From the Last Glacial Maximum to the Late Holocene: Unraveling the dynamic complexities of climate and human history in Western and Southeastern Iran

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Since the early Neolithic (~10,000 years ago), the Iranian Plateau has witnessed the development of sedentary human settlement facilitated by periods of favorable climatic conditions prompting gradual or sweeping changes. Climate factors significantly drove the hydroclimatic conditions in western and southeastern Iran, which varied in response to the Mid-Latitude Westerlies (MLW) and Indian Summer Monsoon (ISM). In addition, the input of dust and its eastward transport from the Arabian Peninsula and North Africa coincided with the North Atlantic cooling events. Peak wet conditions during the early Holocene in southeastern (c. 11.4−9.6 ka BP) and western Iran (c. 10.2−8.6 ka BP) indicate different timings in regional precipitation. The northward displacement of the Intertropical Convergence Zone at the beginning of the early Holocene caused the ISM to expand over southeastern Iran. At the same time, it strengthened the sub-tropical high-pressure and northward expansion over western Iran, resulting in dry conditions. Between 7.8 and 6.3 ka BP, gradual weakening and southward movement of the ISM and the decrease in intensity of the subtropical high-pressure systems over the Zagros region resulted in southeastern Iran becoming mild and the western region humid. Between 6.3 and 5.0 ka BP, a decrease in solar insolation ushered dusty and arid conditions on the Iranian plateau. Notably, human activities in the region started experiencing significant changes around the mid-Holocene. A concurrence exists during the wet (c. 5.0−4.5 ka BP) and dry (c. 4.2−3.2 ka BP) periods, coinciding with the rise and decline of multiple Bronze Age settlements. These settlements flourished in exchange and trade, pyro-technologies, and agro-pastoral production, demonstrating an increasing complexity in social organization and vulnerability to climate change. After transitioning into the Iron Age, southeastern Iran experienced relatively wet conditions c. 2.9 to 2.3 ka BP and 1.6 to 1.3 ka BP coincided with major territorial expansions and advancements under the Achaemenid and Sassanian dynasties. Merging the historical and archaeological data with palaeoenvironmental conditions indicates a concurrence of unfolding climatic and cultural changes, suggesting cascading effects that led to growth or settlement decline and abandonment.

KEYWORDS

palaeoclimate, aeolian, monsoon, westerlies, settlements, Persian empires

1 Introduction

The hydroclimate on the Iranian Plateau exhibits intricate dynamics resulting from the interplay between several atmospheric systems, namely, the Mid-Latitude Westerlies (MLW), the southwest Indian Summer Monsoon (ISM), and the northeast Siberian Anticyclone, showcasing the complexity of the climate systems. (Figure 1A). These complex interactions have significantly influenced the climate and hydrological patterns across the Iranian Plateau since the end of the Last Glacial Maximum (LGM) c. 20 ka BP (Sharifi et al., 2015; Vaezi et al., 2019). Moreover, changes in fluvial discharge and fluctuations in lake levels played a major role in shaping the bio-climatic zones on the Iranian Plateau (Djamali et al., 2010a). These changes are argued to have influenced the emergence and subsequent development of urban societies stretching from Western Asia to the Indus Valley (Staubwasser and Weiss, 2006; Sharifi et al., 2015; Petrie, 2011; Matthews, 2013; Weiss, 2016; Petrie and Weeks, 2018; Sinha et al., 2019; Marchetti et al., 2024). However, this relationship remains complex and the subject of ongoing debate, underscoring the need for further research (Middleton, 2018; Middleton, 2024).

The climates of western and southeastern Iran, the two focus regions in this review, exhibit significant differences due to their distinct geographical and topographical features. Western Iran, characterized by the mountainous Zagros range, experiences a Mediterranean climate with hot, dry summers and cool, wet winters, receiving 400–800 mm of annual precipitation mainly from October to April. This climate supports diverse ecosystems, including forests and grasslands. In contrast, southeastern Iran is defined by arid desert landscapes, primarily the Lut Desert. It features a desert-type climate marked by extreme summer heat exceeding 50 °C with minimal rainfall (50–250 mm annually), resulting in limited biodiversity dominated by drought-resistant vegetation. Overall, western Iran has higher humidity and more consistent rainfall, while southeastern Iran is mainly dry and subject to erratic precipitation patterns.

The palaeoenvironmental reconstruction of Iran, particularly the Zagros region, has played a pivotal role in providing valuable insights into the ongoing discussion surrounding the influence of climate change on the Neolithic transition in West Asia. The unique features and significant role of the Zagros region underscore its importance in the influence of climate change on human history (Petrie and Weeks, 2018; Fazeli Nashli and Matthews, 2013; Matthews and Fazeli Nashli, 2022). It helps understand the societal changes during the early Holocene when humans transitioned from mobile hunter-gatherer lifestyles to largely sedentary farming and herding communities.

The Chalcolithic societies of the seventh and sixth millennia BP, through their consolidation of the lifeways of their Neolithic forebears, established denser, sometimes hierarchical settlement systems. These were built on integrated agro-pastoral production and the development and mastery of specialized crafts producing ceramics and metals (Matthews and Fazeli Nashli, 2022). These significant developments laid the foundations for the emergence of the Early Bronze Age (EBA) settlement on the Iranian Plateau towards the end of the sixth millennium BP. The EBA settlements, with their crucial role in exchange and trade, agriculture, and cultural advancements, were instrumental in shaping the so-called

'Middle Asian Interaction Sphere' (MAIS; Possehl, 2007) that linked societies from Mesopotamia to the Indus Valley and from the shores of the Persian Gulf to Central Asia in the fifth millennium BP (Madjidzadeh and Pittman, 2008; Mashkour et al., 2013; Mutin and Minc, 2019; Beni et al., 2021; Matthews and Fazeli Nashli, 2022). Around 4 ka BP, the MAIS began to disintegrate, ushering in a period characterized by de-urbanization and, in some places, the near-total disappearance of sedentary sites during the fourth millennium BP (Petrie and Weeks, 2018). The subsequent Iron Age witnessed the (re-) emergence of towns and cities. These urban centers integrated under the imperial Persian dynasties and were the catalysts of significant historical and cultural events in this region (Staubwasser and Weiss, 2006; Mancini-Lander, 2009; Sharifi et al., 2015; Cronin, 2021).

Throughout these developments involving shifts in agro-pastoral strategies, alterations in social and political structures, advancements in water management techniques, alterations in land use, and partial or largescale population migrations, the Iranian Plateau experienced ongoing climatic changes and phytogeographic shifts which greatly influenced the potential for human settlement in this region (Mashkour et al., 2013; Sharifi et al., 2015; Gurjazkaite et al., 2018). The transformation in the area dramatically impacted the environment and social structures. This concept has been highlighted in several pre-modern societies, such as the Mayans, Norse Greenlanders, and Easter Islanders, affected by environmental and climate change (Diamond, 2005). Weiss and Bradley (2001) focused on droughts triggering societal disruptions in Mesopotamia and the Near East. Such disruptions are often labeled as instances of societal 'collapse,' defined as a substantial, relatively rapid, and lasting decline in an established level of socio-political complexity, indicated by reduced population, social stratification, economic specialization, centralized control, and trade/exchange networks (Tainter, 1988; Diamond, 2005). Current discussions of 'collapse' recognize the challenges in defining the term and highlight the significant elements of continuity that characterize societies once described as having collapsed. These debates emphasize the need for multifactorial and multi-dimensional explanations influenced by environmental, cultural, and political dynamics and historical contingencies (e.g., Middleton, 2018; Middleton, 2024). The idea that adverse climate events universally triggered a cultural collapse in premodernity does not match the available archaeological evidence from Western Asia, or indeed across the globe, and represents an oversimplification of collective events that were always multi-faceted and nuanced (Butzer and Endfield, 2012; Haldon et al., 2018). Nevertheless, the literature review indicates that despite claims that greater social complexity supported an increasing decoupling of demographic and climatic trends since the mid-Holocene (Palmisano et al., 2021), the variable environmental settings of ancient agro-pastoral communities across Western Asia regularly exposed them to climate change. This seemingly affected social resilience and influenced urban and demographic cycles during the later periods (Fleitmann et al., 2022; Marchetti et al., 2024).

In Western Asia, researchers have examined abrupt events to explore the causality between climate and historical/social changes (e.g., Staubwasser et al., 2003; Thompson, 2006; Sharifi et al., 2015; Marsh et al., 2018; Jones et al., 2019; Sinha et al., 2019; Lawrence et al., 2022). Until recently, studies in Iran
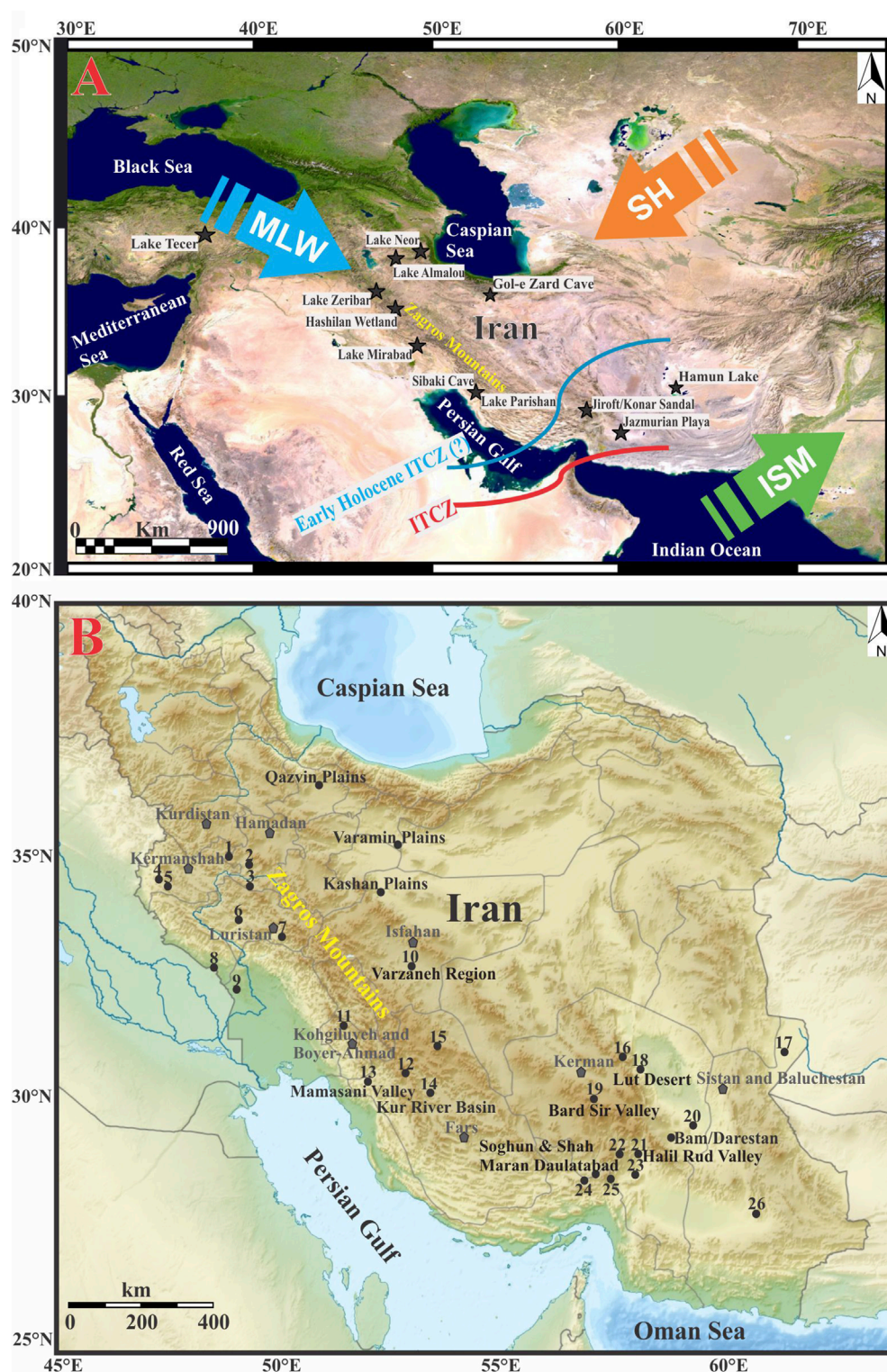
FIGURE 1
Major climate systems in West Asia (Sharifi et al., 2015; Vaezi et al., 2019) and the location of Bronze Age settlements in SE Iran. **(A)** The red and blue lines in panel A depict the estimated present-day position of the Intertropical Convergence Zone (ITCZ) and its location during the Early Holocene, respectively. The abbreviations ISM, MLW, and SH correspond to the Indian Summer Monsoon, Mid-Latitude Westerlies, and Siberian High Anticyclone, respectively. Black stars indicate the locations of palaeoenvironmental studies, primarily along the Zagros Mountains and southeastern Iran. **(B)** Map of the Iranian Plateau showing the locations of archaeological sites: 1- Godin Tepe, 2- Tepe Giyan, 3- Baba Jan, 4- Kalleh Nisar, 5- Bani Surmah, 6- Mir Kheir, 7- Kunji Cave, 8- Deh Luran, 9- Susiana, 10- Tepe Kopandeh, 11- Deh Dumen, 12- Tal-i Malyan, 13- Tol-e Nurabad, 14- Tal-i Bakun/Tal-i Mushki, 15- Hormangan, 16- Tom-e Gavan, 17- Shahr-i Sokhta, 18- Shahdad/Tepe Dehno/Mokhtarabad, 19- Tal-i Iblis, 20- Tal-i Atashi, 21- Jiroft/Konar Sandal/Keshit, 22- Tepe Gav Koshi, 23- Hajiabad Varamin, 24- Tepe Gaz Tavilla, 25- Tepe Yahya, 26- Shamsabad. Principal regions mentioned in the text are marked with black circles. Modern provinces are labeled with grey letters and indicated with five-sided polygons.

