From isolated data silos to an integrated and multi-proxy regional synthesis
Cyprus in the context of exploring ancient patterns of human-environment-climate interaction

Francesca Chelazzi
From isolated data silos to an integrated and multi-proxy regional synthesis: Cyprus in the context of exploring ancient patterns of human-environment-climate interaction.

Francesca Chelazzi
Department of Archaeology, Durham University

Abstract. Multi-proxy studies aimed at exploring the interaction between human and natural communities are becoming increasingly ambitious in scale. This is due to the recent emergence of spatially extensive open-access datasets and the refinement of advanced computational methods, including statistical approaches for co-analysing archaeological and palaeoecological datasets. In particular, the large availability of open-access data responds to a global effort to promote a large-scale adoption of the Open Science Philosophy, where international agencies and governmental institutions passionately encourage a set of behaviours and codes of practice aimed at increasing data sharing and data reuse. However, in this context, we are left with the question of whether these attempts are matched by effective data sharing and data reuse practices. In this paper, I examine the sharing and reuse, in Cyprus and across the Eastern Mediterranean, of the three main types of datasets traditionally used for understanding the interaction among human and natural communities in ancient times: archaeodemographic, palaeoecological and palaeoclimatic proxies. I also investigate the preliminary results of correlating palaeoclimatic proxies with the pattern emerging from the Summed Probability Distribution (SPD) of radiocarbon dates.

Résumé. Les études multi-proxy pour explorer l’interaction entre les communautés humaines et naturelles deviennent de plus en plus ambitieuses. Cela est dû à l’apparition récente d’ensembles de données spatialement étendus en libre accès et au raffinemen des méthodes informatiques, y compris les approches statistiques pour l’analyse conjointe d’ensembles de données archéologiques et paléo-écologiques. En particulier, la grande disponibilité de données en libre accès répond à l’effort mondial visant à promouvoir l’adoption à grande échelle de la philosophie de la Science Ouverte : les institutions internationales et gouvernementales encouragent avec détermination un ensemble de comportements et de codes de pratique visant à accroître le partage et la réutilisation des données. On se demande cependant, dans ce contexte, si ces tentatives sont accompag-ées de pratiques efficaces de partage et de réutilisation des données. Dans cet article, j’examine le partage et la réutilisation, à Chypre et en Méditerranée Orientale, des trois principaux types d’ensembles de données traditionnellement utilisés pour comprendre l’interaction entre les communautés humaines et naturelles dans l’Antiquité : les proxys

Introduction

Over the past decade, many online infrastructures have been created to share research data in all the major academic fields, including archaeology. Nowadays, data sharing is a word that frequently recurs in academia and policy-making, and the European Commission passionately encourages a set of behaviours and codes of practice contained in the concept of Responsible Research and Innovation (RRI).\(^1\) In the same direction go the auspices of the United Nations Educational, Scientific and Cultural Organization (UNESCO), the Organization for Economic Co-operation and Development (OECD), and a multitude of major and minor international agencies.\(^2\) The FAIR principles (Findable, Accessible, Interoperable, Reusable)\(^3\) are the basis for many international data sharing policies and infrastructures, highlighting the necessity to share data in a format that is understandable by humans and machines, and that can be easily correlated with other similar datasets. While we are witnessing this worldwide effort to promote the large-scale adoption of the Open Science Philosophy, we are left with the question of whether these attempts are matched by effective data sharing and data reuse practices.

It is not my intention to go into detail about the modes and problems associated with data sharing and reuse in archaeology,\(^4\) but it is important to stress that data sharing and data reuse do not entirely overlap as theoretical notions and methodological workflows. As Huggett, Marwich and Pilaar Birch have recently argued,\(^5\) archaeologists are much more likely to transfer digital data to an online repository than they are to use digital data from an online repository actively.\(^6\) While data sharing is increasingly requested by governments, funders and universities (especially in the European community), data reuse consists of a more complex macrocosm of obstacles and issues characterised by the common denominator of lacking motivation and incentive. These complementary stories produce a lost opportunity for advancing knowledge and practice, where data sharing and reuse are addressed separately in research and higher education.

This paper aims to demonstrate that practices of data reuse in archaeology can support a new multi-scalar analysis of different types and sources of evidence, opening up new research avenues that can successfully capitalise on the many legacies that archaeology has produced

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2. See the UNESCO Circular Letter 4363 (UNESCO 2021) or the OECD open research agenda setting (OECD 2017).
5. Huggett 2018; Marwich, Pilaar Birch 2018. See also Moody et al. 2021 for examples of data reuse in archaeology.
over time and that are currently dispersed into a fuzzy cosmos of isolated ‘data silos’. Although this approach can also have a positive impact on areas of archaeology that are “stubbornly intransigent in the face of digital technologies” and still rely on self-directed study (as it frequently occurs with research in material culture, for example), the most significant benefit is over the more science-oriented areas of research. In this respect, one of the most benefitted areas of investigation is the analysis of the long-term relationships between changes in human population, land cover and climate through the integration of sources, including pollen archives, radiocarbon dates, settlement surveys, and palaeoclimatic proxies. In the last decade, many intersectoral academic projects have been commenced, opening up the potential of using a complex array of datasets and models that can be mapped onto each other in order to examine long-term, large-scale trends in different datasets calibrated against each other. All these projects are concerned with regional changes rather than changes on a local scale, due to the necessity to have sufficient data coverage for spatio-temporal modelling.

