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Investigating the impacts of 4.2 ka and 3.2 ka BP climatic events on wheat and barley cultivation in the Bronze Age Kingdom of Mukish: Evidence from Tell Atchana and Toprakhisar Höyük (Hatay, Türkiye)

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ABSTRACT

This research investigates the impact of 4.2 ka and 3.2 ka BP climatic events on the agricultural practices of the Bronze Age Kingdom of Mukish by evaluating wheat and barley remains in archaeobotanical data sets acquired from two sites, Tell Atchana (Alalakh), a capital city, and Toprakhisar Höyük, a periphery site, both located in the Hatay province of southern Türkiye. The aim of this study is to determine whether, and to what extent, these climatic events affected the local agricultural strategies. Stable carbon isotope analysis on wheat and barley grains was also carried out to examine the water conditions under which the plants were grown. The findings demonstrated a shift toward drought tolerant barley at Toprakhisar at the end of the 3rd millennium BC, and at Tell Atchana between 1350 and 1200 BCE. Isotopic evidence indicated water stress at Toprakhisar from the beginning of the 2nd millennium BC and at Atchana during the latest phases of the LBA. The timing of shifts in crop preferences and the traces of water stress suggest a response to increasing aridity associated with the 4.2 ka BP and 3.2 ka BP climatic events. At Toprakhisar, the occupation seems to flourish in the corresponding period. By contrast, at Atchana, Hittite administrative control may have further influenced agricultural strategies to buffer the impacts of the 3.2 ka BP event by prioritizing barley production and investments in irrigation as mentioned in the textual sources. Overall, the findings highlighted the drought coping mechanisms adopted by the communities, rather than a total collapse of their agricultural systems during times of environmental variability.

1. Introduction

The Holocene epoch, the last ∼ 11700 years, is the most recent interglacial period of Earth (Walker et al., 2019). Even though interglacial periods provide suitable climate for organisms to flourish, rapid climate changes, caused by factors like solar radiation and ocean water circulation (Clarke et al., 2016; Staubwasser and Weiss, 2006), might lead to changes in the social, cultural, economic, and ideological dynamics of societies eventually affecting how they organize and adapt during these periods. It has been suggested that the Holocene period witnessed six such rapid climate changes on a global scale (Mayewski et al., 2004).

By deriving information from past and contemporary examples, Flohr et al. (2016) suggests that four scenarios are possible when social entities face climatic anomalies. The collapse of the economic system and the subsequent breakdown of social and political structures (Weiss and Bradley, 2001; Weninger et al., 2009), migration to more favorable environments known as refugia (Black et al., 2011; Leppard, 2014; Meze-Hausken, 2000), the development of resilience by adapting systems to the new conditions (Adger, 2006; Leslie and McCabe, 2013), and no response if the climatic anomaly is not large enough to affect societies adversely are the scenarios presented. While these categories provide a

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structured framework for understanding past societal behaviors, responses were often complex and could involve multiple overlapping strategies. In addition, the limitations of monocausal explanations that directly link environmental change to social crises have long been recognized (Butzer, 1982; Rosen, 2007; Rosen and Rosen, 2001). Still, despite their seemingly ordinary and mundane appearance, weather and climate have the power to grab attention and may evoke strong reactions (Strauss and Orlove, 2003). Furthermore, social memories of communities are important sources of information on historical climate change and human adaptation which climate scientists frequently lack access to. As a result, the theoretical position adopted by the archaeologists defines that to what extent climate change is regarded as a significant aspect of human history (Risch et al., 2015; Van De Noort, 2011). Nonetheless, there is a necessity to acknowledge the importance of the climate, as any deviation in it, whether long-term or short-term, directly affects the lives of those who experience it. Even though climate change does not have to be the sole reason for societal change, it can be seen as a contributing factor together with other, possibly destructive, changes in the sociopolitical fabric. Therefore, distinguishing between correlation and causality in the relationship between climate and societal change remains essential. At the same time, human agency and resilience are intertwined, as the ability to adapt and respond to challenges is an inherent aspect of social existence (Hastrup, 2013).

