskatchewan, creating a comprehensive digital database, which was eventually released as a GSC Open File report (Morlan et al. 1996). Soon after, a similar comprehensive database for Manitoba was created and released as an Open File report (Morlan et al. 1999).

Resources at the CMC also dictated the early content of the National database, which Morlan began developing in earnest in the winter of 1996–97. The first national set of records was derived from the more than 1500 dates in the CMC's long-standing ^{14}C dating hardcopy file (Wilmeth 1971, 1978). Next, every issue of the journal *Radiocarbon* was systematically searched for Canadian and American ^{14}C dates, followed by a search of the CMC's Mercury Series volumes. Other archaeological journals and newsletters published in Canada were methodically searched for dates, starting from the latest issue and going back to earlier ones in order to take advantage of citations to previous reports. Thereafter, the work continued geographically, beginning in southeastern Canada, moving westward across the provinces, then turning to northern Canada to include data from the Yukon and Northwest Territories. Permit Reports available in the CMC archives from the Northwest Territories, Nunavut, Yukon, British Columbia, and Alberta were mined for ^{14}C data. The CMC's comprehensive collection of archaeological reports from Parks Canada was accessed, as well as unpublished PhD and MS theses from Canadian universities. Finally, the personal libraries of colleagues at the CMC provided a wealth of published and unpublished reports. The diversity of documentation available to Morlan at the Canadian Museum of Civilization is a fundamental reason why the construction of a comprehensive database was possible. A comprehensive list of the data sources used in CARD is provided in the Acknowledgments section of the CARD Web site (http://www.canadianarchaeology.ca/radiocarbon/card/acknow.htm#acknow).

Although mainly oriented toward archaeological ^{14}C dates, CARD includes coverage of part of the paleontological record. The dates on non-archaeological vertebrate sites come from a variety of sources, but notably from the files of A S Dyke (GSC) and C R Harington (Canadian Museum of Nature; Harington 1978, 2003). These data represented a first step toward the creation of a vertebrate database that was incorporated into the FAUNMAP database established at the Illinois State Museum (Graham and Lundelius 1994). The scientific names of mammals associated with these records, in the "Associated Taxa field," use terminology in Banfield (1977), Graham and Lundelius (1994), and Kurtén and Anderson (1980).

As the database developed, every effort was and continues to be made to track each ^{14}C date back to its original report. Each record is presented in the language in which it has been reported. CARD includes data from the United States, but the compilation of these data has been unsystematic, and is largely the result of references encountered during the primary search for Canadian data, or specific data sets donated by American researchers. Currently, dates are entered in CARD using similar procedures established by Morlan, involving data mining from current periodicals, data donations from colleagues, and reference to edited volumes and dissertations. A new feature of the database was implemented in 2008, called "Submit a Date"; here researchers can enter their data directly into a Web form, which is then emailed directly to the CARD administrator. Numerous records have been submitted through this process in the last few years.

CARD currently contains more than 35,000 records, with more than 28,000 of these fully searchable online. The discrepancy between data maintained on the internal "hardcopy file" and those available online is primarily the result of ^{14}C records with missing data fields or known errors, or in some cases dates that have been submitted to CARD, but which are withheld pending publication (usually at the author's request). The bulk of CARD was created between 1997 and 2004. Since the involvement of Betts after this period, 1758 records have been added to the CARD Web site and digital file.

The database is currently organized as a flat-file, with each record containing 50 fields that describe several aspects of a date, including: ^{14}C date lab number, submitting author, reference(s), material dated, taxonomy of material dated, associated taxa, enclosing material, location (latitude and longitude), elevation, cultural affiliation, suggested age, δ^{13}C measurement, normalized ^{14}C age and error. Latitude and longitude are recorded for every record, but are not provided on the CARD Web site to protect archaeological sites against non-professional access, although this information is available for qualified researchers with legitimate projects. These researchers are required to sign a data licensing agreement, which limits the transfer and publication of the data and sets restrictions on the publication of locational information. Elevation is derived from the original site reports and topographic maps if available, but is not included in all records in CARD (see below).

Cultural affiliation, perhaps the most important field in the CARD database, is derived directly from the interpretation of the original researchers and/or reports/publications associated with the ^{14}C record. In some instances, Morlan or Betts have applied a cultural affiliation based on generally accepted regional chronocultural schemes, using the date of the sample *and* associated artifact assemblages. In instances where the cultural affiliation was in doubt, this field was simply left blank.

For an archaeological database, a unique attribute of CARD is the "Taxa dated" and "Associated taxa" fields, which record the species or genera of dated organic remains when known and a list of faunal materials associated with the deposits, respectively. These data are derived from original sources and faunal reports associated with the contexts that have been dated.

CARD is a work in progress, and the database is known to contain missing data and errors. In the great majority of cases, this is a result of missing contextual data or other information that was not available from published sources or from direct communication with the submitting researcher. The CARD Web site provides an expedient means to correct these errors, and the site is regularly updated based on the advice of researchers who find errors or omissions in the online records.

METHODS

Calibration of Dates

^{14}C dates obtained from archaeological, geological, and paleontological materials are the basic data in CARD and fields for both the uncorrected and $\delta^{13}C$-normalized (conventional) dates are provided. CARD itself does not contain calibrated dates, because calibration is a process that can be undertaken using several different calibration data sets specific to different regions and materials (e.g. Reimer et al. 2009), and decisions about how to utilize the resulting output (e.g. 1-, 2-σ range; median; etc.) may vary depending on the problem being addressed. However, in this paper the CARD dates are presented as median calibrated values so that preliminary comparisons to other data sets can be made, and so some of the potentials and problems associated with the calibration of the CARD data can be illustrated. Researchers who wish to use a calibrated version of this data can undertake calibration using a number of freely available packages, e.g. CALIB (Stuiver et al. 2009) or the Fairbanks0107 calibration program (Fairbanks et al. 2005), for this purpose.

In the Results and Discussion sections that follow, all ^{14}C dates younger than 21,000 ^{14}C yr BP were converted to calibrated years before present (cal yr BP) using CALIB 5.0.1 (Stuiver et al. 2009). Dates were calibrated to the 2-σ range, but in most cases we use the median probability of the calibrated date in our analyses. All material of terrestrial origin was calibrated with the IntCal04 data set (Reimer et al. 2004). All material of marine origin, including marine mammals (n = 803) and mollusks, mussels, and marine shells (n = 848) were calibrated using the Marine04 data set (Hughen et al. 2004). All marine mammals were corrected for the marine reservoir effect using a standard value of –400 yr. The mollusks, mussels, and shells were corrected for the marine reservoir effect using values provided by Dyke (2004), which range from –800 yr in the Pacific to –400 yr in other environments. In cases where the $\delta^{13}C$ value was unknown, we assumed a standard value of –25‰. Dates older than 21,000 ^{14}C yr BP (n = 566), the age limit of the IntCal04 data set, were calibrated using the Fairbanks et al. (2005) calibration curve. A small proportion of entries could not be calibrated (n = 2140; 6.0% of data set) because (a) dates were beyond the limit of the Fairbanks (2005) data set (>50,000 ^{14}C yr BP), (b) dates were modern (e.g. 0 ^{14}C yr BP), or (c) no error was provided in original sources.

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Elevations

As mentioned above, some dates have elevations listed in CARD if elevation information was available in the original publication or site report, which was usually based on reading site elevation from a topographic map. However, in an effort to generate consistent elevations for most of the database, we used a GIS to extract elevations for all sites with a latitude and longitude from an equal area gridded data set (GTOPO30; http://eros.usgs.gov/). This provides elevation values with a spatial resolution of 0.5° (~50 km at 45°N latitude).

Temporal Frequency Distributions

Temporal frequency distributions, or histograms, were prepared using the median probabilities of the calibrated dates. The bin size was 250 yr because >95% of calibrated dates have errors of 250 yr or less (Peros et al. 2010). Temporal histograms were prepared for the entire data set and certain subsets of it, such as the material dated (charcoal, plant remains, animal remains, shells, human remains, cultigens, pottery encrustations) and associated cultural periods as described in CARD. All calibrated dates, including those listed as "anomalous," were used to create the histograms.