focused primarily on western Iran, especially the Zagros region (Djamali et al., 2008; Kehl, 2009; Nicoll and Küçükuysal, 2013), resulting in a lack of comprehensive geographic coverage. Additionally, excavations of prehistoric and early archaeological records face persistent challenges due to the varying survival rates of artifacts, including provenance and inferences drawn from various categories of archaeological evidence (Petrie and Weeks, 2018). Consequently, when examining different sites within a broader geographical scope, diverse growth patterns, decline, settlement, or abandonment can confound, tracing the subtle societal changes that have occurred over time (Petrie and Weeks, 2018; Eskandari, 2021a). This situation is further complicated by the proportionally low and uneven coverage of excavated archeological sites within Iran, making it challenging to build a broad, integrated, and reliable picture of settlement patterns. In particular, it is difficult at some sites to distinguish the effects of human activities and climate on palaeovegetation histories (Djamali et al., 2010b; Roberts et al., 2011; Petrie and Weeks, 2018). Nevertheless, some high-resolution multi-proxy palaeoclimate studies conducted in the Zagros region and southeastern Iran are particularly significant due to the presence of early human settlements that originated in these regions (Djamali et al., 2009a; Djamali et al., 2009b; Jones et al., 2015; Sharifi et al., 2015; Gurjazkaite et al., 2018; Petrie and Weeks, 2018; Safaierad et al., 2020; Vaezi et al., 2019; Vaezi et al., 2022; Matthews and Fazeli Nashli, 2022; see Table 1; Figures 2, 3). These studies are valuable for reconstructing palaeoclimate conditions and their potential to align these climate records with archaeological findings, providing valuable insights into the historical and cultural contexts of early human settlements along the Iranian borderlands. Reviewing these palaeoclimate studies in western and southeastern Iran could help synthesize spatiotemporal changes over larger geographic areas, providing a foundation for understanding the emergence of urban settlements and the development of exchange, trade, and cultural networks during the Bronze and Iron Ages.

2 Methods

By gathering palaeoclimate, palaeoenvironment, and palaeovegetation data focusing on western and southeastern Iran, we aim to construct a regional framework for climate change. This region witnessed the rise and fall of multiple early complex societies (Petrie and Weeks, 2018; Matthews and Fazeli Nashli, 2022; Figure 1). To understand these dynamics, we aim to build a regional framework incorporating data on climate change, settlement scale and density, social complexity, economy, and subsistence, allowing us to explore these interactions. The review focuses on the climatic conditions that prevailed/varied during the post-LGM and Holocene, setting the stage for human migration, cultural development, and the occurrence of early sedentary communities that flourished around the mid-to-late Holocene. The dynamics of this rich cultural heritage have been linked to climate change through a mosaic of interdisciplinary evidence gathered from the multi-proxy records of climate variability and climate-related historical events in archaeology, geochemical proxies (e.g., biomarkers, stable isotopes, elemental ratios), pollen records, sedimentology, and palaeoclimate modeling efforts (e.g., Griffiths et al., 2001; Stevens et al., 2006; Jones and Roberts, 2008;

Djamali et al., 2009a; Djamali et al., 2009b; Djamali et al., 2010a; Djamali et al., 2010b; Jones et al., 2013; Jones et al., 2015; Sharifi et al., 2015; Gurjazkaite et al., 2018; Carolin et al., 2019; Safaierad et al., 2020; Safaierad et al., 2023; Vaezi et al., 2019; Vaezi et al., 2022). Certain periods and locations have been investigated extensively using multiple proxies, allowing for a more comprehensive understanding and enabling researchers to draw richer insights and detailed inferences. The proxies have been interpreted to provide valuable insights into the palaeoenvironmental changes (see Figures 2, 3), e.g., 1) indication of low lake level or lake level decline = dry conditions; 2) high lake level or lake level increase = wet conditions; 3) frequent floods = wet conditions; 4) negative $\delta^{18}O$ in speleothems and ostracod shells = wet conditions; 5) positive $\delta^{13}C$ in speleothem = dry conditions; 6) high percentage of oak-derived pollen = wet conditions; 7) high percentage of *Artemisia* pollen = dry conditions; and 8) aeolian layers in lacustrine and marine sedimentary profiles = dry conditions (Sharifi et al., 2015). However, the varying thresholds and sensitivities to moisture and temperature in different climate proxies and locations pose challenges to predicting regional palaeoclimate interpretations or generalizations.

Additionally, we examined the impacts of external climate shifts on subsistence, settlement patterns, and political structures associated with the mid-to-late Holocene, enhancing the empirical discourse. In doing this, the discussion delves into the intricate tapestry of climatic fluctuations, incorporating data from various sources to provide a nuanced understanding of historical climate dynamics and their impact on human settlements spanning millennia. We unravel the interplay between climate variations and cultural transitions toward more advanced phases by synthesizing evidence from existing literature on climate change and human settlements in the region and the prevalence of famines and droughts linked to climatic shifts in archeological and palaeoclimate studies (Figure 3; Table 2). By expanding the scope of regional data beyond the western and southeastern Iranian plateau, we aim to gain deeper insights into whether droughts, famines, and wet/dry conditions were widespread across the entire Middle East or primarily driven by localized factors.

3 Results and discussion

3.1 Chronological review of the evidence.

3.1.1 Terminal Pleistocene (dry conditions)

The time frame in this interval extends from the latter part of the LGM, c. 20 ka BP, until 14.6 ka BP. Pollen records from Lake Zeribar (Van Zeist and Wright Jr, 1963; Van Zeist and Bottema, 1977), Lake Urmia in NW Iran (Bottema, 1986; Djamali et al., 2008), and Lake Van, Turkey (Wick et al., 2003) show similar assemblages, indicating the prevalence of the Iranian Turanian mountain steppe vegetation along the Zagros Mountains. A new multi-proxy palaeoenvironmental record from the Hashilan wetland in the central Zagros Mountains, western Iran (Safaierad et al., 2023), is consistent with previous evidence of pollen dominance of an *Artemisia-Amaranthaceae* dry steppe vegetation in the Zagros region (Van Zeist and Bottema, 1977; Djamali et al., 2008; Djamali et al., 2010a; Djamali et al., 2010b). These records indicate

TABLE 1 Palaeoclimate archives used in Figures 2, 3, along with their related information.

Record's location	Sedimentary archive and evidence	Dated sample counts/Age model	Chronological date	References
Sibaki Cave, SW Iran	Stalagmite stable isotope ($\delta^{18}O$ and $\delta^{13}C$)	$32\,^{230}Th$ ages; OxCal, depositional age model	24.2–9.6 ka BP	Soleimani et al. (2023)
Konar Sandal/Jiroft, SE Iran	Peat; Multi-proxy sedimentology, geochemistry, and palynology record	$8\,^{14}C$ ages from a 2.5 m core; BACON age model	4.0–0.9 ka BP	Vaezi et al. (2022)
Konar Sandal/Jiroft, SE Iran	Peat; Elemental and mineralogical composition	$7\,^{14}C$ ages from a 5.9 m core	19.0–7.0 ka BP	Safaierad et al. (2020)
Gol-e Zard Cave, NC Iran	Stalagmite; Trace elements, Stable isotopes, and XRD	25 U/Th ages; OxCal Poisson depositional age model	5.2–3.7 ka BP	Carolin et al. (2019)
Jazmurian playa, SE Iran	Lake sediments; Multi-proxy sedimentology and geochemistry record	$12\,^{14}C$ ages from a 5 m core; Clam age model	21.0–0 ka BP	Vaezi et al. (2019)
Konar Sandal, SE Iran	Peat; Multi-proxy sedimentology, geochemistry, and palynology record	$8\,^{14}C$ ages from a 2.5 m core; Clam age model	4.0–0.6 ka BP	Gurjazkaite et al. (2018)
Neor Lake, NW Iran	Lake sediments; Inorganic and organic proxy	$19\,^{14}C$ ages from a 7.5 m core; CALIB program	13.4–0 ka BP	Sharifi et al. (2015)
Lake Parishan, SW Iran	Lake sediments; Ostracod, diatom, stable isotope, and pollen record	4 samples ($3\,^{14}C$ and $1\,^{230}Th$-U) from a 2.5 m core	4.0–0 ka BP	Jones et al. (2015)
Soreq Cave, Eastern Mediterranean	Speleothem; $\delta^{18}O$ and $\delta^{13}C$	$>100\,^{230}Th$-U ages from various speleothems	21.9–0 ka BP	Bar-Matthews and Ayalon (2011)
Lake Tecer, Turkey	Lake sediments; Magnetic susceptibility, grain size distribution, mineralogy	$13\,^{14}C$ ages from a 6.80 m core; CALIB program	6.0–0 ka BP	Kuzucuoğlu et al. (2011)
Lake Almalou, NW Iran	Lake sediments; Pollen record	$8\,^{14}C$ ages from a 4.7 m core	3.7–0 ka BP	Djamali et al. (2009b)
Lake Zeribar, NW Iran	Lake sediments; $\delta^{18}O$ of authigenic calcite	$5\,^{14}C$ ages from various cores cover a depth of 15 m	20.7–0 ka BP	Stevens et al. (2008)
Lisan and Dead Sea Lakes	Lake level records from palaeoshorelines and lithological variations	$38\,^{14}C$ ages from various cores covering a depth of 21 m	10–0 ka BP	Migowski et al. (2006)
Lake Mirabad, Western Iran	Lake sediments; Ostracod	$3\,^{14}C$ ages from a 7.1 m core; DEP-AGE model	9.3–0 ka BP	Griffiths et al. (2001)

a cold and dry climate during the glacial period in the Zagros region, consistent with recent findings from southeastern Iran, which show severe droughts during the LGM and Heinrich Stadial 1 (Safaierad et al., 2023). The positive $\delta^{18}O$ record from Lake Zeribar (Stevens et al., 2001) and stalagmites in Soreq Cave (Bar-Matthews et al., 2003; Bar-Matthews et al., 1999) between 19.0 and 16.6 ka BP (Figure 2) indicate dry and cool conditions. Likewise, stalagmites retrieved from Sibaki Cave in the southern Zagros Mountains of the Fars province have documented distinct growth hiatuses from 17.9 to 17.2 ka BP and from 15.3 to 14.7 ka BP (Soleimani et al., 2023), aligning with dry conditions (high $\delta^{18}O$ and $\delta^{13}C$ values) in Soreq Cave. The alignment of dry conditions on the Iranian Plateau with other regional archives indicates that arid conditions were widespread across the Middle East during the terminal Pleistocene.