Although characterised by a general scarcity of locally produced palaeoclimatic proxies and the uneven distribution of radiocarbon dates, archaeobotanical and archaeozoological datasets, Cyprus is liable to be an excellent case study for testing the applicability of a multi-proxy approach on a local scale of analysis for three reasons. First, throughout history, the island acted as a gateway between the Mediterranean world and the major continental regions of Turkey and southwest Asia, and as such the island was an important cultural and economic hub in both ancient and more recent times. Secondly, although Cypriote society successfully endured over the longue durée, it has been constrained by limited natural resources and a fragile environment, entirely reliant on rainfall and made more fragile by an expanding population. These constraints, along with its island setting, provide the perfect conditions for studying the impacts of climate change on its human populations. Thirdly, while the effects of climate change on Cyprus resemble in many respects those in the Near East, local responses to climatic disturbances appear to have resulted in very different cultural trajectories, characterised by a deliberate insular identity even since its formative periods and distinctive for a combination of vulnerability, resilience, and a capacity for transformational adaptation.

**Data sharing and reuse in Cyprus and the eastern Mediterranean**

Before going into detail on the types of proxies available for the island of Cyprus and the principles on which integrative studies in archaeology are based, it is noteworthy that Cypriot archaeology has a notable attitude towards data sharing thanks to the contribution provided

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7 Cherry 2011, p. 12.
8 Bevan et al. 2019 for a general overview about the sources and methods.
9 See the pioneering EUROEVOL Project in Woodbridge et al. 2014; the Changing the Face of the Mediterranean Project in Bevan et al. 2019, or the most recent CLaSS (Climate, Landscape, Settlement and Society) project in Palmisano et al. 2021.
by foreign expeditions working on the island. By contrast, tracking the intensity and frequency of data reuse practices is difficult. Figure 1 displays the density of eastern Mediterranean datasets uploaded on the three main online repositories dedicated to archaeology: the Digital Archaeological Record (tDAR), Open Context and the Archaeology Data Service (ADS). Turkey has the most significant availability of online data from the region, while the intensity of data sharing in other countries varies from archive to archive. This is primarily affected by the degree of involvement of foreign expeditions, mainly American and British, in the archaeology of the various regions, and the case of Cyprus is highly significant in this regard.

Among the three examined online repositories, the Cypriot datasets are mainly uploaded to the ADS archive due to the long-term engagement of Anglo-Saxon universities in the archaeology of the island. This archive contains the fully available datasets from the archive report for excavations at Kissonerga-Mosphilia 1979-1992, Kissonerga-Mylouthkia 1979-1996 and Souskiou-Laona 1992-2019 by the Lemba Archaeological Project of the University of Edinburgh, as well as the datasets produced by the Sydney Cyprus Survey Project and the Troodos Archaeological and Environmental Project of the University of Glasgow. Likewise, the datasets uploaded to the American Open Context come from American projects, such as the excavations at Polis (Princeton University) and Idalion (Lycoming College) or the Pyla-Koutsopetria Archaeological Project (University of North Dakota, University of Pennsylvania and Messiah College).

The same macro-division between American and English archives can also be detected in other eastern Mediterranean countries. In Syria, the American Northern Mesopotamian Pig Husbandry Project (Massachusetts Institute of Technology) is uploaded on OpenContext, while the British Dayr Mar Alian Archaeological Project (University of Exeter) is stored in the ADS

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**Figure 1** — Density of shared datasets across the eastern Mediterranean: a) the Digital Archaeological Record (tDAR) archive; b) Open Context; c) the Archaeology Data Service (ADS) archive. The dark areas are where more datasets are available; conversely, the lighter areas are where fewer datasets are available. White areas have been not reviewed in this study (DEM ©SRTM NASA).

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11 Respectively Knapp, Given 2003; Given et al. 2007.  
12 Smith 2017; Gaber 2019; Caraher, Moore, Pettigrew 2013.
Similarly, in Egypt, the American ARCE Sphinx Project (Oriental Institute of Chicago and Harvard Semitic Museum) is stored in OpenContext. In contrast, the British archaeological and geological survey at the Royal City of Sais (Durham University) is stored in the ADS archive.

While this enduring localism in the distribution of datasets leads us to reflect, it can be argued that archaeologists working in Cyprus, generally as members of foreign expeditions, have a good attitude toward sharing their data compared to the trend detected in the surrounding countries. This argument is valid for entire datasets from individual projects, but the custom of sharing data on the main thematic online archives is pretty different.

When available online, material culture is usually published as a digital version of the traditional site publication forms. There are some exceptions to this rule, such as for example the Levantine Ceramics Project or the prototypal ceraDAT database, but these datasets are generally aimed at storing chemical, petrographic and mineralogical data. An attempt to determine, integrate and compare the typo-chronology of pottery finds is represented by the excavations-based Data Atlas of Byzantine and Ottoman Material Culture project, which includes Medieval and post-Medieval ceramics from Albania, Greece and Turkey.

A step further in the perspective of storing, integrating and analysing digital archaeological data is represented by the Online Cultural and Historical Research Environment (OCHRE) by the University of Chicago. This platform includes a suite of computation tools for managing and analysing research data. This is a step further in engaging with the entire data cycle because the infrastructure aims not only at integrating and semantically linking dispersed datasets through externally controlled vocabularies but also at supporting data analysis through several built-in R functions made available to scholars via pre-written R packages.