Maps

To examine spatiotemporal patterns in the data set, maps showing the spatial distribution of dates were prepared in ArcGIS. The present-day base map was used despite changes in coastline and proglacial lake extent. The topographic base map for some figures was from GTOPO30 (above) and the ice sheet extent through time was obtained from Dyke (2004).

RESULTS

Major Classification of Dates

The CARD flat file consists of 44 fields, but two of these contain no entries (Table 1). As of November 2009, CARD contained a total of 35,905 entries. Most of the fields are at least 95% complete, although several fields (e.g. taxon dated and site component) contain fewer entries, usually because this information was unavailable in the publications from which the data was derived.

Table 1 Data fields in the Canadian Archaeological Radiocarbon Database (CARD). A total of 35,905 records were present in the version of the database used for this article. Some entries consist of question marks "?"; these were not included in the totals for each field. The order of entries in this table is based on their order in the CARD flat file.

Database code	Explanation	# of records	Percent of total
E	Unique numeric identifier in CARD	35,896	99.97
LN	^{14}C laboratory number	34,705	96.66
FN	Field number	4219	11.75
SU	Submitter of material for dating	30,413	84.70
CO	Collector	3723	10.37
CD	Collection date	2326	6.48
MA	Type of material dated	34,517	96.13
TD	Taxa dated	8592	23.93
EM	Archaeological provenance	28,974	80.70
LO	Locality, may include elevation	35,902	99.99
LA	Latitude (degrees, minutes)	35,839	99.82

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Database code	Explanation	# of records	Percent of total
LAT	Latitude (decimal degrees)	35,829	99.79
LL	Longitude (degrees, minutes)	35,838	99.81
LON	Longitude (decimal degrees)	35,827	99.78
NT	NTS map sheet number	35,619	99.20
EL	Elevation from publication/report/thesis	4089	11.39
ELEV	Elevation derived from DEM	31,458	87.61
UD	Date updated in CARD database	35,687	99.39
SS	Cultural association	35,903	99.99
MG	Classification (cultural/paleoenvironmental)	35,903	99.99
AI	Notes on the technical aspects of the dating	6985	19.45
RF	Reference for date	35,889	99.96
AG	Measured age uncorrected for $\delta^{13}C$ fractionation	12,713	35.41
AN	Normalized (conventional) age, corrected for isotopic fractionation	12,572	35.01
AGERR	^{14}C age error (±)	12,457	34.69
DCraw	$\delta^{13}C$ value	34,490	96.06
DC	$\delta^{13}C$ value	13,663	38.05
DCnotes	Information on $\delta^{13}C$ values	10,516	29.29
AC	Corrected age (for shells only)	2683	7.47
OT	Classification (Cultural, Paleobiological, etc.)	35,852	99.85
AT	Associated taxa	10,253	28.56
BN	Borden number	34,314	95.57
SI	Site name	30,049	83.69
XA	Dec. latitude	26,302	73.25
XL	Dec. longitude	26,302	73.25
CP	Site component	4011	11.17
BB	Borden block	33,616	93.62
SA	Suggested age (estimated age or archaeological period)	3974	11.07
PR	Province or state	35,899	99.98
ANraw	Normalized ^{14}C age plus error	34,516	96.13
AN	Normalized ^{14}C age	34,127	95.05
ANERR	Normalized ^{14}C error (±)	33,806	94.15
CAL_BP	Calibrated ^{14}C age (median value)	33,762	94.03
Comments	General comments	14,230	39.63

The majority of the dates (87%) are classified as Cultural, which refers to any material that is directly associated with human activity (Table 2). This group also includes records where the role of human activity in the formation of the material is unclear, but has nevertheless been hypothesized. By contrast, the other major category, Paleoenvironmental (13%), refers to material that is not directly associated with human activity (e.g. stratigraphic horizons, paleosols, paleontological sites). If the origin of a date is ambiguous or not stated by the principal investigator, it is classified as Unknown.

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Table 2 Frequency and percentage of major categories of ^{14}C dates in CARD.

Major date classes	Frequency	Percentage
Cultural	31,136	86.7
Paleoenvironmental	4625	12.9
Unknown	143	0.4
Total	**35,905**	**100.0**

Cultural Associations

Within the cultural dates, over 75% are specifically affiliated with a particular cultural period, tradition, or phase (Table 3), following the methodology described above. At present, the field describing the cultural association of a date contains information across several scales of "cultural resolution." That is, the cultural affiliation provided in some cases may be very broad (e.g. Woodland), while in others it may be more specific (e.g. Late Woodland), and in others, even more specific (e.g. Huron). In our summary of this field, we grouped dates into major categories that account for the majority of entries in CARD, with the remaining dates (9.3% of total) grouped as "Other" cultural associations. The majority of dates are associated with cultures east of the Rocky Mountains, particularly the Woodland culture, which constitutes 22% of all dates in CARD. We use the general terminology "Woodland" for sites from the Ceramic period from the Plains to the Atlantic seaboard. Dates affiliated with Archaic cultures are predominately from eastern North America, although some dates from the southwestern United States are also considered Archaic. Cultural associations used exclusively in western North America (Early, Middle, and Late Period) account for just over 10% of all dates. There are over 1000 dates associated with various Paleoindian cultures and phases, and several hundred dates associated with the late prehistoric and historic periods representing both European and Aboriginal contexts.

Table 3 Cultural associations of entries in the CARD.

Cultural association	Frequency	Percentage
Eastern North America		
Mississippian	1622	5.2
Plains Village	500	1.6
Woodland	6838	22.0
Archaic	4640	14.9
Western North America		
Late Period	2822	9.1
Middle Period	535	1.7
Early Period	103	0.3
Arctic		
Neoeskimo	568	1.8
Paleoeskimo	88	0.3
Other		
Historic	172	0.6
Late Prehistoric	734	2.4
Paleoindian	1234	4.0
Unknown culture	7282	23.4
Other	2886	9.3
Total	**26,188**	**100.0**

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Material and Taxonomic Distribution

Information regarding the material dated is held in 2 fields; the first provides a general description of the material (e.g. wood) and the second provides the taxonomy, when available, of this material (e.g. *Quercus alba*). The most common material dated is charcoal, accounting for nearly half of all dates in CARD (Table 4). The remaining dates can be broadly divided into material classifications of animal (animal bones and other animal remains), shells (freshwater and marine mollusks), human (human bone and other human remains), plant (wood, cultigens, and other plant remains), pottery encrustation, and various types of sediment and soil. A large percentage of dates (17%) have no information regarding the material from which they originate.

Table 4 Frequency and percentage of ^{14}C dates in CARD by material category.

Material dated	Frequency	Percentage
Charcoal	17,436	48.6
Animal		
Animal bone	4619	12.9
Animal remains (skin, hair, etc.)	526	1.5
Shell		
Marine shell	848	2.4
Freshwater shell	217	0.6
Human		
Human bone	631	1.8
Human remains	46	0.1
Plant		
Wood	2276	6.3
Plant remains	1564	4.4
Cultigen	334	0.9
Other		
Pottery encrustation	113	0.3
Sediment	1058	2.9
Unknown	6209	17.3
Other	28	0.1
Total	**35,905**	**100.0**

As is common in charcoal and faunal ^{14}C samples, the majority (80%) of dates have no information regarding their specific taxonomy (Table 5). However, several thousand samples have been identified to genus or species level: the most abundant taxon is *Bison* spp. with 931 entries (2.59%). Humans (*Homo sapiens*; 1.89%) and large mammals, e.g. whale (1.56%), mammoth (1.04%), caribou (0.95%), and horse (0.55%), also comprise a large number of entries. The most frequent plant remains are those associated with arboreal genera such as juniper (*Juniperus*; 0.87%), oak (*Quercus*; 0.59%), spruce (*Picea*; 0.55%), and hickory (*Carya*; 0.35%) and the cultigens maize (*Zea mays*; 0.71%) and beans (*Phaseolus vulgaris*; 0.15%).