The dust input from c. 18.0 to 16.5 and 15.1 to 14.6 ka BP in a peat bog in Konar Sandal, southeastern Iran, corresponds to the cold Heinrich events (Safaierad et al., 2020). Likewise, sharp increases in dust have been reported in other regional archives, e.g., the western Arabian Sea (Pourmand et al., 2007) and the western Mediterranean Sea (Rodrigo-Gámiz et al., 2011). The enhanced dust input at the onset of Heinrich Stadial 1a (Figure 2) aligns with the documented freshwater discharge from European ice sheets into the North Atlantic between 18.2 and 16.7 ka BP (Bond and Lotti, 1995; Toucanne et al., 2015; Safaierad et al., 2020). The decrease in aeolian activity in southeastern Iran after 16.5 ka BP (Safaierad et al., 2020)
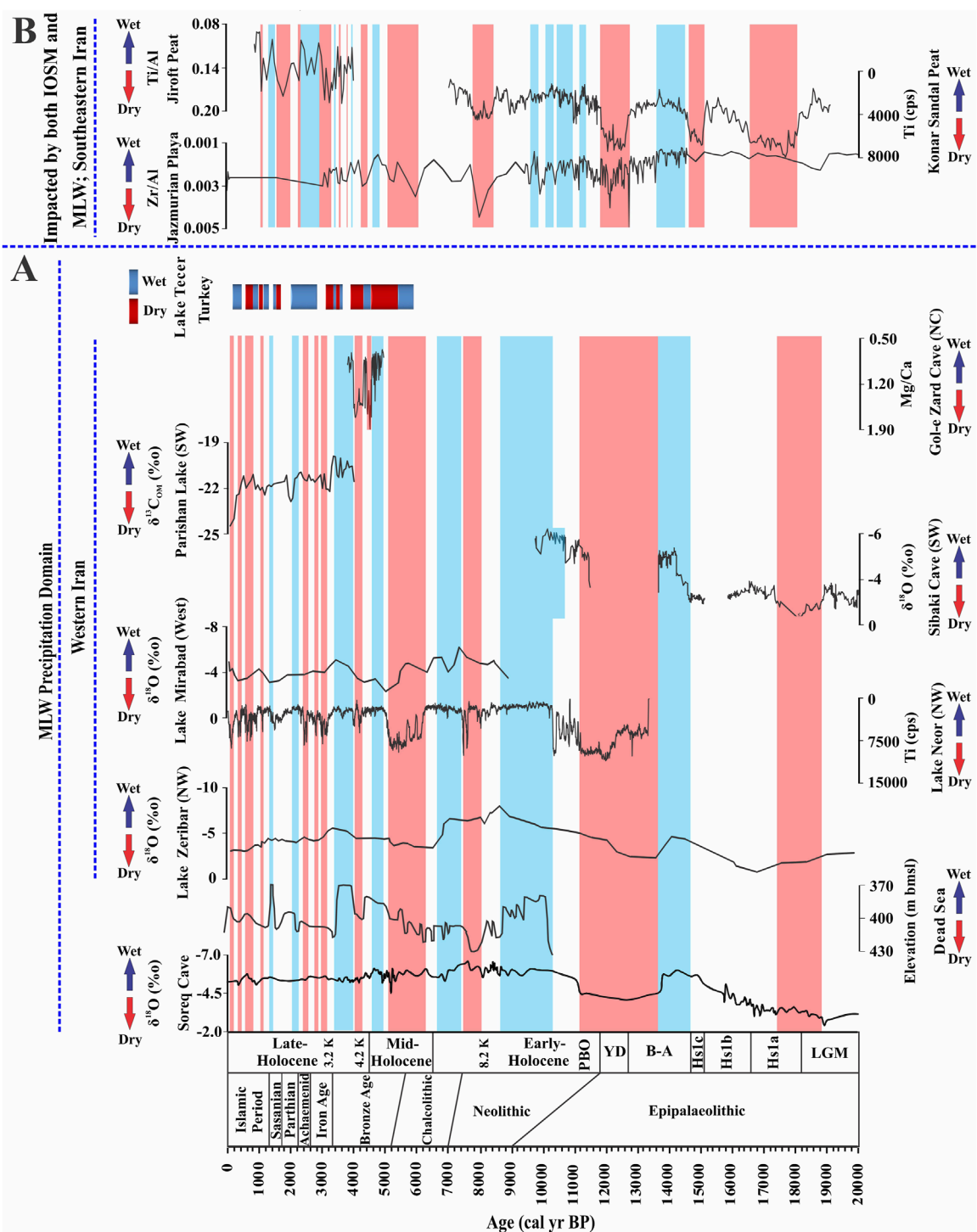
FIGURE 2
Summary of palaeoenvironmental changes for the last 20 ka in western and southeastern Iran (see Table 1; Figure 1 for site locations and supporting references). **(A)** Comparison of palaeoclimate conditions inferred based on different proxies from the Gol-e Zard Cave (Carolin et al., 2019), Lake Parishan (Jones et al., 2015), Sibaki Cave (Soleimani et al., 2023), Lake Zeribar (Stevens et al., 2001), Lake Mirabad (Griffiths et al., 2001), and Lake Neor (Sharifi et al., 2015) in western Iran impacted by MLW and Mediterranean palaeoclimate records from Lake Tecer (Kuzucuoğlu et al., 2011), stalagmites in Soreq Cave (Bar-Matthews et al., 2003; Bar-Matthews et al., 1999), and Dead Sea (Migowski et al., 2006). **(B)** Palaeoclimate data from the Jazmurian Playa (Vaezi et al., 2019), Konar Sandal peat bog (Safaierad et al., 2020), and Daryache peat bog (Vaezi et al., 2022) in southeastern Iran are affected by both ISM and MLW. Summary of regional archaeological chronologies of the Iranian Plateau (Jones et al., 2019). The blue and red bars represent considerable wet and dry periods in western and southeastern Iran, which are correlated with global climatic events: LGM, Last Glacial Maximum; HS1, Heinrich Stadial 1; YD, Younger Dryas; B/A, Bølling−Allerød interstadial; PBO, Pre-boreal oscillation; and the 8.2, 4.2, 3.2 events. These periods are also aligned with the cultural history. Due to academic conventions, the diagonal lines indicate variability in the start and end dates of named periods across different regions. Additionally, significant differences are noted in the onset times of certain periods, particularly the Neolithic, across various areas of Iran.
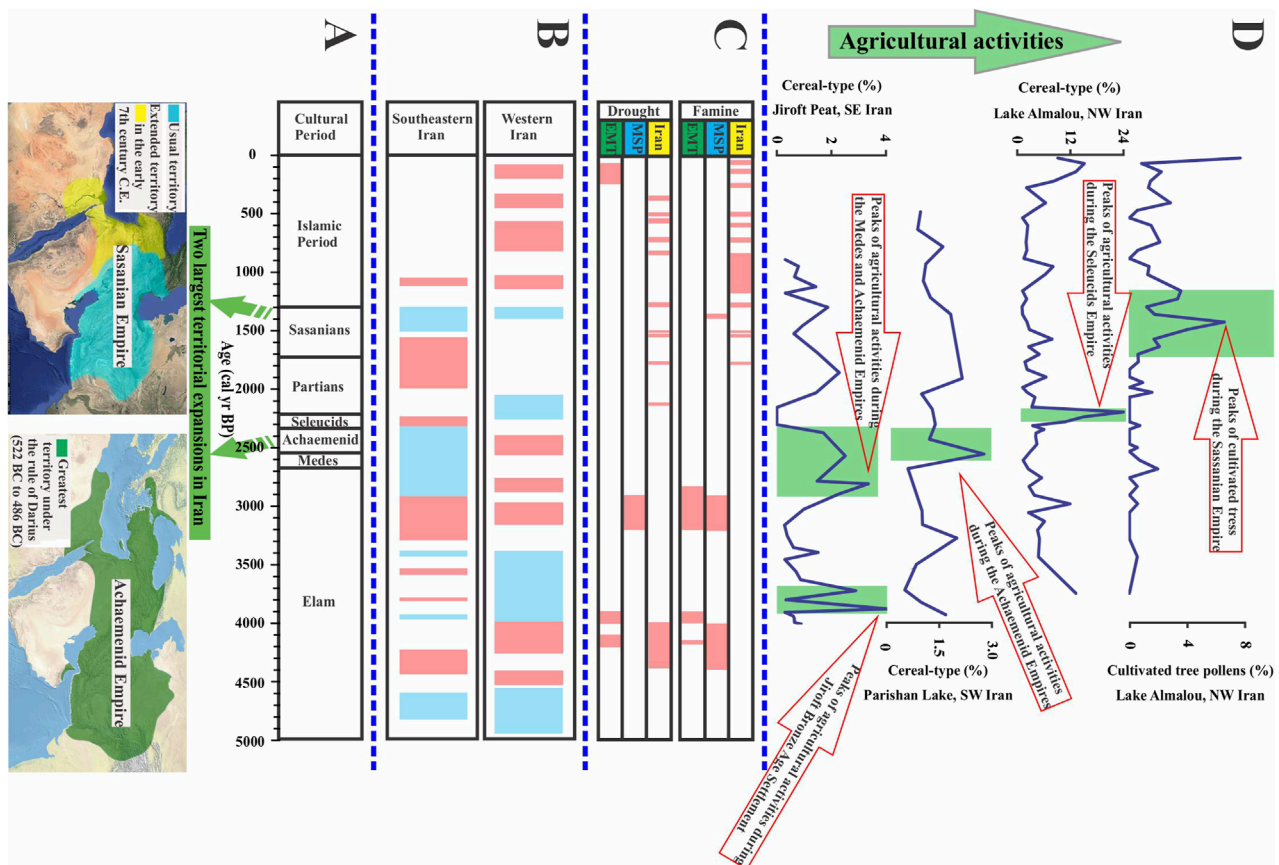
FIGURE 3
Comparison of dry and wet periods and agricultural practices in western and southeastern Iran along with historical and archaeological accounts of climate change and cultural transitions in West Asia since 5 ka BP. **(A)** Major ruling dynasties and cultural periods in Iran since the Early Bronze Age. The humid periods coincided with the most extensive territories (Vaezi et al., 2022) under the Achaemenid rule at its peak c. 2430 BP (Mcdonough, 2011; Colburn, 2013) and Sasanians c. 620 AD (Turchin et al., 2006), respectively. **(B)** The blue and red bars represent the wet and dry periods in western and southeastern Iran. **(C)** Drought and historical records of famine from Iran, Mesopotamia (MSP), and Eastern Mediterranean (EM; Sharifi et al., 2015). For data on panel C, see Table 2. **(D)** Abundance of *Cerealia*-type pollen as an index of intensive agricultural practices from the Daryache peat sequence in southeastern Iran (Vaezi et al., 2022), Lake Parishan in southwestern Iran (Jones et al., 2015), and Lake Almalou (Djamali et al., 2009b) in northwestern Iran. The upper graph shows cultivated trees, including *Juglans, Olea, Vitis, Platanus,* and *Populus* from Lake Almalou (Djamali et al., 2009b). The green bars represent peaks in agricultural activities.

is consistent with the termination of freshwater discharge from European ice sheets (Bond and Lotti, 1995). Safaierad et al. (2020) proposed that the movement of sea ice to the northern regions and displacement of the Northern Hemisphere westerlies initiated this change, implying causality.

3.1.2 Bølling–Allerød (wet conditions)

The dusty and dry conditions in southeastern Iran ended abruptly with the onset of the Bølling–Allerød c. 14.6 ka BP inferred based on the low dust input from 14.6 to 12.7 ka BP in Konar Sandal (Safaierad et al., 2020). During this period, the lack of evaporite minerals and the appearance of illite, along with very low aeolian inputs, suggest a more significant input of freshwater into the Jazmurian playa and wet conditions (Vaezi et al., 2019). The wet conditions in southeastern Iran coincided with increased summer monsoon intensity further east in the Arabian Sea (Overpeck et al., 1996). Comparing the Bølling-Allerød period to the late Pleistocene, the $\delta^{18}O$ and $\delta^{13}C$ values of the stalagmite in

Sibaki cave were relatively lower, while the growth rates were higher (Soleimani et al., 2023). These findings suggest higher temperatures and/or shorter drip intervals, indicating wetter conditions in the region (Soleimani et al., 2023). Similar wet conditions have been recorded in the Socotra Island speleothem (Shakun et al., 2007) based on the negative $\delta^{18}O$ values. The $\delta^{18}O$ record in Lake Zeribar (Stevens et al., 2001) and Soreq Cave (Bar-Matthews et al., 1999; Bar-Matthews et al., 2003) gradually decreased from 16.6 ka BP onwards, reaching their lowest values at the onset of Bølling-Allerød and holding steady until 13.8 ka BP. Thus, wet conditions seem widely prevalent on the Iranian Plateau during the first half of Bølling-Allerød (Figure 2).

3.1.3 The Younger Dryas (dry conditions)

During the period (c. 13.5–11.7 ka BP), the Sibaki Cave experienced dry conditions and lower temperatures, supported by higher $\delta^{18}O$ and $\delta^{13}C$ values in the stalagmite (Soleimani et al., 2023). Growth hiatuses in the stalagmite further confirm the

TABLE 2 Records of drought and famine in Iran, Mesopotamia, and the eastern Mediterranean region inferred from archaeological and palaeoenvironmental studies since the fifth millennium BP.

