Seasonal records of palaeoenvironmental change and resource use from archaeological assemblages

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Abstract

Seasonal climate variability can affect the availability of food, water, shelter and raw materials. Therefore, robust assessments of relationships between environmental change and changes in human behaviour require an understanding of climate and environment at a seasonal scale. In recent years, many advances have been made in obtaining seasonally-resolved and seasonally-focused palaeoenvironmental data from proxy records. If these proxy records are obtained from archaeological sites, they offer a unique opportunity to reconstruct local climate variations that can be spatially and temporally related to human activity. Furthermore, the analysis of various floral and faunal remains within archaeological sites enables reconstruction of seasonal resource use and subsistence patterns. This paper provides an overview of the growing body of research on seasonal palaeoenvironmental records and resource use from archaeological contexts as well as providing an introduction to a special issue on the same topic. This special issue of *Journal of Archaeological Science Reports* brings together some of the latest research on generating seasonal-resolution and seasonally-focused palaeoenvironmental records from archaeological sites as a means to assessing human-environment interaction. The papers presented here include studies on archaeological mollusc shells, otoliths, bones and plant remains using geochemical proxies including stable isotopes ($\delta^{18}O$, $\delta^{13}C$, $\delta^{15}N$) and trace elements (Mg/Ca). The geographical scope encompasses parts of Europe, North America and the Levant, whilst temporally the studies range from Palaeolithic to historical times.

Keywords: seasonality, palaeoenvironment, archaeology, sclerochronology, high-resolution proxy records

1. Climate and seasonality

Anthropogenic climate and environmental change is one of the most pressing issues in today's world, yet our understanding of how human-induced environmental change fits into the Earth's pre-industrial, natural climate variability is limited by the shortness of the instrumental record. Instrumental records of past climate rarely extend beyond AD 1860 (Jones et al., 2001; 2009), yet many modes of climate variability operate on decadal to millennial timescales. Therefore, knowledge of past climate variability over longer timescales is essential to better understand the mode, scale and periodicity of natural climate variability and to establish a longer-term context from which to understand and interpret anthropogenic climate change. We can reconstruct climatic and environmental conditions prior to the instrumental record by analysing proxies preserved within palaeoenvironmental archives. It is essential to develop a broad range of proxy records of climatic and environmental change to enable an understanding of patterns of past climate and environmental change at various spatial and temporal scales (IPCC, 2013). Such data provide a framework of past changes, offer baselines for environmental monitoring, and provide data that can be used in climate modelling scenarios to better predict anthropogenic impacts on the natural climate system (McCarroll, 2010; Schmidt et al. 2014; IPCC, 2013).

Understanding seasonal variations in climate is of fundamental importance for understanding the dynamics of the Earth's system as a whole (Luterbacher et al. 2004; Denton et al., 2005). Climate seasonality significantly influences mean climate and in many components of the climate systems, summer and winter variability can differ significantly. For example, instrumental data since 1861 in the northern hemisphere show increases in winter air temperature during the 20th century of ˜0.8˚C whereas summer temperatures only increased by ˜0.4˚C (Jones, 2001; Jones et al., 1999). In the past, these variations may have been more extreme. Additionally, the operation of many climate modes such as the North Atlantic Oscillation (NAO) is weighted towards a single season. However, many of the most widely studied palaeoenvironmental archives such as ice cores, marine sediment cores and lake cores generally only provide annual or lower resolution palaeoenvironmental proxies. Whilst these records enable an understanding of climate at the broader scale, their resolution is often too low to allow validation with instrumental data (Rutherford et al., 2005).