Table 5 Taxonomy of CARD dates.

Latin name	Common name	Frequency	Percentage
Bison spp.	Bison	931	2.59
Homo sapiens	Modern human	677	1.89
Balaena spp.	Whale	559	1.56
Mammuthus spp.	Mammoth	372	1.04
Rangifer tarandus	Caribou	340	0.95

Table 5 Taxonomy of CARD dates. *(Continued)*

Latin name	Common name	Frequency	Percentage
Juniperus spp.	Juniper	311	0.87
Zea mays	Corn	255	0.71
Quercus spp.	Oak	213	0.59
Equus spp.	Horse	198	0.55
Picea spp.	Spruce	196	0.55
Mytilus californianus	California mussel	188	0.52
Neotoma spp.	Packrat	175	0.49
Salix spp.	Willow	139	0.39
Bivalvia	Bivalves	130	0.36
Cervidae	Deer	124	0.35
Carya spp.	Hickory	124	0.35
Odobenus	Walnrus	105	0.29
Pinus spp.	Pine	98	0.27
Ursus spp.	Bear	86	0.24
Mammut spp.	Mastodon	84	0.23
Phocidae	Seal	78	0.22
Ovibos spp.	Muskox	57	0.16
Phaseolus vulgaris	Bean	54	0.15
Betula spp.	Birch	54	0.15
Pinopsida	Conifer	45	0.13
Oreamnos harringtoni	Goat-antelope	44	0.12
Megalonyx jeffersonii	Ground sloth	43	0.12
Smilodon sp.	Saber-toothed tiger	43	0.12
Juglans spp.	Walnut	43	0.12
Alces alces	Moose	41	0.11
Poaceae	Grass	39	0.11
Yucca spp.	Yucca	38	0.11
Populus spp.	Poplar	36	0.10
Artemisia	Wormwood	34	0.09
Fraxinus spp.	Ash	33	0.09
Celtis spp.	Hackberry	33	0.09
Mammalia	Mammal	32	0.09
Ulmus spp.	Elm	30	0.08
Ovis dalli	Dall sheep	25	0.07
Canis familiaris	Dog	25	0.07
Cucurbita spp.	Squash	24	0.07
Camelops spp.	Camel	21	0.06
Thuja spp.	Cedar	21	0.06
Monodon monoceros	Narwhal	21	0.06
Pseudotsuga spp.	Douglas fir	19	0.05
Pisces	Fish	19	0.05
Arctodus simus	Giant short-faced bear	19	0.05
Gastropoda	Snails	18	0.05
Chenopodium spp.	Goosefoot	18	0.05
Ostreidae	Oyster	18	0.05
Platygonus compressus	Peccary	18	0.05
Cassiope tetragona	Arctic white heather	17	0.05
Castor canadensis	Beaver	17	0.05
Fagus spp.	Beech	17	0.05
Geomys bursarius	Pocket gopher	17	0.05

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Table 5 Taxonomy of CARD dates. *(Continued)*

Latin name	Common name	Frequency	Percentage
Microtus xanthognathus	Taiga vole	16	0.04
Abies spp.	Fir	23	0.06
Larix spp.	Larch	13	0.04
Saiga tartarica	Saiga antelope	12	0.03
Ovis canadensis	Bighorn sheep	12	0.03
Mytilus spp.	Mussel	12	0.03
Chiroptera	Bat	11	0.03
Acer spp.	Maple	11	0.03
Canis lupus	Wolf	11	0.03
Other		683	1.90
Unknown		28,685	79.89
	Total	**35,905**	**100.00**

Temporal Distribution

The histogram of cultural dates (Figure 1a) shows a curvilinear pattern such that recent dates are more abundant than older dates (e.g. Peros et al. 2010). The oldest dates appear around 14 kyr BP and reach their maximum frequency around 700 yr BP. Paleoenvironmental dates are fewer in number, and do not exhibit a curvilinear pattern (Figure 1b). Instead, high frequencies occur during the late glacial (~13 kyr BP) and early Holocene (~10 kyr BP), which may reflect greater sampling intensity due to interest in the major climatic transitions that occurred at these times, and an interest in mapping the pattern of deglaciation using faunal material.

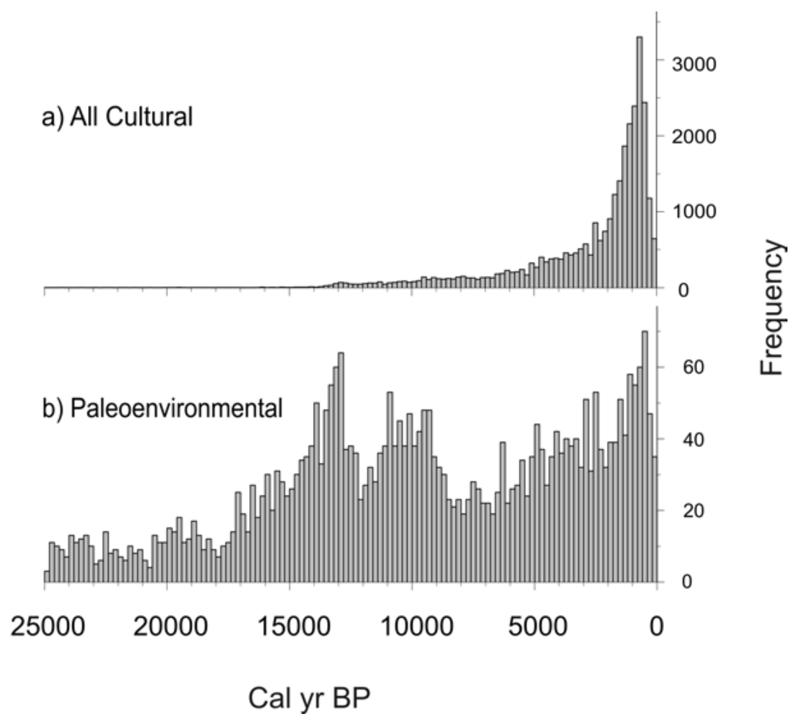

Figure 1 Histogram of dates in the Canadian Archaeological Radiocarbon Database (CARD): (a) Cultural dates; (b) Paleoenvironmental dates.

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When subdivided into cultural period, the histograms generally follow the same general pattern (Figure 2). Paleoindian dates increase in frequency around 13 kyr, gradually decrease, and then undergo a more rapid decrease around 9 kyr BP (Figure 2a). The Archaic period dates are centered around 6 kyr BP, but range from ~11 to 3 kyr BP (Figure 2b).