Date (BP)	Event	Location	Evidence	References
4,400–3,900	Drought	Central Iran	Pollen	Schmidt et al. (2011)
4,350–3,950	General crisis	Near East	Pollen, δ^{18}O	Issar and Zohar (2007)
4,250–4,150	Drought	Palestine	Archaeological surveys: sudden desertion of cities with no signs of violence	Issar and Zohar (2007)
4,150	Abandonment of Tell Leilan by Akkadian Period, arid phase	Tell Leilan, Abu Hgeira2 and Abu Hafur- Syria	Volcanic glass and fine sand	Weiss et al. (1993)
4,200	Arid conditions and the collapse of the Akkadian kingdom	Mesopotamia	Eolian input, Marine geochemical proxies	Cullen et al. (2000)
4,130–4,100	Widespread famines and collapse	Upper Egypt and the Mediterranean	Archeological surveys	Bell (1971)
3,950–3,850	Severe catastrophes and droughts	Upper Egypt and the Mediterranean	Archeological surveys	Bell (1971)
3,150	Extreme heat and dryness	Latakia, Syria	Archeological excavation	Alpert and Neumann (1989)
3,150–2,850	Decline in Babylon, crop failures, famine	Mesopotamia	Textual and nontextual evidence	Neumann and Parpola (1987)
3,150–2,775	Drought	Gibala-Tell Tweini, Syria	Pollen	Kaniewski et al. (2010)
3,150–2,775	Dark age	Eastern Mediterranean	Historical survey	Weiss (1982a)
3,150–2,775	Dark age	East Crete, Greece	Archeological survey	Haggis (1993)
3,100–2,900	Minimum discharge by the Tigris and Euphrates Rivers	Ashdod Coast, Eastern Mediterranean	δ^{18}O, δ^{13}C, Geochemical proxies	Schulman et al. (2001)
3,100–2,900	Minimum discharge by the Tigris and Euphrates Rivers	Mesopotamia	Historical survey	Alpert and Neumann (1989)
			Pollen, δ^{18}O, Population, Lake level	Kay and Johnson (1981)
			Textual and nontextual evidence	Neumann and Parpola (1987)
3,030	Famine	Mesopotamia	Textual evidence	Alpert and Neumann (1989)
3,000–3,957	Drought			Alpert and Neumann (1989)
2,957	Famine			Alpert and Neumann (1989)
3,000	Intense drying	Jerusalem, Eastern Mediterranean	Speleothem δ^{13}C	Frumkin et al. (2000)
2,904	Famine	Mesopotamia	Textual evidence	Alpert and Neumann (1989)
2,890	Famine			
2,800–2,100	Dry conditions, drought	Lake Maharlou, SW Iran	Pollen	Djamali et al. (2009a)
2,750	Desertion of Sussia in southern Judaea	Levant and Dead Sea Region	Archeological surveys	Issar and Zohar (2007)
2,578	Famine	Iran	Historical survey	Daryaee (2023)
1726–1709	Severe drought and famine	Iran	Historical survey	Ketabi (2005)

(Continued on the following page)

TABLE 2 (*Continued*) Records of drought and famine in Iran, Mesopotamia, and the eastern Mediterranean region inferred from archaeological and palaeoenvironmental studies since the fifth millennium BP.

Date (BP)	Event	Location	Evidence	References
1,491–1,466	Drought and famine	Iran	Historical survey	Daryaee (2023)
1,455–1,448	Drought and famine	Mesopotamia and Iran	Historical survey	Ketabi (2005); Melville (1984)
1,451	Famine	Iran		Frye (1983)
1,217	Famine	Sistan, Iran	Historical survey	Ketabi (2005); Melville (1984)
1,115	Drought and famine	Khorasan, Iran		
1,057–1,056	Famine	Khorasan, Iran		
1,015	Famine	Tehran and Rey, Iran		
940	Famine	Qaznein, Iran		
917	Famine	Countrywide, Iran		
840	Famine	Sistan, Iran		
797–796	Famine	Bayhaq, Iran		
770	Drought	Kerman, Iran		
666–664	Drought and famine	Fars, Iran		
651 BP	Drought	Fars, Iran		
750–550	Dry condition	Lake Maharlou, SW Iran	Pollen	Djamali et al. (2009a)
540	Famine	Kerman, Iran	Historical survey	Ketabi (2005), Melville (1984)
310	Simoom (strong, hot, dry, dust-laden winds)	Tabas, Iran		
198	Famine	Isfahan, Iran		
87–86	Lack of winter rain	Fars, Iran		
80–78	Famine	Countrywide, Iran		

[a]Data from Sharifi et al. (2015).

prevalence of dry conditions in southwest Iran during this period (Soleimani et al., 2023). More positive δ^{18}O records from Lake Zeribar (Stevens et al., 2001) and Soreq Cave (Bar-Matthews et al., 1999; Bar-Matthews et al., 2003) imply that dry conditions prevailed in these areas, too. Likewise, the Lake Neor peat sequence in northwestern Iran was impacted by the MLW and indicated dusty and dry conditions over the region between 12.3 and 11.2 ka BP (Sharifi et al., 2015). The highest sedimentation rate correlates with the deposition of coarse sand and high magnetic susceptibility between 12.7 and 11.8 ka BP, indicating a high-energy environment and extensive erosion (Vaezi et al., 2019). Severe arid and dusty conditions during the Younger Dryas were present in southeastern Iran, as indicated by the high Zr/Al, Si/Al, and Ti/Al ratios (Vaezi et al., 2019; Safaierad et al., 2020). The weak ISM and low precipitation during this period were inferred based on the well-dated δ^{18}O record in marine sediments from the western Arabian Sea (Sirocko et al., 1993). Similar arid

conditions prevailed in other ISM-dominated regions, such as the Arabian Sea, Bay of Bengal (Chauhan, 2003), and the Indo-Gangetic plains (Sharma et al., 2004).

In Iran, the arid conditions highlighted by previous workers (Mayewski et al., 1997; Sharifi et al., 2015) coincided with the cold Younger Dryas in northwest Europe (Dansgaard et al., 1989). The North Atlantic cold events caused by the release of freshwater and the breakup of icebergs from the North American ice sheets (Hoff et al., 2016; Ng et al., 2018) impacted the input of dust over the Iranian Plateau (Sharifi et al., 2015; Safaierad et al., 2020). It is suggested that the enhanced interhemispheric temperature contrast during these cold events (Clark et al., 2012; Singarayer et al., 2017) forced the Atlantic meridional overturning (Denton et al., 2005) and ushered a weak ISM (Wang et al., 2001; Stager et al., 2011). This eventually resulted in dry conditions over the Iranian Plateau and reduced surface air temperature over the ice-covered ocean (Kutzbach et al., 2014).

Dusty and dry conditions during the Younger Dryas and the 8.2 ka event occurred due to the release of freshwater and icebergs from the North American ice sheets (Hoff et al., 2016; Ng et al., 2018) into the North Atlantic (Safaierad et al., 2020). This sudden change resulted in severe dusty and dry conditions over the Iranian Plateau (Sharifi et al., 2015; Vaezi et al., 2019; Safaierad et al., 2020). While freshwater and iceberg discharge from the European ice sheets led to a concomitant northward displacement of the Northern Hemisphere westerlies (McGee et al., 2010), it resulted in a gradual increase in aeolian activity over the southeastern Iranian Plateau at the onset of Heinrich Stadial 1 (Safaierad et al., 2020). The increase in dust from North Africa and the Arabian Peninsula during the North Atlantic cooling events since the LGM (McGee et al., 2013) occurred due to the southward shift in the MLW (McGee et al., 2010). The flow of strong Northern Hemisphere westerlies over the world's largest dust bowls (i.e., North Africa and the Arabian Peninsula) during the North Atlantic cooling events, e.g., Heinrich Stadial 1, the Younger Dryas and the 8.2 ka event, resulted in huge dust plumes circling over the Iranian Plateau (Sharifi et al., 2015; Safaierad et al., 2020). It is proposed that the intensity of the northeastern Siberian Anticyclone directly impacted the increase in aeolian activity across northwestern Iran, especially during the Younger Dryas (Sharifi et al., 2015).

3.1.4 Archaeology in the terminal pleistocene

The archaeological record of Iran for the terminal Pleistocene is sparse and uneven and, in most instances, cannot support a close assessment of cultural adaptations to changing climate. The small numbers of known sites and patchy site distributions reflect several confounding factors – bias in survey coverage, limited fieldwork, poor preservation due to the age and ephemerality of most sites complicated by poor chronological control due to limited absolute dating - that mask cultural adaptation during this period (Shoaee et al., 2021).

In general, modern human (*Homo sapiens*) populations are argued to have arrived in Iran at c. 40–45 ka BP (Matthews and Fazeli Nashli, 2022), or possibly slightly earlier (Vallini et al., 2024), replacing existing Neanderthal (*H. neanderthalensis*) populations. This resulted in the characteristic cultural materials of the Iranian Upper Palaeolithic, typically referred to as Baradostian (in the central Zagros and northern Plateau) and Rostamian (in the southern Zagros). Upper Palaeolithic caves, rock shelters, and open-air sites are recorded in the central and southern Zagros, on the western edge of the Iranian Plateau, and the northern fringe of the central desert (Shoaee et al., 2021), and more recently in SE Iran (Anjomrooz et al., 2022). Upper Palaeolithic populations were mobile foragers who moved seasonally to access locally available plant and animal resources. Archaeological sites display preferences for hunting different wild animal species such as onager, sheep, goat, gazelle, boar, or deer (Matthews and Fazeli Nashli, 2022).

There appears to have been a multi-millennial gap, or at least a substantial reduction, in the human settlement of Iran at the end of the Upper Palaeolithic period, coinciding directly with the worsening climatic conditions of the LGM (Matthews and Fazeli Nashli, 2022; Shoaee et al., 2021: Table 1, Figure 11). However, human habitation can be documented in various parts of Iran from c. 20–10 ka BP, termed the Epipalaeolithic period, at sites characterized by variations on a distinctive 'Zarzian' lithic

tradition (Olszewski, 2012; Tsuneki, 2013; Asouti et al., 2020; Shoaee et al., 2021: Figure 9). Epipalaeolithic groups continued a mobile hunting and gathering mode of existence that in the central Zagros is argued to represent moderately long seasonal occupations of caves and rock-shelters, alongside the use of task-oriented open-air camps (Asouti et al., 2020), although regional patterns of site use appear to have varied somewhat (Tsuneki, 2013; Rosenberg, 2003). Zooarchaeological and archaeobotanical studies in Palegawra (Iraq) indicate the exploitation of local grassland, woodland, and wetland habitats (Asouti et al., 2020) for a range of wild plants (grasses, legumes, nuts, and tubers) and wild animals (cattle, red deer, onager, fallow deer, boar, caprine, and gazelle). Contemporary Zarzian groups in the Iranian Zagros exploited an increasingly wide range of local wild animals, including cattle, sheep/goat, equids, gazelle, deer, pig, as well as land snails, birds, and fish (Shoaee et al., 2021). Late Epipalaeolithic sites in the southern Caspian region (e.g., the cave sites of Komishan, Kamarband, Hotu, and Ali Tepe), often termed 'Mesolithic', also showed evidence for exploitation of marine resources such as seal, which varied through time in ways that likely reflect the changing local environment and Caspian Sea levels (Matthews and Fazeli Nashli, 2022; Vahdati Nasab et al., 2019: Table 1).

3.1.5 Early Holocene (wet conditions with abrupt dry intervals c. 9.2 and 8.2 ka BP)

During the early Holocene in southeastern Iran, wet conditions extended from c. 11.4–9.6 ka BP in the Jazmurian playa (Vaezi et al., 2019). The sharp decline in aeolian inputs (indicated by the low Zr/Al and Ti/Al ratios) combined with the absence of evaporites and increasing illite content support the shift in environmental conditions (Vaezi et al., 2019). The presence of illite suggests freshwater input, most likely due to an increase in precipitation. Similarly, in Konar Sandal, the low lithogenic abundance (Al, Ti, Si, and Zr) during the early Holocene and a rise in organic carbon suggest increased humidity in southeastern Iran (Safaierad et al., 2020). Consistent with this, evidence from other palaeoclimate archives, such as the Qunf cave in Oman (Fleitmann et al., 2003), marine sediments in the Arabian Sea (Gupta et al., 2005), and lacustrine sediments in northwestern India (Dixit et al., 2014) support changes during the early Holocene.

The Sibaki Cave records in SW Iran indicate a shift towards a more humid climate observed from 11.2 ka BP onwards that peaked at c. 10.7 ka BP (Soleimani et al., 2023). However, the peak wet conditions in southwest Iran appeared a few centuries before they manifested in west and northwest Iran but occurred a few centuries later than in southeast Iran. During the early Holocene, peak wet conditions dominated western and northwestern Iran c. 10.2 to 8.6 ka BP, while southeastern Iran experienced increased regional precipitation c. 11.4 to 9.6 ka BP. For example, in Lake Neor, the sharp decrease in aeolian activity and wet conditions started c. 10.2 ka BP (Sharifi et al., 2015). The delay in precipitation increased during the early Holocene and was documented in the $\delta^{18}O$ records from Lakes Zeribar and Mirabad (Stevens et al., 2001; Stevens et al., 2006), indicating opposite climatic responses in western Iran. Nevertheless, this trend is consistent with changes in the Northern Hemisphere solar insolation (Sharifi et al., 2018; Safaierad et al., 2023). In contrast, the Hashilan wetland in western Iran experienced prolonged dry summers and frequent spring/summer dust storms

during the early Holocene (Safaierad et al., 2023). These conditions led to seasonal wetland desiccation and delayed oak expansion in Zagros (Djamali et al., 2010a; Safaierad et al., 2023). The significant dominance of aeolian activity observed in western Iran during the onset of the early Holocene, as documented by Safaierad et al. (2023) and Sharifi et al. (2015), Sharifi et al. (2018), contrasts with high-resolution studies in southeast Iran (Vaezi et al., 2019; Safaierad et al., 2020), which do not report aeolian inputs.