In the same perspective of providing archaeologists with a virtual research lab is situated the ARIADNEplus infrastructure, which consists of an online catalogue which integrates and indexes archaeological datasets that are currently dispersed across the many archaeological data repositories in Europe, from big repositories such as ADS to small local projects such the Cypriot Medieval Coins History and Culture digital library. This infrastructure is equipped with a set of analytical tools (ARIADNEPlus_lab), visualisation services (Visual Media Service and EpHEMERA) and an assortment of web services in the realm of landscape research (Landscape Service).

In the following paragraphs, I intend to examine the three main types of datasets traditionally used for understanding the interaction among human and natural communities in ancient times: archaeodemographic, palaeoecological and palaeoclimatic proxies.

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15 Berlin 2021.
16 Hein, Kiliakoglou 2012.
17 Vroom 2017.
19 Richards, Nicolucci 2019.
Theoretical and methodological foundations of multi-proxy research on demography and climate

Before going into detail on the types of proxies available for the island of Cyprus and their characteristics, it is necessary to spend a few words on the principles on which integrative studies in archaeology are based, their benefits and their requirements.

A recent web-based survey across the archaeological community of North America and Europe has revealed that many of the “problems of broad scientific and social interest that could drive cutting edge research in archaeology for the next decade and beyond”\(^{20}\) are pivoted around the understanding of how human and natural communities interacted in the past, how past landscapes were redesigned by patterns of spatial and material reconfigurations, and how local environments shaped cultural practices, subsistence modes, ritual experiences and socio-political relationships. A sign of this increasing interest in the interaction between natural ecosystems and anthropogenic activities is the rising number of dedicated sessions at the most important international conferences in archaeology which have been organised to increase awareness and develop the necessary theoretical and practical instruments.\(^{21}\)

One of the ‘great’ historical questions that archaeology has been trying to answer in the last years is “what factors have enabled some societies to be resilient to a changing climate while others are not?”\(^{22}\) with all its possible time- and space-related manifestations. Obviously, this question is not a new invention, and archaeologists have always been interested in understanding the mechanisms through which past societies, with varying degrees of social complexity, have developed successful practices of adaptation, resilience, transformation or vice versa collapse.\(^{23}\) In recent years, however, the instruments to answer this question have evolved rapidly, particularly concerning the creation of spatially extensive open-access datasets and the refinement of advanced computational methods. Computational automated workflows, agent-based modelling, machine learning, semantic data modelling, and statistical approaches for co-analysing different types of Big(ish) Data\(^{24}\) have created the basis for elaborating increasingly refined analytical models and expanding our toolbox in the field of integrative studies.

In the last decade, a multitude of multi-proxy studies has been commenced to explore the complex networks of interactions throughout the ecosystems by gaining a more comprehensive

\(^{20}\) Kintigh 2013, p. 1; see also Kintigh et al. 2014.
\(^{21}\) See for example the impressive quantity of sessions at the 2021 European Association of Archaeologists (EAA) conference, where one of the themes of the meeting was “widening horizons through human-environment interconnections”.
\(^{22}\) Lawrence 2018.
\(^{23}\) For the recent wave of collapse studies, see McAnany, Yoffe 2009; Cumming, Peterson 2017. For earlies studies see for example the seminal works of Tainter 1988; Yoffe, Cowgill 1988. See Middleton 2017 for a recent overview on collapse and resilience in 21st-century archaeology. See also Gunderson, Holling 2002 for the Theory of Adaptive Change.
\(^{24}\) For a discussion of the big(ish) nature of archaeological data see Huggett 2016.
overview of the situation than could be achieved from a single proxy. In the following paragraphs, I will assess the different potential sensitivities of the three major proxies in human-environment-climate interactions studies, from the spatially and chronologically uneven distribution of radiocarbon dates to the many factors affecting δ¹⁸O values in paleoclimatic proxies.

Several examples of successful multi-proxy studies prove the benefits of this approach, not only in the realm of archaeology but also in the natural sciences. When exploring the interaction between humans and natural communities in antiquity, we can rely upon multiple lines of evidence for tracing the various aspects of past ecosystems, improve our capacity to distinguish between climate-driven and human-driven changes to the environment, and develop an archaeology-based understanding of impact and adaptation.

As Birks and Birks argued, one of the significant challenges in multi-proxy research is avoiding the ‘reinforcement syndrome’ and the tendency to adopt a ‘confirmatory’ approach. There is a general tendency, often subconscious, to try to match small changes (signals) in proxy data to fit or confirm the current paradigm and ignore other larger patterns (noise). This may lead to emphasising the confirmatory results and ignoring the non-confirmatory results. In this sense, contradictions or anomalies can raise new productive research questions concerning both the appropriateness and calibration of the existing datasets and methods, or the ecological significance of the anomalies themselves.

From the 1970s onwards, an impressive amount of archaeological data has been generated due to the popularisation of equipment and instruments for both survey and laboratory activities. A significant example is the archaeological survey practice, which has a well-established tradition within Mediterranean archaeology, providing a remarkable quantity of local datasets that still need to be integrated into a broader understanding of past landscapes. While the awareness of the technological potential of archaeology has prompted the archaeological community to develop the necessary theoretical and practical instruments under the impetus of a certain ‘technological fetishism’, there is no doubt that their scope and usage are currently more essential than ever. This is not only a theoretical matter but also a practical necessity as urban and rural development is utterly transforming our tangible and intangible heritage, and frequently the only legacy at our disposal is a heterogeneous corpus of old reports, surveys, excavations and casual discoveries.