In the context of agricultural systems, farmers have been known to employ diverse exploitation patterns for their subsistence in times of environmental variability. They have been known to reserve emergency foods that are not normally eaten, or to cultivate in dispersed fields in order to minimize the risk of total loss of preferred crops, even if this results in less efficient cultivation (Garnsey and Morris, 1989; Rosen, 2007). The agricultural decision-making in the ancient Near East from Neolithic through Iron Age during the Chalcolithic, Bronze Age, and Iron Age and the effects of climate anomalies on agricultural preferences were previously investigated in several studies that focused on archaeobotanical data (Deckers and Riehl, 2007; Marston, 2017; Riehl, 2010a, 2010b, 2009, 2008; Riehl et al., 2014, 2012, 2009, 2008; von Baeyer et al., 2021). A range of studies have also been conducted in order to investigate the variation and change in archaeobotanical evidence and isotope analysis on cereal grains (Araus et al., 1997; Araus and Buxo, 1993; Ferrio et al., 2007, 2005; Fiorentino et al., 2012, 2008; Flohr et al., 2011; Vignola et al., 2017; Voltas et al., 2008; Wallace et al., 2015).

Building on this foundation, the present study focuses on the 4.2 ka and 3.2 ka BP climatic events of the Holocene epoch, which were described as rapid climate changes (Mayewski et al., 2004). It is carried out on archaeobotanical remains from Tell Atchana and Toprakhisar Höyük, two sites in Amuq Valley of Hatay, which belong to the same regional economic and political system. Tell Atchana was the regional capital, while Toprakhisar was a rural site controlled for olive oil and wine production (Akar and Kara, 2018). This article aims to investigate the possible effects of these climatic events on wheat and barley cultivation in the specified region, based on the premise that these climate events occurred, rather than engaging in debates about their existence or precise nature. We believe that the archaeobotanical remains presented here might contribute to the discussions on how these climatic events were experienced by the societies in Amuq plain and western Syria in general. Additionally, they serve as proxy data and enhance our understanding of how climate anomalies influenced agricultural systems. Examining these remains also enables us to explore how past societies shaped their social and economic responses during these climatic events.

Two key variables were considered when examining the possible agricultural adaptations to climate change in order to meet the abovementioned research objectives. The first variable measures whether communities responded to drier conditions by choosing more drought-resistant grains, i.e., barley (Riehl, 2009). More tangible evidence of past environmental stress is provided by the second variable which examines the existence of drought signals in the stable isotope analyses of wheat and barley.

1.1. 4.2 ka BP event

The 4.2 ka BP event is suggested to have had its most significant impacts beginning around 2200 BCE, continuing for approximately 300 years, according to high resolution climate records (Staubwasser and Weiss, 2006). In many parts of the world, including North and South America, Europe, Africa, and Asia, this climate event was reported (Berkelhammer et al., 2012; Bond et al., 2001, 1997; Booth et al., 2005; Drysdale et al., 2006; Liu and Feng, 2012; Ran and Chen, 2019; Thompson et al., 2002; Wang et al., 2005; Yu et al., 2003) which has led some scholars to propose that the event may have been global in scope. The proxy records of the Nile Valley suggested a more saline sea surface caused by reduced precipitation, decreased water discharge of the Nile River, and extended desertification in the corresponding period (Welc and Marks, 2014). This event was suggested by some researchers as one of the two most damaging climatic catastrophes in the history of the Indus Valley. The Indian summer monsoon lost efficiency due to a drop in the rate of Indus River discharge, according to isotope studies (Ran and Chen, 2019). At the same time, the precipitation brought on by Mediterranean westerlies fell by about 30 % to 50 % (Weiss, 2016). The study by Carolin et al. (2019) identifies two discrete climate events occurring at 4.5 ka and 4.2 ka, with the latter being more protracted and impacting a more expansive geographical area, extending to a significant portion of the Middle East.

Yet, Mayewski et al. (2004) describes the event as “less widely distributed” and suggests the presence of an aridity lower latitudes, retreat of glaciers in Europe and glacier expansion in northwestern North America. Recent research contradicts the notion of a uniformly severe or globally synchronous event. More and more research is showing how complicated this climate event was in terms of spatial and temporal dimensions. This indicates that the 4.2 ka event may lack significance in numerous locations. McKay et al. (2024) indicate that while certain datasets suggest significant climate changes around 4.2 ka BP, these changes are not consistently observed across extensive regions globally. This analysis is grounded in a comprehensive examination of global paleoclimate data derived from various archive and proxy types and suggests that in the broader context of Holocene climate variability, the 4.2 ka BP event appears to be of limited significance. Scroxton and McKay (2024) indicate that high-resolution paleohydroclimate records reveal minimal changes in the Indian Ocean during this period, suggesting that the event had a limited impact on tropical monsoonal rainfall across the basin. James et al. (2025) discuss speleothem-based records from Asia that indicate variations in paleohydrology throughout the Holocene. Nevertheless, the evidence indicates that approximately 4.2 ka BP, these records exhibit inconsistencies throughout Asia, suggesting the occurrence of a regional event. The studies indicate that, although local anomalies may be identifiable, the 4.2 ka BP event is neither as severe nor as coherent as previously suggested in the literature. This indicates the necessity of interpreting the event in relation to the region and considering the contextual factors involved.