With the onset of the early Holocene, high solar insolation led to the northward displacement of the ITCZ and its strengthening, resulting in an overall northward expansion of the ISM, as reported in many studies (Overpeck et al., 1996; Gupta et al., 2003; Fleitmann et al., 2007) and enhanced ISM precipitation in southeastern Iran (Vaezi et al., 2019; Safaierad et al., 2020). On the other hand, this shift in circulation patterns strengthened and extended the dominance of the sub-tropical high-pressure over western Iran (Djamali et al., 2010b; Hamzeh et al., 2016; Safaierad et al., 2023). Consequently, there were northward movements of the MLW storm tracks (Sharifi et al., 2018), resulting in enhanced aeolian inputs reported from the Hashilan Wetland (Safaierad et al., 2023). The atmospheric pressure in the Zagros region could cause a decrease in spring rainfall and an extended dry season (Djamali et al., 2010a).

Except for some short periods, c. 9.2 and 8.2 ka BP, the ISM remained strong over southeastern Iran until 7.8 ka BP when it began to shift southward gradually (Vaezi et al., 2019; Safaierad et al., 2020). The 8.2 ka BP cold and dry event, also known as the Bond Event 5, coincided with the injection of icebergs into the North Atlantic (Safaierad et al., 2020), which caused a southward shift of the ITCZ (Dixit et al., 2014), and abrupt weakening of ISM in the northern hemisphere (Gupta et al., 2003). This change was reflected in the extreme peaks of dust in southeastern Iran (Vaezi et al., 2019; Safaierad et al., 2020). This region influenced by ISM, is highly susceptible to shifts in the ITCZ. Consistent with these events, sudden dry periods during this time have been reported in speleothems from northern Oman and Yemen (Fleitmann et al., 2003; Fleitmann et al., 2007) and southeastern China (Dykoski et al., 2005) indicating the regional nature of these climatic shifts. This cold, dry event is also captured in the Mediterranean palaeoclimate records, e.g., a peak in dust inputs in Lake Neor (Sharifi et al., 2015) in western Iran and a sharp drop in the Dead Sea level (Migowski et al., 2006). The sudden weakening of the ISM circulation c. 8.2 ka BP led to a southward movement of dry MLW (Sharifi et al., 2018; Safaierad et al., 2023). This, caused extensive dust storms during winter in the entire region (both western and southeastern Iran; Sharifi et al., 2015; Sharifi et al., 2018; Safaierad et al., 2020) in the Middle East (Migowski et al., 2006). The arid condition confirms the influence of the North Atlantic fluctuations on decreasing ISM intensity in the Northern Hemisphere (Gupta et al., 2003).

The early Holocene marks an uptick in evidence of human activities in the region, although the archaeological record is still sparse. Although reliable dates are scarce, the Neolithic stages in Iran can be divided into aceramic (c. 11.5 ka BP) and ceramic (after 9.0 ka BP) phases that emerged in the Zagros mountains (Peasnall, 2002; Weeks, 2013; Petrie and Weeks, 2018; Matthews and Fazeli Nashli, 2022; Azadi et al., 2023). Evidence for Neolithic occupation c. 9.0 ka BP in southeast Iran is extremely scarce, comprising only the

site at Tepe Gav Koshi in the Esfandageh region west of Jiroft. This was occupied initially from 9.0–8.7 ka BP and re-occupied towards the end of the ninth millennium BP, broadly coinciding with the 8.2 ka event. According to Fazeli Nashli and Matthews (2013), the Tepe Gav Koshi Neolithic site had some distinct characteristics, such as the use of obsidian and ceramic, the presence of mud-brick structures typical for Neolithic sites further to the west and north, and plant remains that exhibit consumption of pistachio nuts. There was little evidence of agriculture. Notably, the animal remains excavated are predominantly wild species (sheep and goats) hunted by the community. Overall, little connection between climate and cultural changes can be drawn from limited evidence beyond the basic observation that climate aridification did not drive the abandonment of the region.

Archaeological evidence in Western Asia indicates a significant impact of the 8.2 ka cold and dry event on human communities coinciding with abandonment and migration (Flohr et al., 2016; Safaierad et al., 2023). Archaeological records for this period in southern Iran are limited and characterized by highly uneven spatial coverage, making it challenging to connect changes in settlement patterns influenced by the 8.2 ka event. In the Kohgiluyeh region of the south-to-southwest Zagros mountains, traditional settled life began around the eighth millennium BP. Azadi et al. (2023) documented this emergence, revealing a gradual process of Neolithization in the area. The fertile lands were pivotal for the sedentary communities, and their subsistence strategies focused on a combination of cultivation, animal domestication, and herding. In addition, there appears to be a continuity of Neolithic settlement in the SW Iranian lowlands, as represented by material from Deh Luran and Susiana (Delougaz et al., 1996; Alizadeh, 2003; Alizadeh, 2008: 4–6, Table 1). In SW Iranian highlands, Neolithic communities dependent upon domesticated animals and plants and supplemented by hunting are known in small numbers from shortly before the ninth millennium BP, with continuity in settlement until around the eighth millennium BP (Alizadeh, 2021; Azadi et al., 2023). Here, the 8.2 ka BP event has been linked with changing subsistence practices, in particular, an increased reliance on hunting wild animals alongside the exploitation of domesticates at several sites (c. 8.4–8.0 ka BP). This is demonstrated by zooarchaeological remains from Tal-e Mushki and Hormangan and the lithic toolkit excavated at the latter site (Mashkour et al., 2006; Nishiaki, 2010; Abe and Khanipour, 2019).

3.1.6 7.8–6.3 ka BP (semi-wet conditions)

After 7.8 ka BP, a change occurred in the vegetation cover from steppe to forest-steppe, coinciding with the continuous increase of oak forests (Van Zeist and Bottema, 1977; Djamali et al., 2008; Djamali et al., 2010a; Safaierad et al., 2023) around Lake Urmia (Bottema, 1986), Zaribar and Mirabad (Van Zeist and Bottema, 1977) in Iran and Lake Van in Turkey (Wick et al., 2003). These woodlands gradually expanded from 7.8 to 6.0 ka BP coeval to a decrease in aeolian input as the summer season progressively shortened (Djamali et al., 2010b; Safaierad et al., 2023). The long, hot, and dry summers due to the dominance of sub-tropical high-pressure systems in the Zagros region (Djamali et al., 2010a) is the most likely cause of this delay in the expansion of oaks during the Early Holocene (Djamali et al., 2010b; Safaierad et al., 2023). In addition, the expansion of oaks can be due to the decrease in the

length of summer and an increase in spring rains in connection with the reduction in the intensity and duration of the sub-tropical high-pressure system over the Zagros region after 7.8 ka BP (Djamali et al., 2010a; Safaierad et al., 2023).

Gradually, with the progressive displacement of the ITCZ (Fleitmann et al., 2007; Gupta et al., 2003) followed by the sub-tropical high-pressure systems (Djamali et al., 2010b), it is expected that the MLW had more influence on southeastern Iran during winter. The observed delay in the decrease in humidity towards the end of the early Holocene in southeast Iran compared to other ISM-dominated areas has been reported (e.g., Hamzeh et al., 2016; Vaezi et al., 2019). This is because southeastern Iran continued to receive rain during both rainy seasons, supported by the different moisture sources, namely, the MLW and ISM. This interpretation aligns with the observed decrease in dust in southeastern Iran, particularly from 7.8 to 6.3 ka BP (Safaierad et al., 2020). However, geochemical proxies suggest that although Mediterranean precipitation had increased, the reduction in ISM rainfall was more significant, resulting in less rainfall than the wet conditions during the early Holocene.

Eighth millennium BP - This long period spanning c. 7.8–6.3 ka BP coincides with southern Iran's late Neolithic and Chalcolithic periods. Around the eighth millennium BP, in SE Iran, the ceramic Neolithic occupation is more evident through surveys (Prickett, 1986a) and excavations such as Tepe Yahya, Tepe Gaz Tavila (Beale, 1986; Prickett, 1986b), and Tal-i Iblis (Caldwell, 1967). The Darestan region, east of Bam, hosted an extremely dense cluster of Neolithic settlements, with 64 sites identified—39 featuring Neolithic pottery and 25 displaying an aceramic Neolithic pattern similar to Tell-e Atashi (Mutin, 2022). This period marked the use of domesticated plants and animals, with settlements occupying alluvial terrace fans, a common practice for early agricultural communities (Petrie and Thomas, 2012). In the Shah Maran-Daulatabad basin, a cluster of Neolithic sites surrounded Tepe Gaz Tavila, forming agricultural villages unique to Kerman during this time (Prickett, 1986b). Conversely, no Neolithic settlements were recorded in the Halil Rud and areas south of Jiroft or the Bard Sir Valley. In the highlands of SW Iran, Neolithic settlement began expanding significantly during the eighth millennium BP. The Kur River Basin saw fewer than a dozen settlements at the start of the millennium to grow over 100 by the Shamsabad phase (c. 7.6–7.0 ka BP; Sumner, 1990). These settlements relied on small-scale irrigation from springs and dry farming (Sumner, 1994).

Seventh millennium BP - As the seventh millennium BP unfolded, the Neolithic settlement density increased further in SE Iran, particularly in the Shah Maran-Daulatabad basin, with significant growth during the Yahya VI-VB and VA periods (Prickett, 1986b). This growth coincided with agricultural practices shifting as settlements transitioned from alluvial fan margins to low-terraced fields irrigated by captured runoff. However, the Soghun Valley, with its more abundant rainfall, lacked evidence of such irrigation systems (Prickett, 1986b). In the Halil Rud region and areas south of Jiroft, Early Chalcolithic settlement began emerging with Yahya VB-VC pottery types from the late eighth to mid-seventh millennium BP (Pfälzner et al., 2019). Settlement density increased during the Middle Chalcolithic period (Yahya VA pottery) in the latter half of the millennium. In the Bard Sir Valley, a handful of Chalcolithic sites also appeared (Prickett, 1986b). In the highlands

of SW Iran, the Chalcolithic period saw a rise in settlement in the Kur River Basin, particularly during the Bakun period (c. 7.0–6.4 ka BP; Taylor, 2015). Most settlements were small farming villages (>2 ha), though larger sites (6–8 ha) indicated the development of a settlement hierarchy (Taylor, 2015). Agricultural intensification, including irrigation and shorter fallow periods drove this growth (Sumner, 1990; Sumner, 1994).

Late seventh to Early sixth millennium BP - In SE Iran, Chalcolithic settlement patterns became dense in Darestan and nearby regions, with nearly 90 sites dating from c. seventh to sixth millennium BP (Mutin and Garazhian, 2019; Mutin, 2022). Further north, evidence of Chalcolithic occupation emerged in Shahdad region in the Lut Desert at sites such as Tepe Dehno and Tepe East Dehno (Eskandari, 2018). In the Kur River Basin of SW Iran, a decline in settlement during the Late Bakun period (c. 6.4–6.1 ka BP) suggested negative impacts of agricultural intensification, such as soil salinization (Sumner, 1990). This transition coincided with increasing emphasis on pastoralism, particularly sheep and goat herding, leading to greater mobility and the rise of nomadic pastoralism during the sixth millennium BP (Sumner, 1990; Sumner, 1994; Alden, 2013).

Sixth millennium onwards - By the sixth millennium BP, climate change, including the onset of arid conditions c. 6.3 ka BP began to impact settlement patterns and agropastoral practices in Iran. These climatic shifts contextualize the broader changes observed in Chalcolithic settlement during this period. Notably, no evidence of human occupation has been identified before the end of the sixth millennium BP in the Sistan region.

3.1.7 6.3–5.0 ka BP (dry conditions)

Between 6.3 and 5.0 ka BP, Iran experienced relatively drier and dustier conditions, which is consistent with a decrease in solar insolation (Gupta et al., 2003; Fleitmann et al., 2007) that affected most of the Northern Hemisphere (Sharifi et al., 2015). Lake Neor experienced periods of enhanced dust coinciding with the African Humid Period ending between 6.0 and 5.0 ka BP (Gasse and Van Campo, 1994; Sharifi et al., 2015). Around 6.3 ka BP, a return to arid conditions was reported in speleothem records from northern Oman (Fleitmann et al., 2003). Due to the concurrent decrease in solar insolation in the Northern Hemisphere, the ITCZ and ISM moved further south c. 6.3 ka BP (Fleitmann et al., 2003). Since then, the summer monsoon rains in southeastern Iran have decreased significantly. It is likely that areas like southeastern Iran, located along the northern border of ISM, experienced relatively less arid conditions compared to the southern regions due to a shift in rainfall from ISM to a MLW-dominated regime (Hamzeh et al., 2016; Vaezi et al., 2019).