This poses new questions regarding the quality and reliability of the data at our disposal, especially where important datasets were collected a long time back without advanced technological instruments or advanced archaeological knowledge. While nowadays we can date

26 Gehrels, Roe, Charman 2001; Charman, Chambers 2004; Finkelstein, Peros, Davis 2005.
27 Birks, Birks 2006, p. 238.
29 See the definition of ‘signal’ and ‘noise’ in Birks 1998.
entire archaeological sequences through a few charcoals or grams of bones with a few hundred euros, for many decades our dating methods were based on relatively fine-grained sequences of ceramic wares or other classes of material culture. In the same way, our understanding of space benefited from an ever-increasing ability to place objects in their correct geographical position with low-budget technologies. For many decades the archaeologist’s backpack was filled with heavy stacks of papers, maps and reliefs (often measured with questionable accuracy and highly susceptible to the surveyor’s or excavator’s abilities), but nowadays Global Positioning System (GPS) devices, unmanned aerial vehicles (UAV), laser scanners and other tools allow anyone to acquire and record an impressive amount of data with minimal effort.

In this respect, the new wave of integrative studies is characterised by an overall bipolarity of legacy data: on the one hand, an impressive amount of past data which are not easily standardised and transformable into a machine-readable format, and on the other hand an even more significant amount of present fine-grained data that are equally difficult to contextualise. This is not the place to enter into detail on the problems associated with the accuracy, precision and reliability of archaeological legacy data, particularly when considering that archaeology still largely relies upon ceramic typologies. What is certain is that this impetus towards new ground-breaking integrative studies progresses on a highly slippery ground, composed of numerous and heterogeneous data silos that it would be risky to compare with the same degree of confidence.

Demography and climate: proxies from Cyprus and the eastern Mediterranean

The sources of archaeological data are numerous and extremely scattered, including monographs and articles in scientific journals, archives of governmental institutions, online repositories, and grey literature. While the problems associated with monographs and articles, central archives and grey literature are strongly dependent on the country in which the archaeological evidence is located and the research team, the question of online repositories deserves dedicated attention.

In general, digital archaeological data have dramatically increased in the last decades, whether uploaded to online public archives or stored in the private archives of various archaeological projects. The common denominator in this microcosm of isolated data silos is the extreme variability of legacy data in content and output format resulting from several factors, some of which are not always identifiable. Firstly, the scientific interest of the collector and research team, and their scientific background, which result in multiple sources of accuracy and resolution, both spatial and temporal. Secondly, the more general archaeological knowledge in the data collection and analysis period can also be the cause of the variable precision of the input data (e.g. the relative chronologies based on pottery and other artefacts). Other factors affecting

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31 For a critique to the prevailing localism of landscape archaeology studies see Blanton 2001.
32 For a preliminary review see Crema 2012, Bevan et al. 2013a, Bevan et al. 2013b.
33 See the critique in Given 2003.
the variation in data outputs are the scale of the project, the complexity of the archaeological record, the adopted methodology, the available equipment, the resource availability, and the post-collection degree of data manipulation. While standards and guidelines for acquiring, storing and preserving digital data have been established, these are more readily applicable in ongoing projects rather than in legacy data retrospectively.

From a general point of view, the online repositories hosting entire datasets from individual projects require variable levels of data standardisation, from low control policies (tDAR) to a minimum degree of standardisation in output formats (ADS) up to the compliance with controlled vocabularies (Open Context). The situation is different when it comes to the online thematic archives, created with the purpose of aggregating scattered pieces of information on a specific topic and thus demanding a greater level of data standardisation. Online archives such as the Near East Radiocarbon Dates (NERD) archive, the Archaeobotanical Database of Eastern Mediterranean and Near Eastern Sites (ADEMNES) and the Speleothem Isotopes Synthesis and Analysis (SISAL) database are designed according to an internal standardisation based on a limited list of attributes that can work well in each data silos. Other online infrastructures, such as the Paleo Data Search portal of the US National Centers for Environmental Information (NOAA), are flexibly designed to accommodate several archives and allow users to query datasets from separate publishers (e.g. NOAA/WDS, Neotoma, Pangea). Some of these online infrastructures are designed to perform advanced search activities to maximise data queries, while others have simple functions for data mining. Some online infrastructures provide users with internal analytical tools, while others offer data and metadata download functions. In the following paragraphs, I examine and discuss the datasets from Cyprus and the eastern Mediterranean that are stored in the most important online archives dealing with the interaction between human and natural communities in the face of climate change, namely the NERD, SISAL, NOAA and ADEMNES archives (fig. 2). It is indisputable that much archaeology, particularly the impressive quantity of legacy data collected throughout time, stem from the humanities tradition and it generally consists of non-digital grey literature. The problems related to data comparability are rooted in the broad spectrum of intellectual histories and theoretical backgrounds, as well as the varying data collection methodologies.

ARCHAEODEMOGRAPHIC PROXIES

Archaeodemographic modelling is generally based on combining and comparing several population proxies to cope with the many sources of bias that each methodology encompasses.