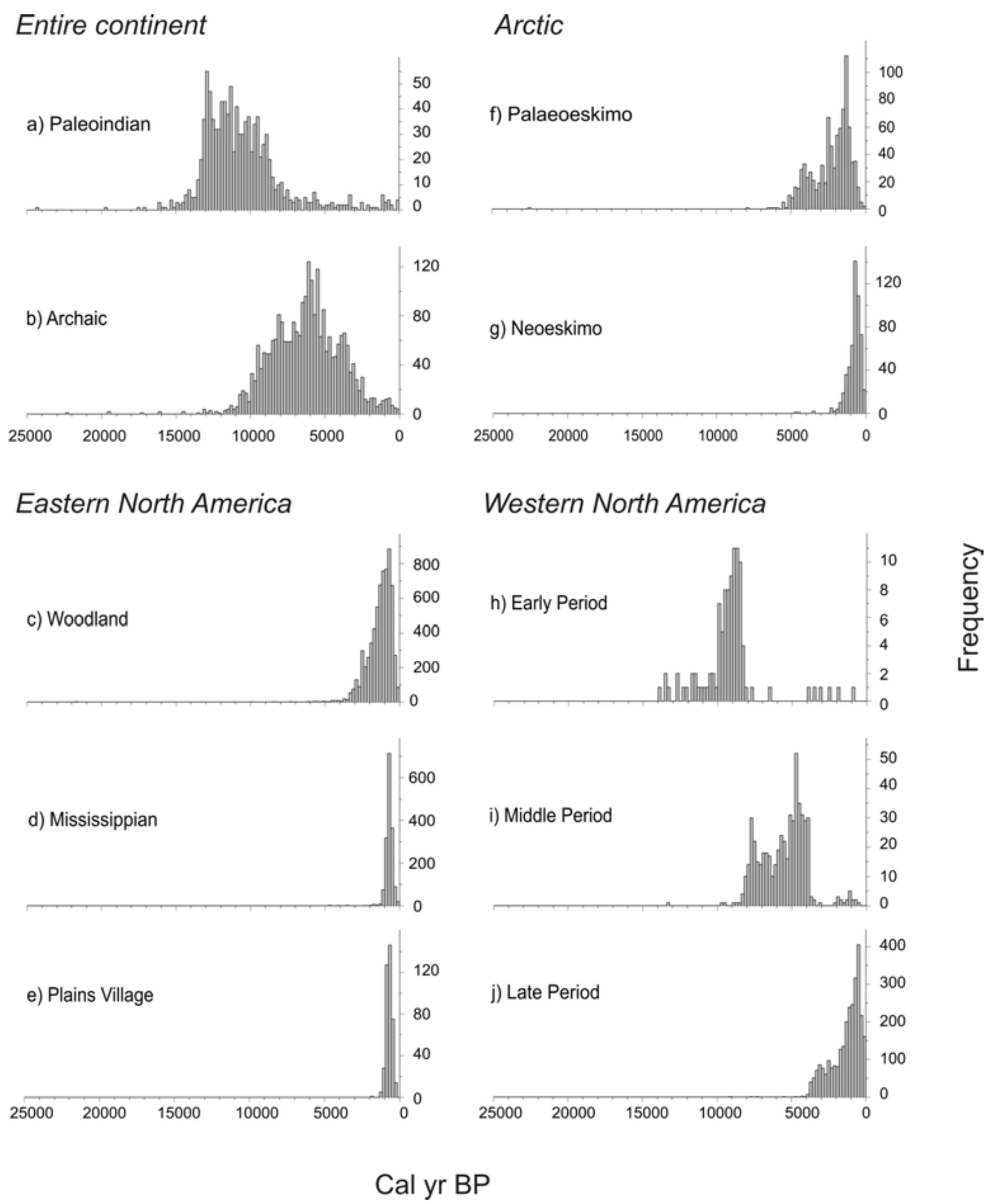

Figure 2 Histograms of all cultural dates in CARD divided by associated cultural period and by region

Following the Archaic, histograms were prepared for different regions of North America. In eastern North America, Woodland period dates first appear ~3 kyr BP and peak ~700 yr BP (Figure 2c). Dates classified as "Mississippian" and "Plains Village" were also separated because these consti-

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tute large groups within the database (Table 3). The dates in both of these groups tightly cluster during the last ~1000 yr (Figure 2d,e). In the Arctic, Paleoeskimo dates appear after 5 kyr BP and increase in frequency until ~1.5 kyr BP, while Neoeskimo dates first appear ~2 kyr BP (Figures 2f,g). Finally, dates from Oregon, Washington, and Idaho show relatively complex distributions (Figures 2h–j). "Early Period" dates appear between ~11 and ~9 kyr BP, but are few in number; "Middle Period" dates show a bimodal distribution, with peaks at ~8 and 4.5 kyr BP and "Late Period" dates, which first appear ~4 kyr BP, reach their maximum frequency during the last 1000 yr. The histograms between successive periods generally overlap, which is not surprising given the gradual nature of many cultural transitions as well as uncertainties in classifying ^{14}C-dated material by cultural period.

When classified by the material dated, all frequency distributions show the typical positive curvilinear pattern seen in many of the other histograms (Figure 3). For all materials, there is a pronounced increase in the frequency of dates around 2 kyr BP, and the maximum frequency occurs around 700 yr BP, but the earliest date for each material class varies. The oldest dates in CARD are from animal remains (particularly bones), with dates on charcoal, plants, shells, and humans becoming more abundant after 15 kyr BP. Dated materials that directly relate to human technologies or innovations, namely pottery encrustations and cultigens, appear only during the late Holocene. The earliest pottery encrustations are dated ~3.3 kyr BP and increase in frequency until ~1 kyr BP. The earliest directly dated cultigens are on squash (*Cucurbita pepo*) during the Middle Archaic (Asch and Asch 1985; Conrad et al. 1984) and from elements of the Eastern Agricultural Complex (*Iva annua*, *Chenopodium* spp.) during the Late Archaic (as defined by the Culture field in CARD). However, it is not until the arrival of maize (*Zea mays*) after ~3 kyr BP that cultigens become more frequent; the earliest ^{14}C-dated maize record in CARD dates to ~2800 cal yr BP (Berry and Berry 1986).

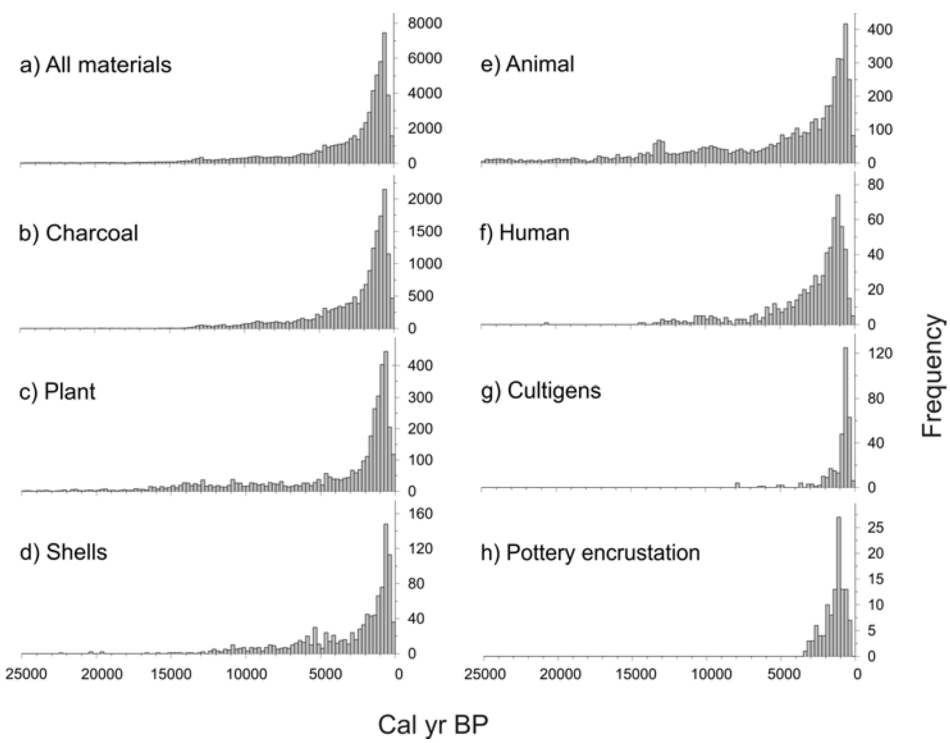

Figure 3 Histograms of cultural dates in CARD divided by material

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Spatial Distribution

To assist in the description of the spatial distribution of dates, the continent was divided into broad cultural regions based on boundaries proposed by Ubelaker (1992, 2006; Figure 4a). The spatial distribution of all CARD dates is far from uniform (Figure 4b). Nearly half of the Cultural dates are located in the Northeast and Great Plains cultural regions (Table 6, Figure 4b). There are also relatively large clusters of dates in Wyoming, along the Pacific coast, Alaska, the Canadian Arctic Archipelago, and the coast of Labrador and Newfoundland. The density of dates is lower in the Arctic cultural region, as well as in the southern half of the United States, south of 35° latitude (Figures 4b,c).