The archaeological period from the mid-sixth to fifth millennium BP incorporates late Chalcolithic and Early Bronze Age developments in southern Iran. In the highlands of SW Iran, this is characterized by a steady decline of known sedentary sites, continuing from the Late Bakun period into the Lapui period (c. 6.1–5.6 ka BP) and the Early to Middle Banesh periods (c. 5.6–4.9 ka BP). By the Middle Banesh period, the site of Tal-e Malyan became the largest recorded and possibly the first 'urban' settlement in the Kur River Basin, covering an area of 50 ha (Sumner, 1990; Alden, 2013). In contrast, the total settled area in the Kur River Basin decreased to its smallest extent since the Neolithic period.

Rather than regarding the settlement data as indicative of concurrent population decline, this period is hypothesized as one in which there was a large-scale transition from settled farming to nomadic pastoralism (Sumner, 1990; Sumner, 1994; Alden, 2013).

Settlement in southeastern Iran can be documented for the entire period from the early sixth to fifth millennium BP, with discernible fluctuations in sites and settled areas. Excavations and surveys in the Shah-Maran-Daulatabad region (Prickett, 1986a; Prickett, 1986b; Beale, 1986) showed a decline during the sixth millennium BP (Iblis IV/V period), followed by near abandonment at the end of the sixth millennium BP (Yahya IVC period). Prickett (1986a: 774) described this period as "characterized by the fragmentation and collapse of the long-developing prehistoric settlement pattern" in Shah Maran-Daulatabad, which was not resettled until the third millennium BP with the advent of *qanat* irrigation (Prickett, 1986a: 782). In the Soghun Valley, Tepe Yahya was abandoned for most of the sixth millennium BP, but a small number of other sites were documented in this region (Prickett, 1986a: 776). Tepe Yahya was re-occupied during the late sixth millennium BP (Period IVC), aligning with the Proto-Elamite culture across the Iranian Plateau. Further east in the Jiroft region, settlement of the sixth millennium BP was documented at Mahtoutabad (Periods I-III; Desset et al., 2013; Vidale and Desset, 2013), the Halil Rud, and areas south of Jiroft (Pfälzner and Soleimani, 2017; Pfälzner et al., 2019). These studies suggest a decline in sedentary settlement in the early sixth millennium BP, followed by a substantial increase in the mid-sixth millennium BP (Late Chalcolithic II), before another decline into the Late Chalcolithic period III (c. 5.4–5.2 ka BP) and the Early Bronze Age I or Proto-Elamite period (c. 5.2–4.9 ka BP). Further north in the Bard Sir Plain, there is a substantial increase in sites during the mid-sixth millennium BP (Iblis IV/V periods) before they decreased during the late sixth millennium BP (Prickett, 1986a: 784, Table. 7.1; Prickett, 1986b: 237). A reduction of settlement leading into the Proto-Elamite period (i.e., the Early Bronze Age) thus occurred in Bard Sir, Jiroft, Soghun, and Shah-Maran-Daulatabad regions of southeastern Iran, resembling the pattern observed in the Kur River Basin during the same period, as well as in other areas of Iran (Alden, 2013) indicating reduced sedentary settlement that coincided with the first significant period of (inter)cultural contacts across the Iranian Plateau.

3.1.8 5.0−4.5 ka BP (wet conditions)

The overall palaeoclimate reconstruction indicates wet conditions over the Iranian Plateau between 5.0 and 4.5 ka BP (Figure 3). The Early Bronze Age coincided with episodes of low dust and humid conditions in Lake Neor (Sharifi et al., 2015). Wet conditions were also recorded in Lake Zeribar, NW Iran, c. 5.1 to 4.9 ka BP (Stevens et al., 2008; Wasylikowa and Witkowski, 2008) and in Lake Maharlou, southwest Iran (Djamali et al., 2009a). Similarly, a wet period occurred in Lake Tecer, Turkey (Kuzucuoğlu et al., 2011), Lisan, and the Dead Sea lakes in the Jordan Rift Valley (Migowski et al., 2006), and in the eastern Mediterranean region (Robinson et al., 2006; Bar-Matthews and Ayalon, 2011). The existence of wet conditions in southeastern Iran between 5.0 and 4.5 ka BP is supported by geochemical evidence from the Jazmurian playa, showing a decrease in aeolian input and an abrupt increase in rainfall between 5.0 and 4.7 ka BP, likely due to the southerly

movement of the westerlies (Vaezi et al., 2019). The southward movement resulted in intensified MLW-driven winter rainfall over the Iranian Plateau (Dehai and Jing, 2012), contributing to a more humid climate (Arsalani et al., 2018). This southward shift in westerlies sustained the wet period.

Urban communities first appeared in Sumer, in southern Mesopotamia, c. 5.5 ka BP, and flourished from c. 5.0 ka BP onwards when favorable climatic conditions and rain dominated the Middle East (Weiss et al., 1993; Staubwasser and Weiss, 2006). Similar arguments have been made for Iran in the Early Bronze Age. The wet conditions between 5.0 and 4.5 ka BP over the Iranian Plateau (Figure 2) coincided with the flourishing of Bronze Age settlements in southeastern Iran, as seen most clearly in Jiroft, Jazzmurian basin, the western Dasht-e Lut, and Sistan (Madjidzadeh and Pittman, 2008; Lawler, 2011). Bronze Age settlement declines in the Shah Maran-Daulatabad basin, and there are substantial periods of abandonment at Tepe Yahya and Tal-i Iblis after the fifth millennium BP (Prickett, 1986a; Potts, 2001; Mutin and Lamberg-Karlovsky, 2013). In contrast, the Jiroft region settlement expanded as indicated by the expansion in area of the Early Bronze Age sites of Konar Sandal South (Madjidzadeh and Pittman, 2008; Mashkour et al., 2013) and Hajjiabad Varamin (Eskandari, 2021a). Occupation of these sites, characterized by extensive evidence for specialized craft production in stone and metal, continued into the second half of the fifth millennium BP. A survey in the regions south of Jiroft (Pfälzner and Soleimani, 2017; Pfälzner et al., 2019) also documents a substantial increase in settlement from the sixth to fifth millennium BP.

In the western Dasht-e Lut, large-scale urban occupation developed from the late sixth millennium BP and peaked in the mid-late fifth millennium BP at sites such as Shahdad, which covered nearly 100 ha (Eskandari, 2021b). This urban site, located on the Takab alluvial fan, was characterized by a dispersed, non-nucleated settlement pattern (Eskandari, 2021b: 40), and relied on water from springs and streams. Contemporary large, isolated, Early Bronze Age urban sites were recorded further south at Mokhtarabad (c. 70 ha) and Keshit (c. 400 ha; Eskandari et al., 2014). These sites are characterized by substantial evidence of specialized craftwork in stone, metal, and ceramics of different provenance. Evidently, a network of exchange, and communication flourished along the western edges of the Dasht-e Lut (Eskandari, 2021a; Eskandari, 2021b).

In Sistan, Shahr-i Sokhta is settled for the first time towards the end of the sixth millennium BP (Period I), reaching its greatest extent (c. 150 ha) in the early-mid fifth millennium BP (Periods II-III), showing continuous occupation into the later fifth millennium BP (Period IV). Other Early Bronze Age settlements are also recorded in various parts of the Iranian Sistan region and along the Helmand region up to Mundigak in Afghanistan–comprising what has been referred to as the 'Helmand Civilization.'

Favorable climatic conditions supported agricultural practices in these dry landscapes and brought prosperity to the Early Bronze Age societies of southeastern Iran. Although evidence is not available from all the sites, it is evident that Bronze Age settlements in the region depended on an integrated oasis agricultural system comprising irrigated gardens of domesticated date palms that provided both fruit and suitable shaded micro-climates for growing other crops (Tengberg, 2012). At Shahr-i Sokhta and Konar Sandal

South, this subsistence adaptation incorporated the cultivation of dates, wheat, barley, pistachio, and grapes, alongside managing domestic goats, sheep, and cattle. At both sites, this diet was supplemented by the hunting of wild animals, and at Shahr-i Sokhta, by the exploitation of Lake Hamoun and its shorelines for the hunting of marsh birds and fishing (Mashkour et al., 2013; Gala and Tagliacozzo, 2014).

In the highlands of Fars, the decline in sedentary settlement accompanying the Middle Banesh period, with its Proto-Elamite material elements, continued up to the early fifth millennium BP (c. 4.9–4.6 ka BP). A very large wall, encircling up to c. 200 ha, was built around the key site of Tal-e Malyan, although it is unlikely that the entire area inside the wall was settled. However, this is the only site known in the Kur River Basin from this period. Thus, early urbanism in Fars is characterized by a "radically reduced" sedentary population followed by a nearly four-century-long near-abandonment of the region by agriculturalists from the mid-fifth millennium BP. Sumner (1989) ascribed this to extensive salinization of agricultural soils.

In Luristan, central Zagros, the early fifth millennium BP is associated with a virtual absence of sedentary settlement. The archaeological record for this period consists entirely of burials from sites such as Mir Khair, Kalleh Nisar, and Kunji Cave (Emberling et al., 2002). The long-lived tradition of isolated cemeteries continued through the fifth millennium BP in Luristan, as seen at the EBA II-III sites such as Bani Surmah and Kalleh Nisar, and also further south-east at Deh Dumen (Kohgiluyeh and Boyer-Ahmad Province). Although Hole (2007) has documented Early Bronze Age villages in the Khorramabad Valley in the mid-fifth millennium BP, he notes that "for long stretches of time, Luristan may have lacked permanent settlements." The evidence from Bronze Age Luristan has suggested a dominant pastoral nomadic lifestyle during this period built on seasonal transhumance. Sedentary settlement emerged to the north and east, in Kermanshah and Hamadan Provinces, as at Tepe Giyan and Godin Tepe. The latter shows discontinuous occupation phases from the early fifth millennium BP (period IV, when the site was characterized by material of Early Trans-Caucasian type) and from the mid-late fifth millennium BP to the later fourth millennium BP (periods III:6-III:2) (Gopnik and Rothman, 2011).

The Early Bronze Age settlements observed in southeastern and southwestern Iran and the central Zagros region differ from each other and from that of the central Iranian Plateau. In the central plateau, the fifth millennium BP is associated with the disappearance of all sedentary settlement in areas such as Varamin, Qazvin, and Kashan (Schmidt et al., 2011; Matthews and Fazeli Nashli, 2022: 263; Kirsten et al., 2023; Pollock et al., 2023). A somewhat different pattern characterizes the Qom region to the south, where early fifth millennium BP settlement is documented at Qoli Darvish (Matthews and Fazeli Nashli, 2022: 263). The Early Bronze Age footprint is also seen in the Varzaneh region east of Esfahan, on the southern Central Plateau, documented in surveys that recorded c. 50 Early (and possibly Middle) Bronze Age sites at Tepe Kopandeh and elsewhere (Pollard et al., 2013; Rafiei-Alavi et al., 2023).

3.1.9 4.5−4.0 ka BP (dry conditions)

The wet period was followed by a shift to dry conditions between 4.5 and 4.0 ka BP (Table 2; Figure 3). The multi-proxy sediment records from the peat sequence in the Lake Neor catchment suggested dry conditions with high aeolian activity between 4.3 and 4.1 ka BP (Sharifi et al., 2015). The decline in lake levels and dry conditions have also been recorded during this period in Lisan and Dead Sea Lakes (Migowski et al., 2006), Lake Tecer (Kuzucuoğlu et al., 2011), and the Eastern Mediterranean region (Robinson et al., 2006; Bar-Matthews and Ayalon, 2011) indicating a regional prevalence and occurrence.

Abrupt climate events, such as sudden droughts occurring c. 4.5 to 4.0 ka BP are linked to a decline in population and social complexity, which may have contributed to the collapse of ancient civilizations in the Middle East (Degroot et al., 2021; Lawrence et al., 2022; see Table 2 for cultural shifts related to inferred paleoclimate conditions). Adapting to the changing environment likely became increasingly challenging for the agro-pastoral communities during this period. The vulnerability of the early communities to natural catastrophes, e.g., famines, droughts, and floods driven by climate change, is being increasingly recognized as a possible cause for these changes observed in cultural centers extending from Mesopotamia to China (Weiss et al., 1993; Staubwasser and Weiss, 2006; Zhang et al., 2008; Dixit et al., 2014; Sharifi et al., 2015; Sinha et al., 2019; Degroot et al., 2021; Laskar and Bohra, 2021). For example, investigations suggested that the fall of the Akkadian Empire c. 4.2 ka BP coincided with high aeolian activity (Weiss et al., 1993; Cullen et al., 2000; Lawrence et al., 2022). Severe droughts occurred in central Iran (Schmidt et al., 2011; Carolin et al., 2019) and Palestine (Issar and Zohar, 2007), coinciding with the decline in upper Egypt and Mediterranean regions. The decline could have happened due to climate variability sweeping through west Asia and further into the Indus Valley (Mashkour et al., 2013; Sharifi et al., 2015; Sarkar et al., 2016; Fallah et al., 2017; Carolin et al., 2019; Petrie and Weeks, 2018). This change is speculated to have affected agriculture, exchange and trade, and daily livelihoods, with even greater significance in southeastern Iran, where its location at the desert fringe makes it particularly vulnerable to climate fluctuations.