Seasonally resolved palaeoclimate records enable a better understanding of the intricacies of the climate system, yet, there are comparatively few archives that capture the full range of seasonal variation (Denton *et al*., 2005; Ferguson *et al*., 2011; Prendergast et al. 2016a; 2017). Speleothems and tree-rings can offer continuous terrestrial records at seasonal resolution (e.g. Abram et al. 2013; Orland et al. 2014; Wong and Breecker 2015; McCarroll and Loader, 2004), whilst archives such as terrestrial gastropods, pollen, microfauna and insects may provide seasonally weighted proxies of the terrestrial system (Colonese et al. 2007, 2013; Ngomanda et al. 2009; Mignino et al. 2018; Prendergast et al. 2016b; Yanes et al. 2009, 2014). Corals (e.g. Gagan et al. 2000; Cobb et al., 2003, 2013; Tierney et al. 2015) and coralline red algae (Halfar et al., 2008, 2011; Kamenos et al., 2008; Herzinger et al. 2009; 2011) can capture long, continuous records of marine seasonal variability, however, their growth is generally restricted to tropical waters. Other biogenic proxies such as bivalve shells (e.g. Goodwin et al., 2003; Grossman and Ku, 1986; Schöne et al., 2004, 2005; Versteegh et al. 2012), gastropod shells (e.g. Mannino et al. 2003, 2008; Schöne et al. 2007; Burman and Passe 2008; Surge & Barrett 2012; Wang et al. 2012; Prendergast et al. 2013; Prendergast & Schöne 2017), and fish otoliths (e.g. Müller et al., 2015; Surge and Walker, 2005; Disspain et al. 2011) can provide high-resolution internally temporally well-constrained palaeoenvironmental archives from aquatic ecosystems in both tropical and temperate regions. However, they offer only short time windows of climate reconstruction based on the longevity of the organisms from years to decades and occasionally, centuries (Schöne 2008). Other aquatic archives such as alkenones and ostracods may offer weighted-seasonal reconstructions, generally biased towards either summer or winter reconstructions (Börner et al. 2013; Prahl et al. 2001; Timmerman et al. 2014).

2. Seasonal records and human activity

Understanding seasonal variability is of fundamental importance to reconstructing human-environment interactions. Seasonal changes in climate and environment play a critical role in the interplay between humans and their environment. Changes in seasonality can affect the timing and availability of resources including food, water, shelter and raw materials. Many studies of human-environment interaction use regional-scale climate records or climate records that may be tens to hundreds of kilometres away from the archaeological sites used to reconstruct behavioural changes. The application of such records to understand human-environment interaction can be problematic because local climatic conditions may not necessarily mirror regional-scale changes and environments may change dramatically over kilometer scales due to factors such as local topographic changes. Furthermore, many regional-scale records of past climate have decadal to millennial resolution at best, whereas humans primarily respond to climate on seasonal to annual timescales (Denton et al. 2005; Shea et al. 2008; Prendergast et al. 2016b; Roberts et al. 2016). Robust assessments of the impact of climate change on human behaviour therefore require knowledge of climate at both local and seasonal scales. The best way to ensure that palaeoenvironmental records directly relate to human behavioural records is to get them directly from archaeological sites from which the human behavioural changes are interpreted.

Seasonal information can be obtained from various biological material types routinely preserved in archaeological sites. Faunal material, such as mollusc shells, otoliths and mammalian skeletal elements, accumulated in archaeological deposits as a result of hunting and foraging activities, can provide insights into palaeoenvironments and seasonal site use, through traditional zooarchaeological studies and geochemical analyses. Meanwhile, macrobotanical and pollen remains, incorporated into archaeological sediments, can offer insights into seasonal temperature or precipitation variations and the length of growing seasons.

Geochemical and growth pattern signatures from biogenic carbonates are being increasingly employed to understand seasonal palaeoenvironmental variability and resource use from archaeological sites (Prendergast et al. 2017). Mollusc shells, fish otoliths and faunal teeth in particular are routinely preserved in the archaeological record. Many archaeological sites contain freshwater, marine, terrestrial and estuarine mollusc shells, and freshwater, marine, and estuarine otoliths likely to be refuse from foraging and fishing activities (Andrus 2011; Colonese et al. 2011; Prendergast and Stevens 2014; Disspain et al. 2016; Twaddle et al. 2016), and faunal teeth and antler likely to be the result of hunting activities (Hillson, 2005; Pryor et al. 2016; Reade et al 2016, 2018; Pilaar-Birch et al 2016; Stevens and O'Connell 2016). These archives are particularly relevant to reconstructing human-environment interaction as their presence in archaeological sites is generally the result of foraging, fishing, and hunting activities (thus live-collection). Therefore, these archives can provide local palaeoenvironmental records that can be directly linked both spatially and temporally to records of human habitation and behaviour. Such data are crucial for generating robust data on human-environment interaction (Prendergast and Stevens 2014; Prendergast et al. 2016b). Biogenic carbonates also offer the additional advantage that they can be directly dated using methods such as radiocarbon (e.g. Magnani et al. 2007; Butler et al. 2009a; Reimer 2015; Bosch et al. 2015b; Hill et al. 2017), U-Th series (e.g. Magnani et al. 2007; Rowe et al. 2015), or amino acid racemisation (e.g. Murray-Wallace et al. 2005; Demarchi et al. 2015). This allows the reconstruction of high resolution, time-series of palaeoenvironmental change.