36 See for example the online tools for calibration, modelling and Bayesian analysis provided by OxCal4 (Bronk Ramsey 2001, Bronk Ramsey 2009), or the already discussed OCHRE and ARIADNEplus infrastructures.
37 For the problems associated with chronological uncertainty in survey data, see Palmisano, Bevan, Shennan 2017.
Traditional techniques inferred from archaeological survey data (e.g. raw site counts, aoristic sum, randomised site start date and duration, estimated settlement size) are usually compared to explore spatial and temporal patterns in changing population densities. However, many of these techniques require the availability of survey data accompanied by the almost complete set of traditional information associated with site-based data, including the estimated site size and a certain chronological granularity. These attributes are not regularly published in the literature and are usually not accompanied by the precise positioning of the mapped evidence.

An additional technique has been tested and adopted to infer archaeodemographic patterns from radiocarbon dates in the last decade. The Summed Probability Distribution (SPD) of radiocarbon dates is rooted in the assumption that “the more people living in a given region, the more garbage, the more organic materials, the more radiocarbon collected and dated.”\(^{38}\) This technique is not exempt from sources of bias,\(^{39}\) including the possible over/underestima-

\(^{38}\) Rick 1987, quoted in Palmisano et al. 2021, p. 6.

\(^{39}\) Summary in Crema, Bevan 2021; Williams 2012.
tion of population density in some areas or periods due to a certain degree of temporal uncertainty and the uneven distribution of radiocarbon samples in space and time. This problem is relevant mainly for the pre-classical periods because later periods are characterised by the general absence of radiocarbon dates and rely almost exclusively on the traditional typo-chronologies. On the other hand, extensive open-access datasets (e.g. OxCal, Radon, Bandora, CalPal, EuroEvol) allow a quick application of this technique across the ancient Mediterranean region, and several studies have already demonstrated its utility in inferring past population trends.40

However, a certain amount of criticism towards the SPD has emerged in the last decade, along with the increasing application of this technique in archaeology. The principal scepticism concerns the use of radiocarbon ‘dates-as-data’,41 as proxies for event counts in point-wise comparisons. Through the comparison between SPD (function) and partially-Bayesian kernel density estimation42 (KDE), Carleton and Groucutt43 emphasise that our qualitative assessment of through-time variations (i.e. point-wise comparisons) suffers from the effects of chronological uncertainty. The main critique, in fact, is that SPD conflates the density of our dates with uncertainty about their temporal positions. The second point of criticism concerns the sensitivity of the method itself and, in particular, the problems related to the strength of the signal in demographic fluctuations, which influences the detection rate. The greatest objection is that this might lead to false-positive signals resulting exclusively from the random distribution of the data and not from any ‘real’ underlying pattern.44 In order to minimise the false-positives problem, the Monte Carlo simulation method is traditionally used, and it consists in the production of simulated data distribution under an adjusted null mode.45 The third source of criticism relates with the impact of taphonomic bias in estimating frequency distributions, including taphonomic loss, discovery bias and scientific bias.46 As far as the application of SPD in archaeology, the criticisms focus on the factors affecting the visibility and level of preservation of the archaeological record.47 Additional skepticism concerns the effects that the different C14 calibration curves have on SPD,48 the problems resulting from the internal chronology of archaeological sites49 and the issues associated with the character of past human

41 See the title of the original Rick 1987 paper.
43 Carleton, Groucutt 2021.
44 Hinz 2020; Contreras, Meadows 2014.
45 Shennan et al. 2013. This method has been recently refined to tests specific population trends from small sample sizes and short duration events, on the order of 100-200 years: see Edinborough et al. 2017.
46 Ballenger, Mabry 2011; Surovell, Brantingham 2007; Surovell et al. 2009.
47 Prates, Politis, Steele 2013; Williams 2012. For the taphonomic problems associated with the use of SPD in geomorphological studies see Bleicher 2013; Chiverrell, Thorndycraft, Hoffmann 2011.
48 Bamforth, Grund 2012; Williams 2012.
49 Crombé, Robinson 2014.
activity, including settlement patterns, subsistence strategies, depositional practises, and dietary customs.\textsuperscript{50}

In the last five years, the Near East Radiocarbon Dates (NERD) archive was prepared under the umbrella of the projects “Changing the Face of the Mediterranean: Land Cover and Population Since the Advent of Farming” and “CLaSS – Climate, Landscape, Settlement and Society: Exploring Human-Environment interaction in the Ancient Near East”. The archive is the largest existing repository of uncalibrated radiocarbon dates from the region, and it covers an extensive time span lasting from the Late Pleistocene to the Late Holocene (15000-1500 cal. BP).\textsuperscript{51} The archive is based on the review of multiple sources, including digital databases, journal papers, volumes and excavation reports. It includes 11027 radiocarbon dates from 1023 sites, including 494 dates from Cyprus (fig. 3, left). The total number of radiocarbon dates from Cyprus largely satisfies the sample size of 200-500 dates to produce a reliable SPD within a time interval of 8000-1000 years.\textsuperscript{52} Additionally, it should be noted that the number of existing radiocarbon dates is undoubtedly higher than 500 because the NERD archive needs to be updated with the new dates from Chlorakas-Palloures, Hala Sultan Tekke and Pyla-Kokkinokremos.\textsuperscript{53}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Distribution of the NERD radiocarbon dates (left) and the ADEMNES archaeobotanical and archaeozoological datasets (right) from the main countries in the eastern Mediterranean. The dots indicate respectively the density of dates per site and of sites with datasets per 100 sqkm (data from the NERD archive).}
\end{figure}

\textsuperscript{50} Torfing 2015.
\textsuperscript{51} A review of the available data is provided in Palmisano et al. 2022.
\textsuperscript{52} Michczyńska, Pazdur 2004; Michczyńska, Michczyński, Pazdur 2007.
A preliminary review of the materials analysed for radiocarbon dating (fig. 4, left) reveals that the majority of the Cypriot dates come from charcoals (56.0%) and seeds (21.9%). This pattern is in line with the trends across the main eastern Mediterranean countries, where the dates obtained through the analysis of charcoals account for more than 50%. The dates from seeds, grains, and organic materials are highly variable across the analysed countries. They are very popular in Israel (45.2%) and Syria (36.5%) but rare in Egypt (5.3%). Animal bones, frequently characterised by a very poor preservation state, are generally underutilised for radiocarbon dating (1.3-12.1%), as well as the other analysed typologies of material.