In recent years, researchers have aimed to pinpoint the timing of the abrupt increase in dry and dusty conditions in the Middle East, which coincided with significant societal changes c. 4.2 ka BP. Stalagmite records from Gol-e-Zard Cave in North Central Iran identified two distinct dry or dusty periods, occurring abruptly: c. 4.51 to 4.40 ka BP and 4.26 to 3.97 ka BP (Carolin et al., 2019). Notably, urban settlements in northern Mesopotamia were abandoned c. 4.19 ka BP, coinciding with the fall of the Akkadian Empire, and there were no signs of repopulation until c. 3.9 ka BP (Carolin et al., 2019). The study established a strong correlation between a significant dust event c. 4.26 ka BP and the collapse of these settlements, suggesting that these regions were vulnerable to aridity, as both phenomena lasted approximately 290–300 years. The 4.2 ka BP event resulted in a significant decline in rainfall and a decrease in discharge from the Indus River, located in a region susceptible to changes in the ISM rainfall (Giesche et al., 2019). This change aligned with the decline of the urban phase of the Harappan civilization (Kotlia et al., 2018; Giesche et al., 2019). Likewise, a speleothem from the Dharamjali Cave in the Himalayas indicates 230 years of intensified drought c. 4.2 to 3.97 ka BP, with notable dry episodes occurring c. 4.19, 4.11, and 4.02 ka BP (Giesche et al., 2023).

Shahdad was largely abandoned at the end of the fifth millennium BP, an event that has been tentatively linked with a

significant episode of flooding at the site related to the 4.2 ka BP event and associated climatic variability (Eskandari, 2021b). However, graves excavated at the site suggest continued human presence into the early centuries of the fourth millennium BP (Eskandari, 2021b). While the 4.2 event is characterized as an arid phase (Staubwasser and Weiss, 2006), the prevalence of floods raises questions. It is plausible that deforestation linked to aridification contributed to more pronounced flooding during peak rainfall. Shahr-i Sokhta appears to have been destroyed and abandoned mainly towards the end of the fifth millennium BP, although there is still some debate about the chronology (Helwing et al., 2019; Biscione and Sajjadi, 2022).

The downturn in climate towards the end of the Early Bronze Age has been regarded by many as critical to the decline/collapse in settlement, especially large urban sites, that characterized eastern Iran during the fourth millennium BP (Madjidzadeh and Pittman, 2008; Magee, 2013; Pittman, 2013; Gala and Tagliacozzo, 2014; Gurjazkaite et al., 2018; Biscione and Vahdati, 2020). Although the timing of these developments is not strictly synchronous, and regional and site-level variations can be seen, this situation is broadly described by Biscione and Vahdati (2020), who note "the abandonment by 1800/1700 BC of almost every proto-urban center east of the Tehran-Bandar Abbas line". This picture contrasts significantly with other areas of Iran, including the southwestern regions of Fars and Khuzestan, the central Zagros region (Luristan, Kermanshah), and the Central Iranian Plateau. The resurgence of sedentary sites in the Kaftari period (c. 4.2–3.6 ka BP) marks the region's densest pre/proto-historic settlements phase. Kaftari settlements relied on organized riverine irrigation systems and produced an agricultural surplus to engage with local mobile pastoralists. Analyses of charcoal deposits from the Banesh and Kaftari periods at Tal-e Malyan (Miller, 1985) indicated long-term vegetation changes across the fifth millennium BP, including deforestation of the Kur River Basin and the need to expand fuel procurement from the surrounding mountains.

3.1.10 4.0−3.4 ka BP (wet/semi-wet conditions)

This is recorded as a wet period in Lake Zeribar (Stevens et al., 2008; Wasylikowa and Witkowski, 2008). Similarly, the Jeita Cave, Lebanon, suggested a wet condition (Verheyden et al., 2008), while Lake Tecer in central Turkey recorded humid conditions c. 3.9 ka BP and from 3.6 to 3.4 ka BP (Kuzucuoğlu et al., 2011). Wet conditions in northern Syria between 4.0 and 3.7 ka BP (Fiorentino et al., 2008) and humid conditions in the eastern Mediterranean region between 3.9 and 3.7 ka BP (Roberts et al., 2008) were also reported. Likewise, geochemical records from Mediterranean lakes showed several moist episodes dominating the region between 3.9 and 3.4 ka BP (Roberts et al., 2008).

A new multi-proxy palaeoenvironmental study near the archaeological complex at Konar Sandal, southeast Iran, showed that c. 3.9 ka BP, low Ti/Al and Si/Al, and high K/Al, along with high $\delta^{13}C$ in organic matter and low C/N, suggest a wet period (Vaezi et al., 2022). Between 3.9 and 3.3 ka BP, Jiroft experienced wet/semi-wet conditions based on the average values of various elemental ratios (Si/Al, Ti/Al). The prevalence of wet conditions, extending from 3.8 to 3.5 ka BP, is further affirmed based on the dynamics of aquatic vegetation cover and abundance (Gurjazkaite et al., 2018). The semi-wet conditions in southeastern Iran are punctuated by two dry periods (Vaezi et al., 2022). They occurred c. 3.8 ka BP and c. 3.6–3.5 ka BP, respectively. The dry period is in agreement with a sharp decline in the Dead Sea level (Migowski et al., 2006; Neumann et al., 2007), and a short drought c. 3.6 ka BP in northern Syria (Fiorentino et al., 2008). The abundance of *Cerealia*-type pollen from Lake Almalou in northwestern Iran (Djamali et al., 2009b), Lake Parishan in southwestern Iran (Jones et al., 2015), and the Daryeche peat sequence in Konar Sandal (Gurjazkaite et al., 2018) are important indicators of agricultural activities during this period (Figure 2). Despite the overall minimal signs of agricultural activity from 4.0 to 3.2 ka BP, there are two possible periods of extensive agricultural activity c. 3.9 and 3.7 ka BP (Figure 3), as indicated in the pollen assemblage from Konar Sandal (Gurjazkaite et al., 2018). Consistent with this trend, the *Cerealia*-type pollen record from Lake Parishan in southwestern Iran (Jones et al., 2015) demonstrates an increase from 3.5 ka BP, reaching its peak c. 3.3 ka BP, and subsequently declining (Figure 3).

Many sites with ceramic assemblages closely related to the Oxus Civilization of southern Central Asia are now known in the Iranian and Afghan Sistan provinces (Biscione and Vahdati, 2020). They documented the continued human presence in the region into the first few centuries of the fourth millennium BC after the major urban sites and their satellites had been abandoned. Notably, both individual settlements and the overall settlement system in southeastern Iran appear to have witnessed a steep decline from the Middle Bronze Age (fourth millennium BP) onward. Although Tepe Yahya shows occupation during this period (IVA, c. 4.0–3.6 ka BP), potential contemporary settlements in Konar Sandal South (Thornton, 2012) and some nearby sites (N. Eskandari, personal communication) were abandoned during this time until c. 3.2 ka BP (Prickett, 1986a; Pfälzner et al., 2019; Shahsavari et al., 2024). After the occupation of Tepe Yahya (period IVA), which ended c. 3.6 ka BP, there is no evidence of sedentary settlement in the region for several centuries (Prickett, 1986a; Pfälzner et al., 2019; Shahsavari et al., 2024). A similar situation occurs in the Lut desert, Sistan, and Bard Sir Valley. Further afield, a dramatic reduction in known settlement at this time is also characteristic of Pakistani Baluchistan, extending even to the Indus Valley and to southern Central Asia. Biscione and Sajjadi (2022) refer to this period as the 'crisis of Bronze Age urbanism.' However, a contrasting situation arises in highland southwestern Iran, whereby the Kaftari period represents a peak in sedentary occupation in the Kur River Basin. Subsequently, in the later fourth millennium BP (Qaleh/Shogha-Teimuran periods, c. 3.6–2.9 ka BP), there was a significant decline in population at the Kur River Basin, reaching a low point in the early centuries of the third millennium BP (De Miroschedji, 2003). Additional contrasting patterns occur in Susiana and central western Iran around the fourth millennium BP. Susiana witnesses a dramatic growth in population and Elamite regional power (c. 4.0 ka BP), peaking during the Middle Elamite period (c. 3.5–3.1 ka BP) before a steep decline occurs in the subsequent Neo-Elamite period (De Miroschedji, 2003). At this time, Luristan continues to be mainly represented archaeologically by graveyards. In contrast, occupation further north in Kermanshah has identified a distinct upturn in settled occupation from the early fourth millennium BP and into the Late Bronze Age (Matthews and Fazeli Nashli, 2022).

On the central Iranian Plateau, settlements do not re-appear in the archaeological record until the mid-fourth millennium BP,

contrasting with the concurrent decline observed in southern Iran. This pattern has been linked with climate change, characterized as the 'Central Iranian Drought' (Kirsten et al., 2023, p. 2). In contrast, the Qom region exhibits a different pattern, where the settlement appears to have increased through the fourth millennium BP across the Bronze Age to Iron Age transition (Matthews and Fazeli Nashli, 2022: 263).

3.1.11 3.4–2.9 ka BP (dry conditions)

Dry conditions have been reported during this period in Lake Neor, NW Iran, with enhanced deposition of dust (Sharifi et al., 2015). Dry episodes occurred at about the same time in Lake Zeribar (Stevens et al., 2008; Wasylikowa and Witkowski, 2008), western Iran, and in Lake Maharlou, southwest Iran (Schulman et al., 2001). The change is inferred based on evaporite minerals and low fluvial input (Brisset et al., 2018). Similarly, Lake Tecer experienced dry conditions and a sharp decline in lake levels during this period (Kuzucuoğlu et al., 2011). Droughts were also reported in Lake Van c. 3.3 ka BP (Lemcke and Sturm, 1997) and the Dead Sea between 3.3 and 3.0 ka BP (Migowski et al., 2006). The dusty and dry conditions are consistent with increased Ca and K levels in the GISP2 ice core in Greenland. Mayewski et al. (1997) used K trends to indicate that the Siberian High dominated during this period.

From c. 3.3 to 2.9 ka BP, the Jiroft region was exposed to dry and windy conditions based on the high Ti/Al and Si/Al ratios and very low δ^{13}C in organic matter along with the presence of long-chain alkanes derived from terrestrial plant waxes (Vaezi et al., 2022). The prevalence of dry conditions in the region is further supported by the abundance of *Artemisia* and *Calligonum* pollen (Gurjazkaite et al., 2018). The dry conditions coincide with extended regional droughts and a pronounced decrease in cereal cultivation in the Jiroft region from 3.4 to 3.2 ka BP (Figure 3; Vaezi et al., 2022). Subsequently, the abundance of Cerealia-type pollen in the Daryache peat sequence gradually rises until it peaks at c. 2.8 ka BP.

The driest condition occurred c. 3.2 ka BP on the Iranian Plateau and coincided with dramatic disruptions in Late Bronze Age settlements in ancient Mesopotamia and the eastern Mediterranean region typically labeled as a 'collapse' (Weiss, 1982b; Table 1; Haggis, 1993; Kaniewski et al., 2010; Paulette, 2012; Kaniewski et al., 2010; Weiss, 2016; Manning et al., 2020; Baten et al., 2023). Similarly, hot and dry conditions c. 3.2 ka BP have been reported in archeological excavations from Ugarit, Syria (Alpert and Neumann, 1989). This period coincided with the decline in fluvial discharge in the Tigris and Euphrates Rivers, resulting in crop failure and the prevalence of widespread famines in Mesopotamia, ushering a steady decline (Kay and Johnson, 1981; Neumann and Parpola, 1987; Alpert and Neumann, 1989; Schulman et al., 2001; Kaniewski et al., 2010; Weiss, 2016; Manning et al., 2020; Baten et al., 2023).