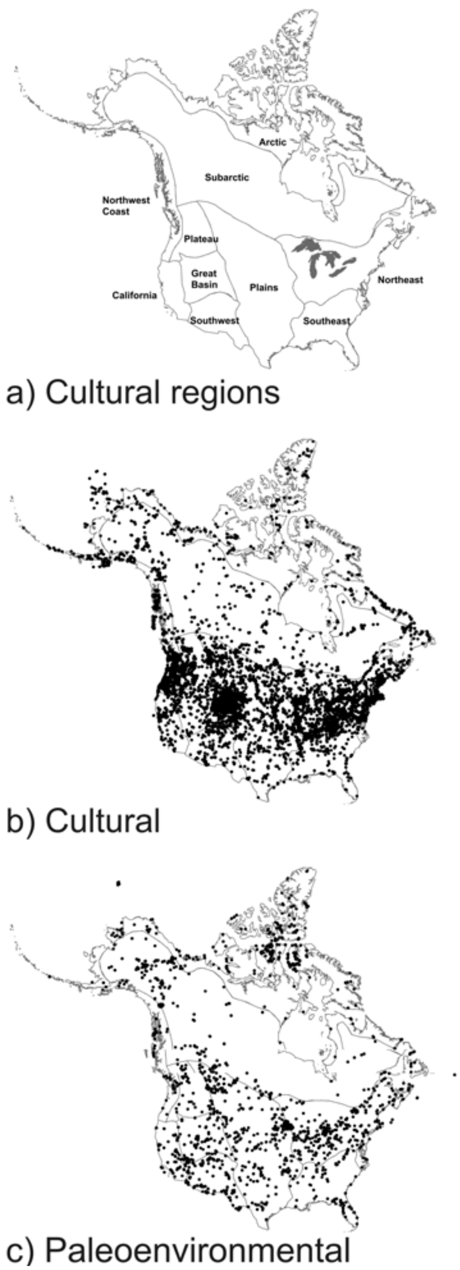

Figure 4 (a) Cultural regions used in this paper based on Ubelaker (1992, 2006); (b) locations of all Cultural dates in CARD; (c) locations of all Paleoenvironmental dates in CARD.

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Table 6 Frequency and percentage of ^{14}C dates in CARD by cultural area.

Cultural area	Frequency	Percentage
Arctic	1851	5.2
Subarctic	2847	7.9
Northeast	10,144	28.3
Southeast	1668	4.6
Plains	6380	17.8
Southwest	1540	4.3
California	716	2.0
Great Basin	3045	8.5
Plateau	2571	7.2
Northwest Coast	2476	6.9
Other	2667	7.4
Total	**35,905**	**100.0**

This distribution reflects a sampling bias that was focused primarily on obtaining records from Canada and, later, the northern continental United States (see above). Within Canada, where the data set is more comprehensive, the spatial distribution likely reflects broad prehistoric settlement trends, but also reflects factors such as archaeological sampling strategies and the distribution of modern population centers (Buchanan 2003). South of the 49th parallel and west of the 141st meridian, the distribution is more indicative of sampling bias on the part of the database creators. Notably, this northern/southern US sampling bias is not as obvious in the Paleoenvironmental data (Figure 4c); this may be because some of these data were obtained from pre-existing databases that contained data with a more continent-wide distribution.

Mapping entries in CARD based on their cultural affiliation (Figure 5) provides additional information on sampling biases as well as the spatial distribution of prehistoric cultures. Paleoindian dates are found throughout formerly unglaciated North America south of the Arctic cultural region, and are most concentrated in the Plains and Northeast; however, as Anderson et al. (2008) point out, they are underrepresented in the Southeast (Figure 5a). Archaic dates are also prevalent throughout most of North America, with the exception of the Arctic, Plateau, and Northwest Coast (Figure 5b), as the term “Archaic” is not used in CARD to describe dates from these regions. ^{14}C dates associated with Woodland cultures are found east of the Rocky Mountains, and are concentrated in the Northeast region (Figure 5c). Late Prehistoric agricultural cultures in eastern North America, such as the Mississippian (Figure 5d) and Plains Village (Figure 5e) cultures, constitute a substantial proportion of entries in the database but may be underrepresented south of the Canada-US border. Paleoeskimo and Neoeskimo dates are found throughout the Arctic, with the latter having a slightly more northerly distribution (Figures 5f,g). Finally, the Early, Middle, and Late Period dates are from the states of Washington, Oregon, and Idaho, with a small number occurring in central California (Figures 5h–j).

Space-time mapping of the various materials dated shows the changing spatial distribution of ^{14}C dates from the period ~15 kyr BP to ~500 yr BP (Figure 6). The chronological periods are based on the timing of major climatic transitions documented in paleoclimatological records from North America (Viau et al. 2006): 1) the earliest Paleontological dates (~25 kyr BP) to just prior to the onset of the Younger Dryas (13 kyr BP); 2) the approximate dates for the Younger Dryas chronozone (13–11.6 kyr BP); 3) the end of the Younger Dryas to the 8.2 kyr BP transition; and 4) the Holocene subdivisions as defined by pollen records.

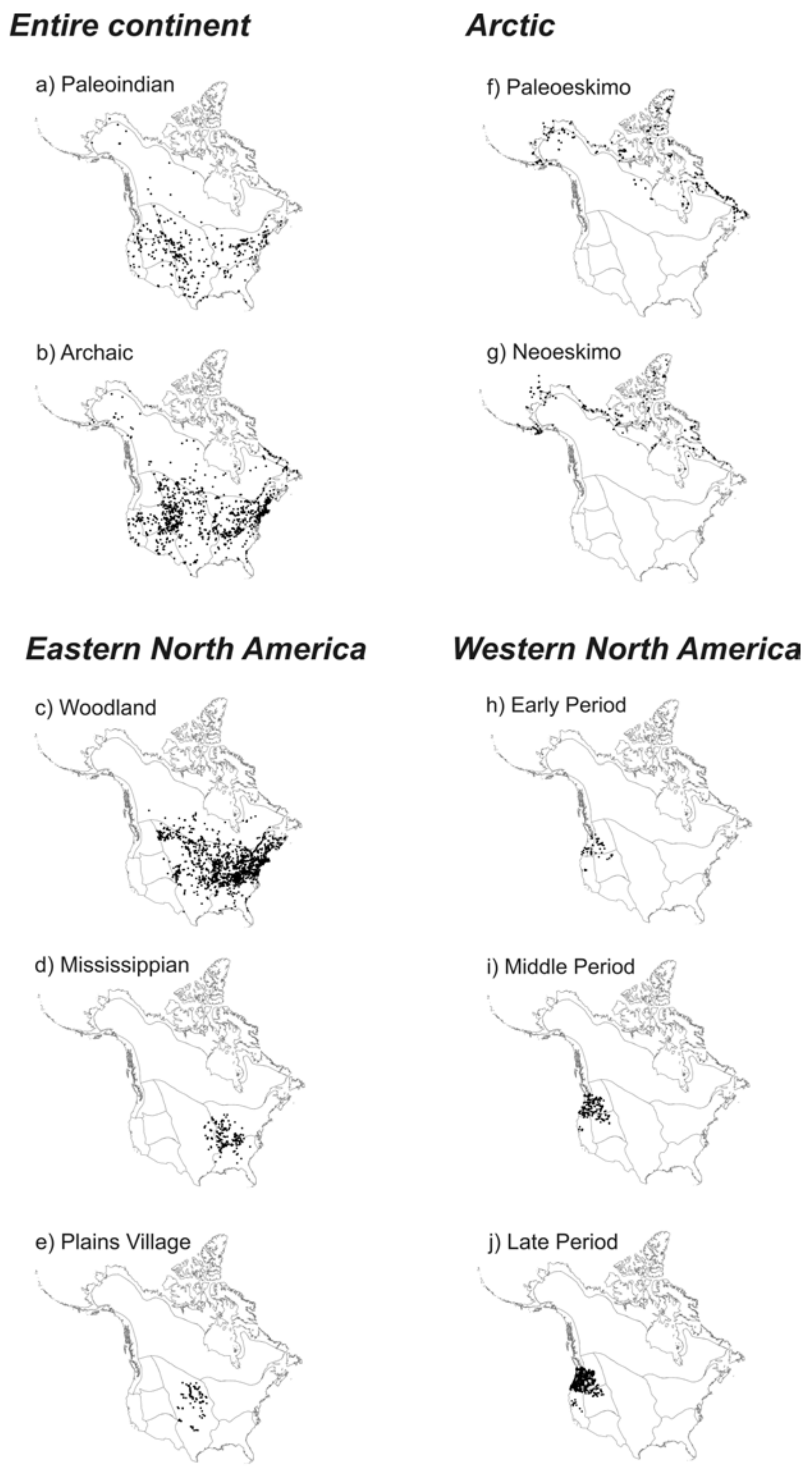

Figure 5 Maps showing the location of all ^{14}C dates in the CARD, stratified by region and cultural association.