The incremental growth structures in many biogenic carbonate proxy archives such as mollusc shells, otoliths and teeth enable the reconstruction of chronologically-constrained, high-resolution records of palaeoenvironmental variability (Prendergast et al. 2017). The study of the structure and chemistry of the incrementally deposited hard parts of organisms is known as sclerochronology. This field has expanded exponentially in the past few decades (see Schöne and Surge, 2005; Gröcke and Gillikin, 2008; Oschmann, 2009; Wanamaker et al., 2011; Schöne and Gillikin 2013; Butler and Schöne 2017; Prendergast et al. 2017 for recent overviews). The time span and resolution that can be obtained for palaeoenvironmental records from sequentially deposited biogenic carbonates depends upon on the sampling method used, and the growth rates and longevity of the organism (Schöne 2008). Physical and chemical analyses of the annual, and in some cases, fortnightly and daily increments allow the reconstruction of chronologically constrained records of palaeoenvironmental variability at unparalleled high temporal resolutions.

Shelled bivalve and gastropod molluscs have been consumed by humans all over the world from Palaeolithic to recent times (Colonese et al. 2011; Twaddle et al. 2016). They can provide records of palaeoenvironmental change stretching over tens of thousands of years. Such records are particularly important in coastal regions where sea level changes may have obscured coastal records of human habitation and environmental change (Gutiérrez-Zugasti et al. 2016). These archives can cover both tropical and temperate regions in both the northern and southern hemispheres and allow reconstructions from terrestrial, marine, freshwater, and estuarine palaeoenvironments. They therefore offer the opportunity for high-resolution palaeoenvironmental reconstructions across many time intervals, all over the globe (see Andrus 2011; Prendergast and Stevens 2014; Leng and Lewis 2015; Thomas 2015; and Twaddle et al. 2016; Butler and Schöne 2017; Prendergast et al. 2017 for recent reviews). The analysis of mollusc shells for palaeoenvironmental reconstruction has been growing steadily over the last couple of decades (Butler and Schöne 2017). Additionally, by analysing the pattern of geochemical variation in the terminal growth increments of archaeological mollusc shells, the season in which the shellfish were foraged can be determined. Combining such data with other archaeological subsistence data enables a more complete picture of site use patterns (e.g. Helama & Hood 2011; Mannino et al. 2007; Burchell et al. 2013; Jew and Fitzpatrick 2015; Prendergast et al. 2016a; Hausmann and Meredith-Williams 2016).