Interesting insights come from the analysis of the temporal distribution of the available radiocarbon dates. Fig. 4 right displays the subdivision of available dates according to a very schematic periodisation to simplify the analysis, as it is not the primary goal of this paper to describe in detail the chronological problems of the different countries (Pre-Neolithic: pre 10,000 cal. BC, Neolithic: 10th-6th millennium cal. BC, Chalcolithic: 5th-4th millennium cal. BC, Bronze Age: 3rd-2nd millennium cal. BC, Iron Age: 1st millennium cal. BC, Roman and Byzantine periods: 0-600 cal. AD).

As expected, a significant number of radiocarbon dates comes from sites dated to the 10th-6th millennium cal. BC, not only in Cyprus (39%) but also in Jordan (28%), Syria (46%) and Turkey (37%). In many of the reviewed countries, the vast majority of the radiocarbon dates was collected at Bronze Age sites, with remarkable rates in Cyprus and Egypt (47%), Lebanon
It is interesting to note that the availability of dates belonging to the 1st millennium cal. BC is extremely variable in space, where some countries are characterised by a very low number of dates (Cyprus, Syria and Turkey), while others have an extensive record (Israel, Palestine and Jordan). This is certainly due to the numerous excavations at the main cities of the Iron Age Kingdoms in the Levantine region. For instance, Tel Rehov and Tel Dan in Israel, Khirbat en-Nahas and Tell es-Sa’idiyeh in Jordan have been excavated employing an intensive and systematic strategy for radiocarbon dating. Eventually, the contexts with radiocarbon dates belonging to the Roman and Byzantine periods are very scarce, as archaeologists usually tend to rely on ceramic dating methods. These dates mainly come from Jordan and Israel, and they respectively result from the consistent amount of samples from the ship in the Dor/Tantura Lagoon, and the extensive excavation of Petra and Jerash.

As for the character and distribution of the radiocarbon dates on the island of Cyprus, the main point that emerges from this review is the uneven distribution of dates in space and time. Some regions of the island lack a significant collection of dates (i.e. the North and the Troodos), while other areas are probably overrepresented due to the presence of important clusters of analysed samples. It should also be noted that from 4000 cal. BP onwards, the SPD analysis underestimates accurate population levels as archaeologists rely increasingly on ceramic dating methods. This distributive aspect suggests that some caution is necessary for data interpretation from SPD analysis, particularly to infer regional patterns in archaeodemography. On the other hand, its validity on a super-regional scale was largely demonstrated by analogous multi-proxy studies coupling SPD with other archaeology-inferred techniques.

The preliminary processing of the NERD radiocarbon dates from Cyprus is displayed in fig. 5, which includes the result of the Summed Probability Distribution of radiocarbon dates from 15000 to 0 cal. BP. The model was processed through rcarbon, which is an R package for the analysis of extensive collections of radiocarbon dates. The available dates have been calibrated using the IntCal20 curve and aggregated by creating artificial bins (cut-off value of 100 years) to mitigate the effects of the strong inter-site variability in sample size. The grey shaded region represents a critical Monte Carlo envelope encompassing the middle 95% of the simulated SPDs, with red and blue areas highlighting portions of the SPD where positive and negative deviations are detected.

For a rough estimation of the radiocarbon dating from these sites, refer to Van Der Plicht, Bruins, Nijboer 2009; Hinz et al. 2012; Higham et al. 2005; Weinstein 1984. See respectively Carmi, Segal 1995; Saliège et al. 2013; Lichtenberger et al. 2015. See, for example, the overestimation of the Neolithic and Late Bronze Age population size in the south-east due to the impressive number of dates from Parekklesia-Shilloourokambos (52), Kalavasos-Tenta (18), Kalavasos-Agios Dimitrios (18) and Maroni-Tsaroukkas (24). Conversely, the Chalcolithic population size in the region of Paphos is probably overestimated due to the clusters of dates in Lembas-Lakkous (17), Kissonerga-Mosphilia (29) and Kissonerga-Mylouthkia (14).


One of the principal online repositories for archaeobotanical and archaeozoological data is the Archaeobotanical Database of Eastern Mediterranean and Near Eastern Sites (ADEMNES), created between 2010 and 2015 by the University of Tübingen, and currently updated by the University of Durham. The database aims at storing these two ecological proxies from several countries in the eastern Mediterranean and the Near East. The ADEMNES infrastructure includes 18 datasets from Cyprus, of which only one pertains to the ancient fauna (from

**Figure 5** — Top: the five selected palaeoclimatic proxies relatable to Cyprus (data from the NOAA and SISAL archives). Bottom: Summed Probability Distribution (SPD) of unnormalised calibrated radiocarbon dates (solid line) compared with a 95% Monte-Carlo confidence (grey envelope) of population growth (data from the NERD archive).