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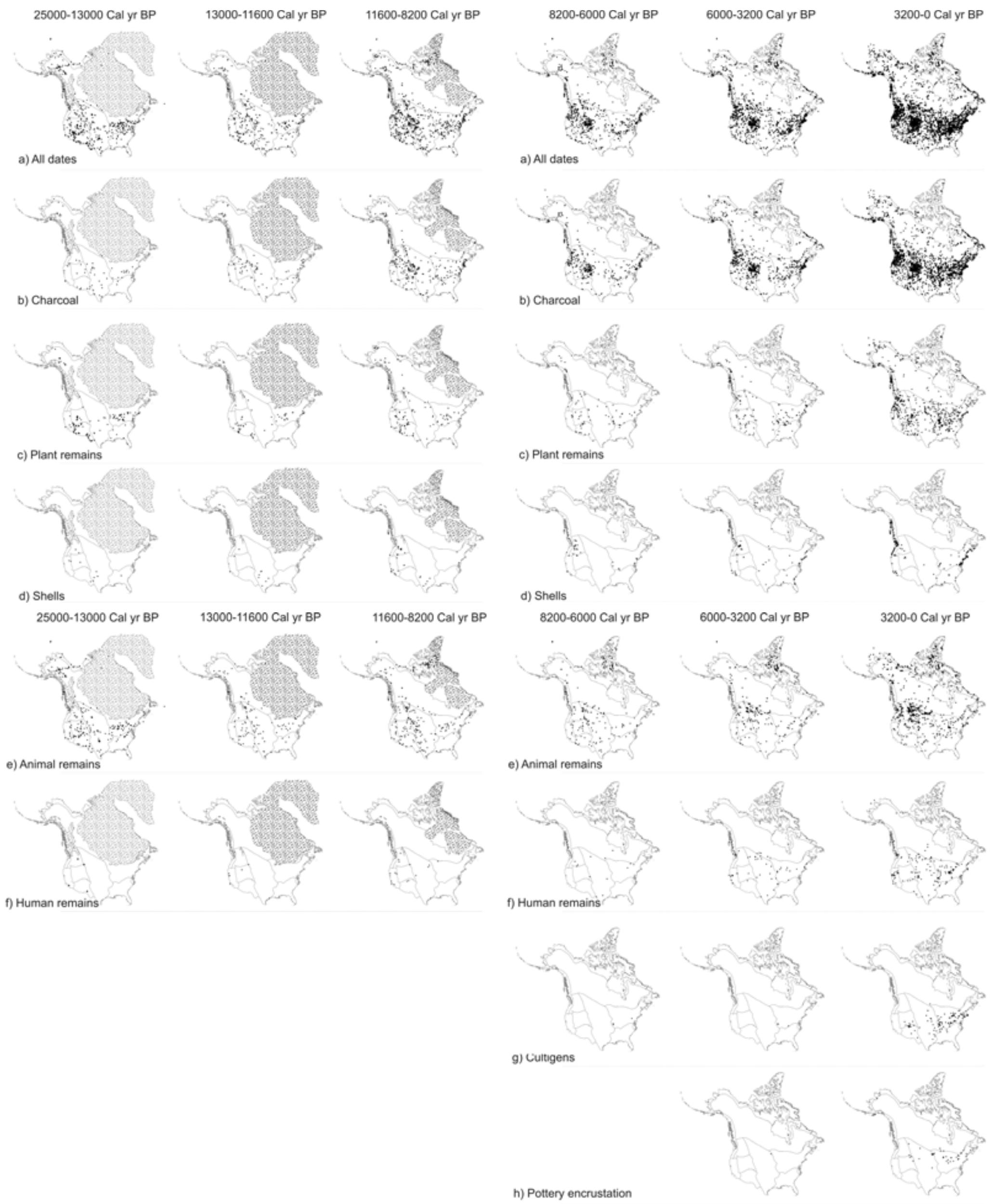

Figure 6 Radiocarbon dates in the CARD, for several time intervals and material dated. Location of ice sheet (shaded) from Dyke (2004).

The maps of all dates show increasing numbers and density of sites with time (Figure 6a). The earlier periods are characterized by 2 distinct clusters of dates: those found south of the Laurentide Ice Sheet, and those located in eastern Beringia. As time progresses, new dates quickly appear following deglaciation, although the Boreal region, which constitutes much of the area of present-day Canada, has relatively few dates during all periods. During the middle Holocene (8.2–6.0 kyr BP), the underrepresentation of dates from the southern Unites States becomes especially apparent.

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Dates on anthropogenic charcoal (Figure 6b) are found across the continent, and the spatial distribution of this material through time is similar to that of the group representing all the material in the database. Paleobiological dates, such as on plant (Figure 6c) and animal (Figure 6d,e) remains, are also prevalent throughout most of the continent, and the spatial density of these materials tends to be higher where and when there are fewer dates on charcoal, such as the in the Arctic (more animal remains) and the Southwest (more plant remains). Particularly with the charcoal and plant remains, dates occurring south of the Canada-US border tend to be separated into 2 clusters, with few dates appearing along a north-south axis through the center of the continent. In the most recent chronological period (3.2–0 kyr BP), however, dates are more common in this area.

Dated shells are found predominately in western North America until the mid-Holocene, when freshwater and marine shells become more prevalent in the rivers and along of the coasts of the Northeast and Southeast cultural regions (Figure 6d). Dated human remains are rare, and the distribution is probably mostly determined by changing archaeological practices (Figure 6f). Cultigens are not found in the database until the mid-Holocene, with the earliest cultigens found at a low density in the Northeast (Figure 6g). By the late Holocene, cultigens are found in the southwest, eastern Plains, Northeast, and Southeast cultural regions. ^{14}C-dated pottery encrustations also appear for the first time during the mid-Holocene, and are not prevalent until the late Holocene, when they are found in the Northeast, Plains, Great Basin, and Arctic cultural regions (Figure 6h).

DISCUSSION

Databases such as CARD are an important resource for archaeologists and Quaternary scientists. CARD can be rapidly searched, using simple search or sorting tools for published information about a particular region. A researcher can extract the actual data that may have been provided only in graphical or map form in a previous paper to enable more detailed comparison to their own results. Some caution is needed, as a lack of data in CARD may be simply due to the fact that it has not yet been entered.

Uses of CARD

CARD can be used to document the minimal spatial or temporal extent of the dated object, which can then be compared to, for example, the vegetation types or climate episodes. Stratigraphic range diagrams or histograms of ^{14}C dates have been used by paleontologists to study the extinction of large mammals in the late glacial (e.g. Guthrie 2006; Barnosky 2008). Again, these patterns need to be interpreted cautiously, because a lack of data does not necessarily indicate a lack of the target organisms at that point in time and space. However, the presence of a dated fossil, especially if extensively replicated, does provide information about presence of the culture or resource.

There is also an interest in using these data sets to estimate population numbers in the past (e.g. Gamble et al. 2004; Peros et al. 2010). Differences in the frequency of dates in time can be interpreted as representing changes in population numbers or population density, based on the premise that more people will leave a larger amount of cultural carbon on the landscape. This idea is based on the fundamental assumptions of statistics, such that a very small, random sample can be used to infer the statistics of the entire population. In fact, even with very small non-random samples, methodologies of sampling theory can be used to make inferences about the original population, although this requires careful planning (Cochran 1963). This assertion needs further study, however, perhaps using local and regional analyses, and through analysis of the database using different methods.