Otoliths are small calcium carbonate structures found in the inner ear of teleost fish (Popper and Fay 2011). Otoliths have been used to determine the seasonality of archaeological site occupation and palaeoenvironmental conditions in both the northern and southern hemispheres (Higham and Horn 2000; Hufthammer et al. 2010). Although preservation in the archaeological record can be quite variable they can provide important seasonal palaeoenvironmental information. At some archaeological sites, only a few otoliths may be recovered, whereas at others large assemblages from multiple species may be present (Gabriel *et al.* 2012; Scartascini and Volpedo, 2013). Their aragonite structure makes them more susceptible to diagenesis than bone in certain burial contexts (Disspan *et al.* 2016). Otoliths can provide several lines of seasonality evidence. First, as many species of fish move seasonally, the presence of otolith of a specific species at an archaeological site shows that people were exploited those species at a particular time of the year. The absence of certain species could however, be due to human choice rather them not being available for exploitation. Second, growth bands in the aragonite structure of the otoliths of temperate species coincide with seasonal variations in environmental conditions. Thus, the season of death and exploitation by humans can be established through examining a cross section of the otolith and recording whether the growth lines at the outer edge represent the faster growing warm season or slower growing cool season (Disspain *et al.* 2016). Third, geochemical analyses such as trace-element and stable isotope analysis of growth increments can be used to provide information on the seasonal changes in environmental conditions during the fish's life and the season of fish exploitation (Andrus et al. 2002; Hufthammer *et al.* 2010; Scartascini *et al.* 2014). Furthermore, advances in high-resolution sampling and in situ analyses are enabling high resolution isotope profiles to be constructed which provide very detailed palaeoenvironmental data (Aubert *et al.* 2012, Disspain *et al.* 2016).

Teeth are readily preserved in the archaeological record due to the high crystallinity and low porosity of enamel hydroxyapatite (Hllison, 2005; LeGeros, 1991), thus offering the opportunity to extract seasonal data from a multitude of locations and time periods (e.g. Balasse et al., 2003; Julien et al., 2012; Hartman et al., 2016; Sharma et al., 2004). The application of stable isotope analysis to enamel ($\delta^{18}O$ and $\delta^{13}C$) and dentine ($\delta^{13}C$ and $\delta^{15}N$) provides seasonal data spatially resolved to the animal's home range, related to seasonal variations in temperature, rainfall, landscape use, vegetation cover, resource competition, and in the case of domesticated animals, human-controlled management practices (e.g. Feranec et al., 2009; Makarewicz, 2017; Nelson, 2005). These archives can therefore provide seasonal climatic and environmental data at spatial-scales relevant to understanding seasonal landscape use and resource exploitation by past human populations. However, understanding the complex, often species-specific tooth formation processes, is key to the interpretation of these geochemical signals and to the development of appropriate sampling strategies. There is an ever-growing body of work that is contributing to this area of research (e.g. Bendrey et al., 2015; Blumenthal et al., 2014; Guiry et al., 2016; Reade et al., 2015; Trayler and Kohn, 2017; Zazzo et al., 2005; 2012). While the geochemical signatures of enamel and dentine are set during the process of tooth growth, which occurs in early life, dental cementum can provide additional end-of-life information. Cementum incremental analysis, or cementochronology, uses the cyclic variations of cementum deposition to provide season of death and age estimations, offering a further proxy to explore the seasonality of human resource exploitation (e.g. Pryor et al. 2016; Jones, 2012; Niven et al., 2012; Schmaus et al., 2018).

Animal bones can provide information on season of animal exploitation and animal management patterns. The presences of animals such as geese and duck, which migrate seasonally, provide evidence that people used an archaeological site at a particular time of the year (Serjeantson 1998; Yeomans and Richter 2018). Age estimate and season of death data can be obtained from foetal bone length, the sequence of epiphyseal fusion of bones, antler casting, tooth eruption sequences, crown height and tooth wear (Carden and Hayden 2015; Speiss 1979; Aaris-Sørensen et al. 2007; Greenfield et al. 2015). Individually these methods have their limitations, for example the epiphyseal fusion of bones does not provide a continuous record of growth once adulthood is achieved (Greenfield et al. 2015). Collectively, however, these techniques can build up a picture seasonality of human resource exploitation at specific sites, and more broadly of human presence or movement within a landscape. Nevertheless season of death determinations rely on the assumption that the timing of conception and birth, and rates of development were the same in past animal populations as today. This may or may not have been the case for wild animals, and in domestic animals season of birth is often manipulated by humans in order to extend the duration of availability of animal resources such as milk and meat (Balasse et al. 2017).