**PALAEOECOLOGICAL PROXIES (ARCHAEOBOTANY AND ARCHAEZOOLOGY)**
Kissonerga-Mylouthkia). It should be noted that the number of available datasets is indeed higher than 18, as a preliminary review of the published literature indicates that 19 excavated sites on the island yielded archaeobotanical samples, 11 sites archaeozoological data, and both archaeobotanical and archaeozoological data have been collected at 13 sites.

This means that only a tiny percentage of the datasets from Cyprus is currently uploaded to the primary scientific open-access repository in the field. Although this infrastructure is not aimed at being complete and exhaustive, it should be noted that less than half of the published datasets (41.9%) from Cyprus is included in the database at the moment. And a similar estimate can likely be made for the other countries included in the repository. Interestingly, most of the data currently stored (fig. 2b) comes from Turkey (102 datasets) and Israel (85 datasets), where many archaeological expeditions are based on a multi-disciplinary design, including specialists in the field of archaeobotany and archaeozoology (two examples are the large and multi-disciplinary teams of the Megiddo Expedition and the Çatalhöyük Research Project). If we consider the size of the main eastern Mediterranean countries included in the repository, it is interesting to note that Cyprus is one of the best-represented countries in terms of the density of datasets. Excluding the case of Israel (0.41 datasets per 100 sqkm), Cyprus is the country with the highest density of ecological proxies (0.19 datasets per 100 sqkm), followed at a great distance by Greece (0.05) and Jordan (0.049). Although the infrastructure needs to be integrated with all the site data available from Cyprus, the island appears to be one of the relatively best-represented countries in terms of archaeobotanical and archaeozoological datasets.

A source of valuable information is constituted by the fossil pollen archives from sediment cores that provide continuous data to map long-term vegetation change. Three pollen cores have been analysed in Cyprus: one continuous core in the Larnaka Salt Lake and two peat cores from the Troodos area, sampled in the localities of Almyrolivado and Pasa Livadi. The cores have a very heterogeneous spatial distribution and lack a consistent temporal overlapping. The chronological sequence from Almyrolivado starts at 7772 cal. BP and ends at 2893 cal. BP, the Pasa Livadi core starts at 3347 cal. BP and ends at 1409 BP, while the sedimentary sequence from the Larnaka Salt Lake starts at 3290 cal. BP and ends at 820 cal. BP. Although the last two datasets partially overlap, their very different spatial location makes any pollen-inferred land cover model highly unreliable.

Despite this, these available datasets are valuable for understanding the possible impact of some broader climate and vegetation changes on the island. A significant example is the reduction of forest vegetation pollens recorded at 5000-4500 cal. BP in the core at Almyrolivado (Zone III), which coincides with a progressively drier climate during the Chalcolithic period, as inferred from the available proxies at Gölhisar Gölü, Jeita Cave and Soreq Cave. Similarly, the fall of dinoflagellate cysts and *Posidonia* fibres in the sedimentary sequence of the Larnaka

59 Fyfe, Woodbridge, Roberts 2018; Woodbridge, Roberts, Fyfe 2018.
60 Kaniewski et al. 2013.
61 Christodoulou 2015.
Salt Lake at 1450-1350 cal. BC suggests a shift from sheltered marine to lagoonal environments, which finds consistent comparisons with the climate proxies from the Soreq and Jeita Caves.

**PALAEOCLIMATIC PROXIES**

While Cyprus lacks natural palaeoclimatic archives, important insights about the climatic conditions on the island during the Holocene can be inferred from palaeoclimatic proxies collected in the nearby regions, including the Levant and Anatolia. Palaeoclimatic proxies are archives reflecting past hydro-climatic patterns which are traditionally based on the analysis of stable oxygen isotope ratios ($\delta^{18}O$) from stalagmites or lake sediments. In the semi-arid regions of the eastern Mediterranean, precipitation levels are believed to correlate with vegetation and surface water availability. Stable oxygen isotopes from stalagmites and lake sediments are generally used as reliable hydrological indicators due to their fine-grained temporal resolution, which is based on radiocarbon or uranium-series dating methods. Lower and higher values of $\delta^{18}O$ indicate respectively wetter and drier climatic conditions. However, it should be remembered that $\delta^{18}O$ values can be affected by several environmental factors, including vegetation and open water evaporation. Additionally, the $\delta^{18}O$ of the speleothem calcite is considered by many scholars to represent the precipitation amount of the winter season rather than the average annual precipitation. Conversely, $\delta^{18}O$ values from lake carbonate are believed to correlate with hydroclimate conditions during the summer.

Palaeoclimatic proxies collected and analysed on the island do not exist so far, but there are useful stable oxygen isotope ratios measured from stalagmites and lake sediments in the surrounding area, from the Levant and South Anatolia. Table 1 shows the eleven proxies located around the island of Cyprus, of which raw data are available in the NOAA and SISAL online archives. Their temporal resolution is variable, embracing a wide time span from the Late Pleistocene to the Holocene. Among the available proxies, five are particularly important for their chronology covering the Holocene period: Dim Cave, Jeita Cave, Jerusalem West Cave, Soreq Cave and Lake Hula. The first two proxies have a fine-grained chronological resolution, while the remaining three have large sampling intervals.