Importantly, this period represents one of the few phases of near synchronicity in emerging settlements across southern Iran, in which nearly all regions display minimal evidence of sedentary occupation. In southeastern Iran, occupation was not attested to Sistan, the western Lut, the Bard Sir Valley, or the Bam region before c. 2.8 ka BP (Petrie and Weeks, 2018). However, recently published work demonstrates that, just across the border in Afghan Sistan, settlements existed in the Sar-o-Tar region c. 3.0 ka BP, supported by large-scale irrigation (Allen and Trousdale, 2019). Settlement decline, as seen in Iranian Sistan, was also thought to characterize

the Jiroft region; however, recent research has documented early Iron Age sites (c. 3.3–3.0 ka BP) at Tom-e Gavan and Konar Sandal North (Mashkour et al., 2013; Shahsavari et al., 2024), partially filling the long settlement gap and aligning with the gradual rise in *Cerealia*-type pollen recorded in the Daryache peat sequence. The dramatic reduction in settlement in the Kur River Basin through the Qaleh/Shogha-Teimouran periods was noted above, with rare occupation possibly attested further to the west at Tol-e Nurabad in the Mamasani Valley (Petrie et al., 2009). In Khuzestan, the period extending from the late fourth to the early third millennium BP witnessed a dramatic decline in settlements before a modest rise occurred in the Neo-Elamite II period (mid-third millennium BP; De Miroschedji, 2003). In Central Zagros, the Late Bronze Age sites such as Baba Jan and other sites are deserted or shrink dramatically in size at the transition to the Early Iron Age. This pattern is seen in Luristan and Kermanshah and implies a change in subsistence practices with a greater emphasis on herding over agriculture. This adaptation is thought to have been initiated by changing climate or ecology (Neumann and Parpola, 1987; Overlaet, 2013).

3.1.12 2.9–2.3 ka BP (wet vs dry conditions in Iran)

The low C/N ratios and abundance of aquatic lipids and *Sparganium*-type pollen between 2.9 and 2.3 ka BP imply that waterlogging could have been sufficient to support dominant submerged/floating macrophyte populations in Konar Sandal (Gurjazkaite et al., 2018; Vaezi et al., 2022). This multi-proxy study in southeastern Iran suggested a different climatic condition that is mainly wet, compared to previous palaeoenvironmental studies to its west on the Iranian Plateau (Figure 2). For example, dry conditions have been reported from Lakes Neor and Zeribar, northwest Iran (Stevens et al., 2008; Wasylikowa and Witkowski, 2008; Sharifi et al., 2015), and Lake Maharlou, southwest Iran (Issar and Zohar, 2007). However, consistent with the wet conditions in the Jiroft region, Lake Tecer experienced humid conditions between 2.8 and 2.0 ka BP (Kuzucuoğlu et al., 2011). Notably, there is no sign of agricultural activity in Lake Almalou, NW Iran (Djamali et al., 2009b), in contrast to the extensive agricultural practices in southeast and southwest Iran. Perhaps the dry conditions in western Iran (Figure 3) prevented agriculture, while favorable climatic conditions supported agriculture to flourish in southern Iran.

The period extending from 2.9 to 2.3 ka BP corresponds with the termination of the Elamite kingdom, followed by the rise of the Medes and the Achaemenid Empires in Iran. The rise of these dynasties coincided with the wettest period and significant agricultural activities in the Jiroft region since the decline of the Bronze Age (Gurjazkaite et al., 2018; Vaezi et al., 2022). Vaezi et al. (2022) speculate that favorable climatic conditions may have played a role in supporting socio-economic stability, supporting resource provisioning, and the territorial expansion of the Achaemenid dynasty (Figure 1). Consistent with this, an increase in known settlements has been documented in Iranian Sistan since the Achaemenid period. Similarly, an increase in settlement in Jiroft began before the Achaemenid period but was particularly clear from that period onwards (Maresca, 2018). In southwest Iran, the Achaemenid period ushered a period of substantial and consistent settlement and growth spanning more

than a millennium in both highland (Fars) and lowland (Khuzestan) regions (Sumner, 1986; De Miroschedji, 2003). Nonetheless, the simultaneous occurrence of widespread agriculture, favorable climatic conditions, and the rise of imperial powers (Medes, Achaemenids, and Seleucids) suggests a plausible climate-culture association and interdependence that should not be disregarded.

3.1.13 2.3 Ka BP to recent (mild conditions with short episodic droughts)

Dry conditions reappeared in Jiroft c. 2.3 to 2.2 ka BP based on increased aeolian input coeval with the decline in total aquatic lipids and *Sparganium*-type pollen. Notably, *Cerealia*-type pollen is absent in the peat sequence in Konar Sandal for c. 200 years (Vaezi et al., 2022). Around the same period, the highest *Cerealia*-type pollen counts occur in Lake Almalou in northwest Iran (Djamali et al., 2009b), corresponding to the rise of the Seleucid Empire between 2.3 and 2.2 ka BP (Figure 3). Likewise, a significant decrease in aeolian activity in Lake Neor (Sharifi et al., 2015), Lake Tecer (Kuzucuoğlu et al., 2011), and the Dead Sea lakes (Migowski et al., 2006) were consistent with a wet period. Thus, more investigations are needed to understand the reason for the sudden changes in land use and flip-flops in precipitation between the northwest and southeast regions in Iran.

A major increase in aeolian activity and dry conditions are predicted between 2.0 and 1.6 ka BP based on the high Ti/Al and the lowest δ^{13}C values in the Daryache peat sequence (Vaezi et al., 2022). Despite the prevailing dry conditions, Jiroft experienced a significant increase in agricultural activity between 2.05 and 1.87 ka BP, which corresponds to the rule of the Parthian dynasty (Vaezi et al., 2022). Although it may have had less agricultural activity than the Medes and Achaemenid Empires, it still witnessed agricultural productivity during dry periods not seen since the late Bronze Age. The impressive agricultural productivity observed during the Parthian dynasty could be attributed to cultural adaptation to the arid environment and significant advancements in farming practices, such as the innovative maze of qanats/canals that was developed (Petrie and Weeks, 2018).

The Jiroft region experienced wet conditions again between 1.6 and 1.3 ka BP (Vaezi et al., 2022), aligning with the expansion of the later period of the Sassanian Empire (Daryaee, 2023). The favorable climatic condition was inferred based on the sharp decrease in aeolian inputs (Ti/Al) and high values of K/Ti coupled with low C/N and high δ^{13}C in organic matter. Very low aeolian activity in Lake Neor (Sharifi et al., 2015), wet conditions in Lake Tecer (Kuzucuoğlu et al., 2011), and a sharp increase in Dead Sea lake levels (Migowski et al., 2006) are coeval to the ongoing changes in southeast Iran (Figure 3). A considerable increase in the cultivation of various trees around the Lake Almalou catchment, coinciding with the Sassanian Empire, has been reported (Djamali et al., 2009b). Thereafter, between 1.3 and 0.8 ka BP, Jiroft had mild conditions. However, the presence of *Cerealia*-type pollen is low (Gurjazkaite et al., 2018). Agricultural activities on the Iranian Plateau were marginal during this period, perhaps due to political instability and weak succession (Djamali et al., 2010b; Daryaee, 2012). Notably, several short droughts with high aeolian activity over the Iranian Plateau prevailed since 1.3 ka BP; these events were associated with war, political instability, and crises over access to resources (Sharifi et al., 2015). The decline of the Sasanian (1.3 ka BP)

and Safavid Empires (0.95 ka BP) (Djamali et al., 2010a; Daryaee, 2012) also coincided with periods of high levels of atmospheric dust deposition as in Lake Neor (Sharifi et al., 2015). Similarly, the dry conditions recorded in central Anatolia from 1.8 to 1.9 AD (c. 0.2 ka BP to present) coincided with high aeolian input in Lake Neor (Sharifi et al., 2015). The unfavorable conditions may have exacerbated socio-economic instability, potentially playing a role in weakening the Sasanian Empire and facilitating its defeat by the Islamic armies.

4 Conclusion

The high-resolution palaeoclimate records spanning the LGM and post-LGM events provide a valuable and comprehensive overview of environmental changes sweeping the Iranian Plateau. Records spanning the last 20 ka provide distinct insights into the region's temporal variability of climate and hydrological patterns. In addition, these studies advance our knowledge about palaeoclimate changes and their potential impacts on past human settlements and cultural transformations. This multifaceted approach sheds light on the complex interactions between environmental conditions and human societies, contributing to a holistic comprehension of the historical trajectory since the Neolithic period.

The strong correlation between the dust input over the Iranian Plateau with North Atlantic cooling events, e.g., Heinrich Stadial one and the Younger Dryas, supports the idea that atmospheric teleconnections most likely existed between these regions. Peak wet conditions during the early Holocene in southeastern Iran extended from 11.4 to 9.6 ka BP, whereas in western Iran, they occurred from 10.2 to 8.6 ka BP. During the early Holocene, high solar insolation played a significant role in causing changes in atmospheric circulation. Firstly, it led to the northward displacement of the ITCZ and the subsequent strengthening and northward expansion of the ISM. This caused increased rainfall and wet conditions in certain regions. On the other hand, the high solar insolation strengthened the descending air in sub-tropical high-pressure systems, leading to their northward expansion over the western Iranian Plateau. This caused dry conditions in the area, counteracting the wet conditions caused by the northward expansion of ISM.

Neolithic settlements emerged in Iran around the mid-11th millennium BP. They were founded on a mixed economy exploiting domesticated plants and animals, which allowed both seasonal and permanent sedentary settlements. First established in the Zagros mountains, Neolithic settlements were notably scarce in southeast Iran until later millennia. In eastern Iran, Neolithic settlements were strategically established around alluvial fans, allowing access to fertile soils and groundwater alongside irrigation by surface runoff capture.

Dusty, arid conditions covered the Iranian plateau c. 8.2 ka BP and subsequent cold and dry events coincided with the injection of icebergs into the North Atlantic Ocean. Between 7.8 and 6.3 ka BP, western Iran experienced a period of high humidity coinciding with the gradual expansion of oak forests. This is due to the decreased intensity and duration of the sub-tropical high-pressure systems over the Zagros region. During this period, southeastern Iran experienced a mild climate and increased precipitation. However, this region received less rainfall compared to the early Holocene.

Between 6.3 and 5.0 ka BP, a decrease in solar insolation ushered in an arid period. The reduction in insolation impacted the amount of summer monsoon rains in southeast Iran, and the region shifted from the ISM to a MLW-dominated system. However, it is essential to note that a stable climate did not characterize the late Holocene period. Instead, the region experienced fluctuations in its climatic conditions, which were attributed to the irregularity in the atmospheric circulation of the MLW during the mid-Holocene period.

Notably, there was a significant change in environmental conditions over the Iranian Plateau c. 5.0 to 4.5 ka BP. During this period, aeolian activity decreased, followed by a corresponding increase in rainfall, indicating a shift towards wetter conditions. The beginning of this wet phase coincided with Early Bronze Age settlements flourishing in southeastern Iran, suggesting improved environmental conditions may have been beneficial. This period coincided with the consolidation of an integrated oasis-based agricultural system, a fundamental adaptation for all future human settlements in eastern Iran. Concurrent developments in technologies and exchange systems marked this period as the first instance of intense intercultural contact, representing a transformative period that experienced substantial growth in socioeconomic complexity. Subsequently, the region encountered arid conditions between 4.5 and 4.0 ka BP, which was evident from increased aeolian input and dry conditions, particularly c. 4.2 ka BP in Western Asia. This downturn in climate towards the end of the Early Bronze Age is coeval to the observed decline of large urban sites that characterized eastern Iran from the early fourth millennium BP. This dramatic change in environmental conditions is associated with the widespread decline of Early Bronze Age settlement across many (but not all) regions from Mesopotamia to China. The environmental changes likely impacted agricultural productivity and are correlated with the abandonment or relocation of settlements on the Iranian Plateau. Except for a wet period in the western region and a semi-wet phase in southeastern Iran from c. 4.0 to 3.4 ka BP, overall arid conditions prevailed in both regions from c. 4.5 to 2.9 ka BP. The driest conditions centered c. 3.2 ka BP coincided with the regional Late Bronze Age cultural decline across many areas of Iran, Western Asia, and the Mediterranean.

Consistent with various studies, we believe favorable climatic conditions contributed to increased socioeconomic stability, which seems more than coincidental and likely played a role in the success of the Persian Empires. The wet conditions from c. 2.9 to 2.3 and 1.6 to 1.3 ka BP, aligned with the expansive reigns of the Achaemenids and Sassanians. Despite arid conditions, the impressive agricultural productivity during the Parthian rule is attributed to cultural adaptation to the dry conditions and advancements in farming practices. Droughts during specific historical periods likely affected agricultural productivity, access to water resources, and overall food security, which could have

destabilized these empires. Nevertheless, the interplay between environmental changes and the rise of organized human settlements is a complex and multidimensional phenomenon that calls for a comprehensive and more nuanced understanding of the historical, archaeological, and climatological evidence.

Author contributions

AV: Conceptualization, Data curation, Formal Analysis, Investigation, Writing–original draft, Writing–review and editing. LW: Conceptualization, Formal Analysis, Writing–original draft, Writing–review and editing. JR: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Project administration, Writing–review and editing, Writing–original draft.

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