Human and animal hair are formed of the protein keratin. Preservation of hair is best in very arid locations or cool, permafrost environments, and so the recovery of hair from archaeological settings is more limited than skeletal remains. Yet where hair is present its geochemical signatures can provide very high-resolution seasonal data as hair grows rapidly and does not remodel. Mammal hair growth patterns vary between species. Some have cycles of synchronous hair growth followed by seasonal molting, whereas others such as humans have a mosaic pattern of hair growth where different follicles are at different stages of the hair growth cycle (Thompson *et al.* 2015). Carbon, nitrogen, sulphur, oxygen and hydrogen isotopes analyses of sequential hair samples of ancient humans and animals can provide evidence for seasonal changes in diet, mobility, physiological state and climate (O'Connell and Hedges 1999; Iacumin *et al.* 2005; Williams et al 2011; Williams and Katzenberg 2012;

d'Ortenzio et al 2015, Britton et al. 2018). However, determining the geographical movements of an individual or climate variations through stable isotope analysis of hair can be confounded by a number of factors. These include differential incorporation of different elements such as oxygen and hydrogen, and differing seasonal variability in isotope signatures between locations (Reynard *et al.* 2015).

Various floral proxies are available for investigating seasonality of past human activities (Dark 2004). Palynological data may be recovered from contexts ranging from lake sediments (Kealhofer and Penny 1998) to coprolite samples (Reinhard and Bryant 1992; Shahack-Gross 2011) and can provide reconstructions of changing temperature and precipitation seasonality based on the changing vegetation composition through time (Peyron et al. 2011). Meanwhile, size variations in annual growth rings in woody taxa have been widely studied for decades for dendrochronological dating purposes (Schweingruber 1989), yet growth rings also encode useful information concerning seasonality in the proportion of early and late wood in each growth ring (Hughes et al. 2002; Marguerie and Hunot 2007). Alongside dendrochronological applications, growth features in wood and charcoal have therefore been used for seasonal palaeoclimatic reconstruction (Beresford-Jones et al. 2011) and understanding seasonal human activity via reconstructing the felling season of wood (Rocek 1988; Eckstein 2007). Analysis of carbon isotope ratios in fresh and charred plant remains has also been successfully applied in non-archaeological situations to recover useful palaeoenvironmental information (see review in McCarrol and Loader 2004; Bégin et al. 2015), and less commonly to plant remains in archaeological contexts (Voltas et al. 2008; Hall et al. 2008).

3. The papers in this special issue

This special issue brings together some of the latest research on seasonal records from archaeological sites. Methodologically, this special issue encompasses geochemical approaches (stable isotopes, trace elements) as well as growth increment analyses. Some of the papers provide traditional palaeoenvironmental and palaeoseasonality reconstructions, whilst others offer more novel applications including the determination of collection environments. Geographically, the papers cover many regions of the northern hemisphere including North America, Europe and the Levant. The temporal scope of the studies ranges from Palaeolithic to historic times. The archives include mollusc shells, otoliths, plants and animal bones and the environmental proxies include $\delta^{18}O$, $\delta^{13}C$, $\delta^{15}N$, Mg/Ca, and growth increment analyses. This special issue stems from a session entitled "Seasonal palaeoenvironmental records from archaeological sites" held at the XIX INQUA Congress in Japan. The session attracted a wide range of presentations, some of which are included in this special issue, with additional papers arising from an open call for submissions. The papers in this special issue have been organised based on the environmental archives analysed. The first three papers focus on mollusc shell geochemistry (Bosch et al. 2018, this issue; Burchell et al. 2018 this issue; Mouchi et al. 2018, this issue). The next paper focuses on otoliths (Hesler et al. 2018, this issue); whilst the final two papers focus on bones and plants (Shishlina et al. 2018, this issue) and bones (Carlson et al. 2018, this issue).

The first paper in this special issue (Bosch et al., 2018, this issue) uses $\delta^{18}O$ analysis of marine gastropods to investigate the seasonality of shellfish exploitation during the Palaeolithic in the Levant. They focus on the archaeological assemblage from Ksâr 'Akil, revealing year-round use of shellfish resources throughout most of the Upper Palaeolithic, and use this data both as a proxy from the timing of site occupation and in the discussion of seasonal resource exploitation strategies.