Biases and Issues When Using Radiocarbon Databases

CARD is missing many data from the United States and it is doubtful that it contains a random sample of the ^{14}C-datable material across Canada, nor do these archaeological remains constitute a random sample of sites or cultural activity through time. However, if the various biases can be controlled for or modeled, then reasonable estimates of populations through time may be obtainable. It has to be recognized that these are relative estimates, and that these will be modified with more information. When estimates based on the CARD are compared to estimates based on alternate methods, more confidence in these population estimates is possible (see below). In any event, several issues and biases need to be addressed when using databases such as CARD. We can identify at least 4 issues that need to be considered on a case-by-case basis; there may be others, and new considerations will develop as the database is used.

1. First is sampling bias, including both interest and spatial biases, and including incompleteness of the database (e.g. Buchanan 2003). At the present time, it is difficult to compare different regions in terms of absolute site numbers. The low density of sites in the southern United Sates is a result of the focus on Canada in the construction of the data set. Related to this is an "interest" bias. Because questions of the first arrival of humans to the continent and megafaunal extinctions have attracted significant research interest, there may be a tendency for more dates to be submitted for older samples. There may be biases for certain cultures that have been the object of particularly intense study. In areas near major universities, or areas for which important rescue archaeology efforts have been made, a higher sample proportion of the original site population may have been found or studied than in more remote areas. These kinds of biases can be at least acknowledged; they may also not be significant if the study is restricted to a small region. In the short term, it may be possible to still analyze these data geographically, by normalizing in some way, or investigating anomalies from long-term regional trends. Weighting data by region based on sampling effort can counteract incomplete data, and a stratified sampling scheme used to estimate population parameters (Cochran 1963).
2. Taphonomic issues need to be considered. Over time, geological deposits are lost due to diagenesis, inundation, erosion, and anthropogenic activity, such that it is more likely to find more recent sites than older ones. This "taphonomic rate" is a well-known issue in paleontological and archaeological research, and has been studied on many occasions, although there is no simple nor universally accepted solution. Studies that have analyzed taphonomic bias in archaeological ^{14}C databases include Surovell and Brantingham (2007), Surovell et al. (2009), and Peros et al. (2010). This bias is confounded with the expected increase in populations through time, a problem not necessarily present when geologists study taphonomic biases in older deposits.
3. For higher-resolution studies, issues of ^{14}C calibration need to be considered (Fiedel 1999; Waters and Stafford 2007). The analysis and interpretation of chronologies using ^{14}C-dated archaeological artifacts remains is not straightforward. For example, frequency distributions of ^{14}C dates are commonly used in archaeological studies to determine rates of change in paleopopulation densities, migrations, and timing of abrupt changes in the records (Riede 2009; Collard et al. 2010). However, the age relationship between ^{14}C and calendar years is complicated by 2 distinct differences that result from variations in atmospheric ^{14}C production (Stuiver et al. 1991). The first-order difference is a gradual long-term tendency for ^{14}C ages to be younger than calendar years and the second-order difference is the presence of shorter-term "steps" and "plateaus" that can lead to ambiguous interpretation of the timing and rates of change in the records (Bartlein et al. 1995). For example, short-term plateaus can lead to overestimation of the timing and rate of change by creating false peaks in the frequency distribution histogram.

Conversely, short-term steps can lead to underestimations of the timing and rate of change by spreading the dates over a longer period of time, thus flattening frequency distributions. The implications are seen in Figure 7, where the banded structure indicated by the arrows is due to the non-linear relation between ^{14}C and calendar years. Although first-order differences may be secondary considerations in interpreting the archaeological record, it is still not fully understood to what extent these short-term variations in the ^{14}C ages affect the interpretation of transitions found in a frequency distribution of ^{14}C dates as seen in other studies (Viau et al. 2002; Gajewski et al. 2006). Therefore, caution should be taken when interpreting ^{14}C-dated paleoenvironmental records.

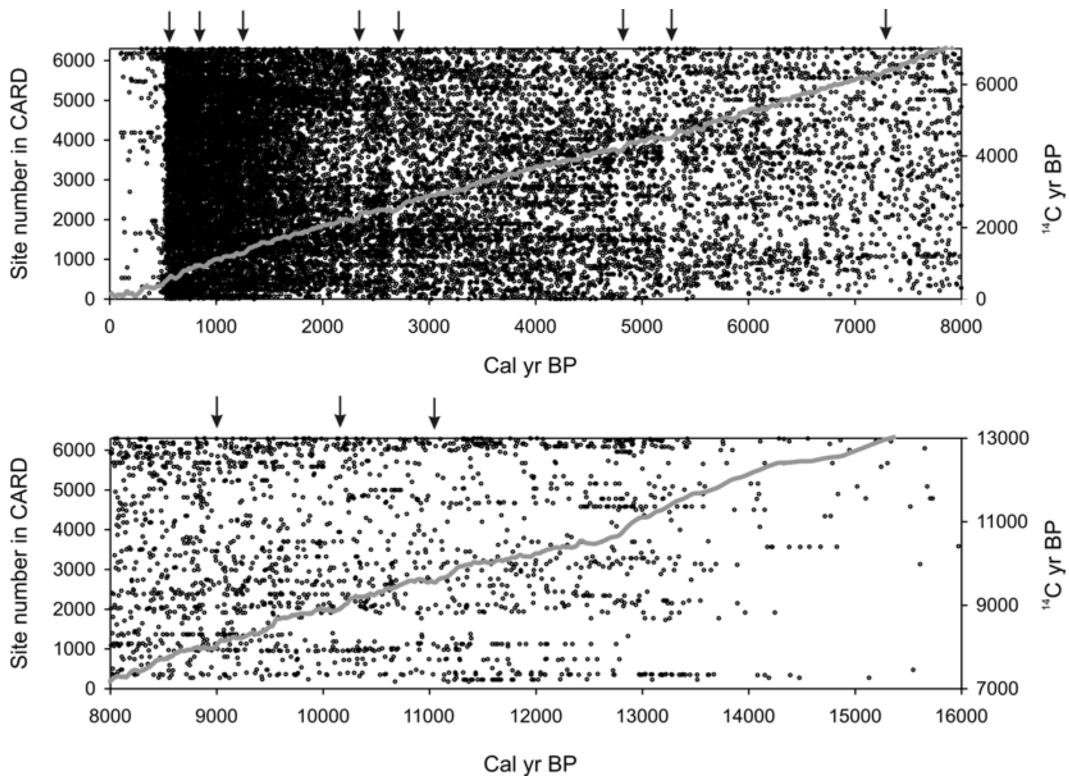

Figure 7 Density plot showing the dates in the CARD through time: (a) 0–8000 kyr BP; (b) 8000–16,000 kyr BP. The gray curve shows the ^{14}C age curve plotted against calendar year BP. Arrows indicate "gaps" in the density plot, associated with plateaus in the ^{14}C curve.

Preferably, when using ^{14}C dates, calibration or converting ^{14}C years in calendar years is necessary to avoid some of these issues (e.g. IntCal04; Reimer et al. 2004). Telford et al. (2004) recommend using the weighted average or median estimates rather than the commonly used intercept method (Stuiver and Reimer 1993). When possible, the full distribution of the calibrated ^{14}C probability density function should be used (Telford et al. 2004).

4. When using the database to study questions of cultural change or cultural relations to the environment, biases in assigning cultures to the material need to be considered. CARD provides the cultural affiliation originally assigned by the author of the first published record of the date. These fields are updated as new information is available, based on new interpretations and changing chronocultural schemes. However, many dates in CARD clearly suggest a temporal

range beyond reasonable assumptions for certain cultural periods (see Figure 2). Many of these dates are caused by errors in the ^{14}C dating process, or unrecognized taphonomic or stratigraphic issues in the site. Still other cultural designations may be "out of date" or wrong because of the erroneous interpretations of the original author. There is no statistical means to adjust for this sort of bias, and research that focuses on spatial and temporal distributions of specific cultures in CARD must carefully filter all date records based on current understandings of culture-history, with a careful regard for potential dating errors, and an understanding of each date's archaeological context. In many cases, this will require consultation of the original source material, which can be accessed in the references section of CARD.