Although there is a lack of palaeoclimatic proxies directly collected on the island, the contribution provided by the nearby proxy data is essential for understanding the palaeoclimatic conditions in the eastern Mediterranean, especially from the perspective of a multi-proxy analysis. Figure 5 shows the correlation between hydro-climatic conditions and the results of the SPD analysis in the period from 15000 cal. BP to today. While palaeoclimatic data are also available for the post-Medieval period thanks to the stable oxygen isotope ratios from Jeita

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63 Kaniewski et al. 2013, fig. 3.
The SPD pattern is marked by an early significant positive deviation at 14907-11735 cal. BP, which relates to the first arrival of human communities on the island. Palaeoclimatic data indicate that this period was generally warm and moist (14700-12700 cal. BP, the Bølling-Allerød interstadial), followed by a drying and cold climate during the Younger Dryas (12700-11700 cal. BP); 67 this climatic change is well visible from the Dim and Jeita caves proxies.

Throughout the Aceramic Neolithic, the SPD analysis indicates several episodes of demographic growth that probably correspond with repeated landings of newcomers during the PPNA and PPNB, as well as a general economic improvement due to the translocation of new plants and animals. 68 During this period, palaeoclimatic proxies suggest favourable climatic conditions in the regions around Cyprus and, probably, also on the island.

Concomitantly with the 8.2k cal. BP event, 69 stable oxygen isotope ratios from Jeita Cave, Jerusalem West Cave and Soreq Cave suggest a period characterised by increasingly low temperatures and aridity. In the same period, the archaeodemographic pattern is marked by a

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67 Dean et al. 2015, Roberts et al. 2008.
68 Simmons 2011.
general decrease in the Cypriot population size, and several negative deviations are identified during the first half of the Ceramic Neolithic (7868-7795 cal. BP, 7791-7783 cal. BP, 7781-7769 cal. BP, 7612-7391 cal. BP).

The Chalcolithic period was characterised by a persisting arid climate, punctuated by even drier periods (at around 6000 cal. BP), as suggested by the palaeoclimatic record from Jeita Cave. Unsurprisingly these climatic conditions coincide with a low demographic rate and also a possible demographic decline that probably relates with a phase of agricultural de-intensification. From the Late Chalcolithic onwards, the population size increased again, coinciding with an increase in crop cultivation and caprine husbandry.

During the Bronze Age, the population size of Cyprus expanded progressively, with significant positive local deviations at 3965-3878 cal. BP and 3393-3049 cal. BP. It should be noted that the SPD peak at 3500-3000 cal. BP is probably the result of an overestimation of the demographic pattern due to the large number of radiocarbon dates from several Late Bronze Age excavations, including Kalavasos-Agiós Dimitrios, Hala Sultan Tekke, Maroni-Tsaroukkas and Maroni-Vounres. Interestingly, the SPD pattern does not indicate any consistent population decline in correspondence with the 4.2k cal. BP event, although different impacts probably characterised this event according to the local conditions.

As regards to the Late Bronze Age societal ‘collapse’, archaeodemographic data are complex and difficult to read. The changing climatic conditions at the end of the Late Bronze Age are visible in the measured ratios of $\delta^{18}$O from the Jeita Cave and reflected by the pollen-derived clusters from the Larnaka soil core. Nevertheless, any correlation with the archaeodemographic pattern would be strongly distorted by the uneven temporal distribution of radiocarbon dates on the island, which is strongly biased by a general lack of $^{14}$C dates in the Iron Age era.

**Conclusions**

In the last decade, the availability of spatially extensive open-access datasets and the refinement of advanced computer methods have enabled archaeologists to engage with a new season of multi-proxies studies to explore the interaction between humans and natural communities in the face of climate change. The immense archaeological legacy can now be synthesised and co-analysed through new and sophisticated analysis techniques to understand how the environment and human communities are interconnected, co-dependent, and profoundly entangled. New techniques, such as the Summed Probability Distribution of radiocarbon dates, can produce archaeodemographic models even where past survey data are hard to standardise and transform into machine-readable formats.

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71 Lucas, Fuller 2020.
72 See Lawrence, Palmisano, De Gruchy 2021 for its impact in the Fertile Crescent; see also Manning et al. 2020 for the varying impact of this event on the different regions of the eastern Mediterranean.
73 Comparative cases in Palmisano et al. 2021.
The archaeological legacy data collected on the island of Cyprus in the past decades provide a solid basis to take the first steps into this broader process of multi-proxy analysis, but some gaps still remain. Firstly, no palaeoclimatic proxies have been collected on the island directly, and the only local data consist of three pollen cores from Larnaka and the Troodos. In addition, the amount of archaeobotanical and archaeozoological datasets freely available online is limited, and their reliability is strongly affected by varying methods of data collection and analysis. A few archaeological surveys are in progress on the island; the successful 1990s season of surveys today has almost vanished, and the very patchy coverage of survey data indicates that we still have a lot to learn about some Cypriote regions.

In spite of this, some preliminary analysis can be performed from a multi-proxy perspective, including the correlation between palaeoclimatic and archaeodemographic patterns. As argued in this paper, interesting assumptions can already be formulated based on the pattern emerging from the Summed Probability Distribution (SPD) of radiocarbon dates. Its timing, and the possible occurrence of episodes of decline or growth in the Cypriot population size in correspondence with the varying hydro-climatic conditions, can provide new insights for exploring the complex interaction between humans and natural communities on the island.
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