Burchell et al. (2018, this issue) reconstruct seasonality of shellfish consumption at an Inuit campsite in southern Labrador using stable oxygen isotope analysis of mussel shells. Their study includes some valuable method development work comparing two different methods for assessing season of death in mussel shells, namely stable isotopes versus seasonal growth line markers based on colour bands in the shell. Their results show that high-resolution isotopic sampling produces the most reliable indicator of season-of-death and thus harvesting seasonality, while the growth marker method failed to produce clear or consistent data and was often inaccurate for the mussel species they analysed. This is despite the fact that colour is a reliable method in other shellfish species in other parts of the world.

Seasonal to sub-seasonal resolution analyses of biogenic carbonates from samples such as mollusc shells and mammalian teeth are useful for distinguishing the different types of environments these were collected from by ancient human foragers (e.g. Andrus et al. 2012). This has the potential to provide an extra layer of detail in the foraging practices of ancient humans. In this issue, Mouchi et al. (2018, this issue) use high-resolution Mg/Ca and stable isotope analyses from oyster shells (*Ostrea edulis*) to provide information on the environments in which the shells grew. They provide constraints on the environment of collection of oyster shells from Gallo-Roman sites in France.

Geochemical analyses of otoliths are being increasingly used to obtain palaeoenvironmental records from archaeological sites (e.g. Disspain et al., 2011; 2016). Helser et al. (2018, this issue) report seasonally-resolved, high resolution measurements of δ^{18}O in modern and archaeological Pacific cod otoliths recovered from the Pacific coast of Alaska. They quantify the relationship between seawater temperature and otolith aragonite δ^{18}O in the modern samples. They then use this relationship to predict the themography of fish life history, enabling estimates of nearshore water temperature for the last 200 years. Their reconstructions indicate significant cooling of ocean waters during the Little Ice Age c. 1810 to 1880, followed by a period of warming over the last 100 years. Helser et al. conclude by linking these changes to cultural transitions and altered settlement patterns visible in the archaeological record of coastal communities.

The impact of seasonal extremes in climatic parameters including temperature and precipitation amount on the isotopic composition of tissues averaged over long time periods is becoming ever-more widely appreciated when interpreting datasets. In another demonstration of this, Shishlina et al. (2018, this issue) combine archaeological and contemporary data to demonstrate the effects of increased seasonality and particularly summer aridity on δ^{13}C and δ^{15}N values of plants and animals in the Bronze and Early Iron Ages of the North Caucasus and south Russian Plain. Variations in the isotopic compositions of contemporary plants between 2006-2015 are linked with changes in summer temperatures showing a particular increase in δ^{15}N values in hotter summers. The impact on drought-intolerant pasture-fed sheep is then presented and the results applied to refine the interpretation of seasonal grazing practises observed among the archaeological pastoral communities.

Finally, Carlson et al. (2018, this issue) use analyses of bison bone as a proxy for environmental change during the Younger Dryas. They found a latitudinal grade of climate intensity occurred across their study area and surmised that droughts occurred during both Bolling/Alerod and Younger Dryas phases.

Conclusion

Climate seasonality significantly influences mean climate and plays a critical role in the interplay between humans and their environment. Robust seasonal-resolution palaeoclimatic and palaeoenvironmental data are important for understanding the Earth's climate system as a whole. Understanding past climate change at seasonal and sub-seasonal resolution allows current and future climate change to be contextualised. These high-resolution palaeoenvironmental records are useful for testing and refining global and regional climate models, enabling a better understanding of the overall climate system and an enhanced ability to predict future climate change. When these seasonal records are obtained from archaeological sites, they enable more robust interpretations of human-environment interaction. Providing environmental frameworks from which to understand the behavioural changes and interactions of past peoples with their environment. Furthermore, many of these palaeoenvironmental proxies along with other floral and faunal evidence preserved in archaeological assemblages also enable reconstructions of seasonal site use, resource use and subsistence patterns. This allows a more detailed and nuanced understanding of past resource use and human-landscape interaction through time, particularly where several different lines of seasonality evidence are studied from a single archaeological assemblage. The contributions in this volume provide several new records of seasonal palaeoenvironment and seasonal resource use directly associated with archaeological sites. These studies provide valuable data that allows a more thorough assessment of the complex interplay between humans and their environment.

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