Can these biases be controlled? We here provide an example from 1 region where the estimates of relative changes in population number, based on 2 alternate approaches, are in agreement (Munoz 2010). Munoz and Gajewski (2010) studied the impact of Native American agriculture on the forests of southern Ontario during the past 2000 yr. Their primary interest was paleoecological and the question was: Did Native American activities, especially agriculture, have an impact on the forests of southern Ontario at a regional scale, to the extent that could be determined in pollen diagrams? Using scan statistics, they demonstrated that pollen sites surrounded by higher densities of archaeological dates were associated with more maize pollen and evidence of disturbance, and that the forest succession differed between impacted and non-affected sites. This showed that the maize agriculture in the region as significant enough to have affected forest composition in areas of higher population density.

As part of the study, Munoz (2010) compared an independent reconstruction of population change in southern Ontario from the 1200 cal yr BP to the historic time period by Warrick (2008) with the temporal frequency distribution of corresponding entries in CARD (Figure 8). CARD contains many entries which are not ^{14}C dated but are inferred dates based on artifacts, such as European trade goods, which the principal investigator was able to date using an independent established chronology or historical records. These entries are more prevalent in CARD after initial European settlement in North America, when European goods and historical records can provide greater temporal precision than ^{14}C dating. Changes in population derived using the temporal frequency distribution of both "historically dated" and ^{14}C-dated entries in the CARD and the reconstruction by Warrick (2008) are very similar; and show a rapid increase of the indigenous population beginning ~600 cal yr BP and a decline ~300 cal yr BP.

Radiocarbon Data and Environmental History

We have discussed several examples where ^{14}C databases have been used to provide insight into paleoenvironmental changes in the past. We conclude by showing several other examples of the uses of CARD, indicating some results that have been obtained, as well as discussing how some of the biases have been dealt with.

At a continental scale, Peros et al. (2010) attempted to estimate the population of North America from the initial colonization through to the European period using CARD. They used a taphonomic correction developed by Surovell et al. (2009), based on volcanic eruption records from the geological record, and also corrected for an archaeological interest bias. Testing a number of reasonable assumptions, they provided an estimate of the general population growth on the continent. This estimate did not account for environmental fluctuations, however, and this is the object of ongoing work.

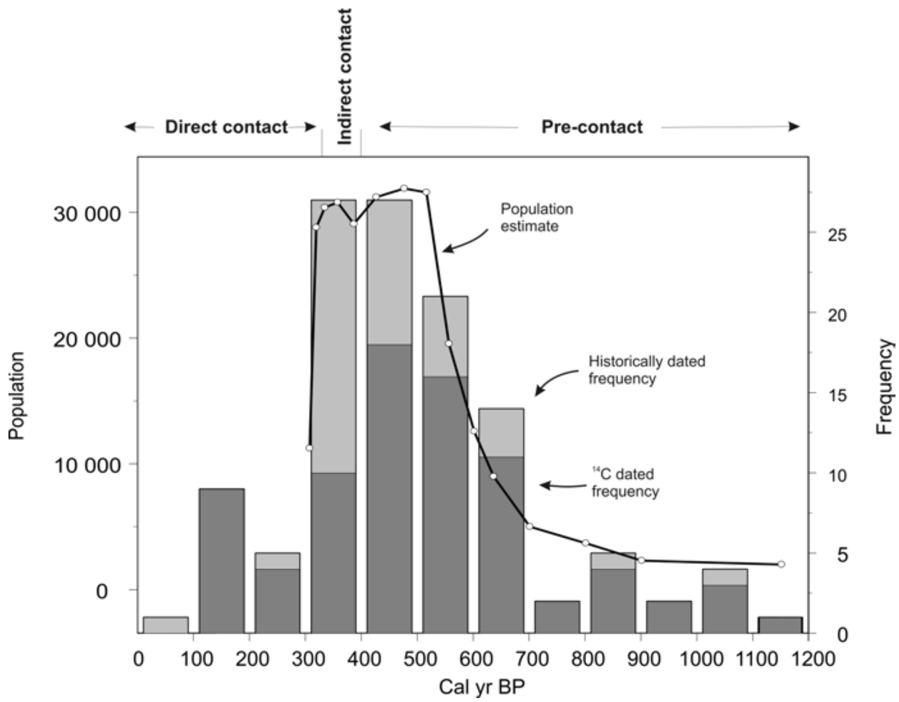

Figure 8 Comparison of 2 reconstructions of the changes in the native population of southern Ontario for the past 1200 yr. Line: population estimates of Warrick (2008) using archaeological surveys. Bars: temporal frequency distribution of archaeological artifacts in CARD. Dark bars represent the frequency of ^{14}C-dated artifacts, and light bars represent the frequency of artifacts whose age was estimated by the primary investigator based on its association with other materials.

In an earlier use of CARD, Buchanan et al. (2008) tested the hypothesis that the Younger Dryas was the result of a comet impact by reasoning that such an event would have negatively affected Paleoindian population numbers as recorded in the temporal frequency distribution of dates in CARD. As part of their analysis, they tested the influence of taphonomic bias on relative changes in temporal frequency distributions and found that even at a high rate of site destruction relative peaks and troughs (inferred as demographic change) are unlikely to be removed. Buchanan et al. (2008) found no evidence of a population decline at the beginning of the Younger Dryas, but their analysis has fostered discussion on the use of CARD as a paleodemographic proxy (Anderson et al. 2008; Culleton 2008; Collard et al. 2008; Steele 2010).

At a regional scale, Munoz et al. (2010) analyzed the CARD data from the northeastern United States in relation to the postglacial environmental history of the region. They plotted changes through time in the numbers of ^{14}C dates associated with the different cultures in relation to vegetation transitions, defined from pollen data, and climate inferences from lake sediments. Although a general relationship has long been hypothesized between cultural transitions and environmental change (e.g. Stoltman and Baerris 1983; Anderson 2001), the availability of large databases of both culture and vegetation enabled a comparison of human culture, population numbers, and terrestrial ecosystems. Munoz et al. (2010) found that major environmental transitions are associated with changes in culture and population numbers throughout most of prehistory, until the adoption of maize agriculture ~1 kyr BP, when cultural and demographic change seemed to occur in the absence of any major environmental reconfiguration.

Regional- to continental-scale paleoenvironmental studies are an important part of an overall research strategy for understanding late Quaternary environmental change and better understanding how these changes impacted human population numbers and activities. These studies provide only part of the necessary information to interpret past observations, along with detailed local studies and modeling exercises. Often, studies of the CARD and similar databases can only provide hypotheses, based on correlations or other inferences that need to be tested by modeling or explanatory studies. Nevertheless, patterns that emerge from these studies, such as the examples given above, are providing reasonable explanations for observed phenomena. These frequently provide the first step in a research program to explain the phenomena. For example, the close association of cultural, demographic, and environmental changes during the Holocene suggested for northeastern North America (Munoz et al. 2010) has long been suggested by archaeologists, and studies using CARD have further refined these hypotheses by showing that they emerge using only ^{14}C dates and the assumed relation between numbers of dates and population density. Work is needed to establish the causal relations, however.

Analyses based on CARD are based on fundamental ideas of statistical sampling and inference, where small samples can be used to estimate population parameters (e.g. Peros et al. 2010), and the key observation that with larger samples, errors decrease (e.g. Viau et al. 2006). Although any one ^{14}C date may have a large error, with many dates, the estimate of the error decreases. Just as statistics of opinion polls indicate, very small samples can provide reasonable estimates of the population; Peros et al. (2010) show another example. Because the CARD has many tens of thousands of data points, it is at the stage where exploratory studies can be performed, hypotheses tested, and syntheses attempted. Making a few reasonable assumptions and applying models (such as taphonomic corrections) from other fields of study should lead to new insights into the nature of environmental change.

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