In the context of Anatolia, the present results are also contradictory. While the proxy records taken from Lake Van (Lemcke and Sturm, 1997; Wick et al., 2003), Nar Gölü (Dean et al., 2015), and Eski Acıgöl (Roberts et al., 2008) point to a decrease in lake levels, as well as a decrease in humidity and vegetational change towards drought-tolerant plant species, a more recent study suggests no strong or consistent signal indicative of a regional climate shift for Anatolia around 4.2 ka (Ön, 2023).

The challenges of directly correlating climate change with social transformations in Western Asia, along with the spatial and chronological complexity of the event, has also been extensively debated (Kuzucuoğlu and Marro, 2007; Meller et al., 2015). 4.2 ka BP climatic anomaly has been attributed by some to the breakdown of various states and urban centers. According to Staubwasser and Weiss (2006), Mohenjo Daro and Harappa lost their urban characteristics due to gradual abandonment and became rural sites at about 4.2 ka BP event.

Staubwasser et al. (2003) speculate that the decrease in yearly rainfall may have resulted in a decrease in water discharge of the Indus River, on which Indus agriculture is heavily reliant. In the Khabur Valley in North Syria, the Akkadian occupations were abruptly abandoned in 2175 ± 150 BCE. Weiss et al. (1993) consider this to be evidence of a drop in agricultural output and link Tell Leilan's abandonment to climatic change. Further studies of various proxies testified to aridity for the same period and various researchers have connected the climate anomaly with the downfall of the Akkadian empire (Cullen et al., 2000; DeMenocal, 2001; Fiorentino et al., 2008). Furthermore, Weiss (2016) claims that the "global megadrought" produced by 4.2 ka BP event resulted in "habitat-tracking" behavior in the populations of other settlements of western Syria and northern Mesopotamia. The new habitat tracking necessity is caused by insufficient products coming from rainfed agriculture. However, these claims have been met with a degree of skepticism by Marro and Kuzucuoğlu (2007), who argue that there is a lack of evidence to support the claims of an overall crisis or collapse in settlement patterns in Upper Mesopotamia and Northern Syria at the end of the third millennium BC. Moreover, settlement data, multi-proxy environmental records, and bioarchaeological studies indicate the existence of either local resilience and adaptation or continuity (Sołtysiak and Fernandes, 2021; Ur, 2015) in the Near East throughout this period. Going beyond the climate-related explanations, Lawrence et al. (2021) and Wilkinson (1997) assert that, independent of the 4.2 ka event, the environmental conditions in the region already became unsustainable due to resource overexploitation during that time period. Collectively, these studies challenge the concept of a unified climatic catalyst for collapse and promote a more complex, context-specific understanding of the socioeconomic implications of the 4.2 ka BP event.

The integration of archaeological, archaeobotanical, and stable isotope analyses carried out at Troy by Blum and Riehl (2015) suggests changes in agricultural conditions from 2500 to 2000 BCE which are linked to a reduction in moisture and nitrogen availability. Although many settlements along the western coast of Anatolia faced a decline in cultural and economic relations with the surrounding regions during this period, Troy seemingly preserved continuity and demonstrated resilience even during the so-called collapse linked to the 4.2 ka BP event. Similarly, research carried out in Anatolia indicates that the effects of this climatic event did not uniformly lead to societal collapse. For instance, Abay (2007) points to a brief crisis at the end of the 3rd millennium BC in the Karababa dam region of southeastern Anatolia that is characterized by disruptions in the political and economic systems that did not affect material culture or occupation patterns. Massa (2014) proposes that the rise in fire incidents and the demise of villages in central and western Anatolia between 2250 and 1950 BCE may be attributed to the arrival of migrating populations displaced by environmental pressures which is a pattern also suggested for Northern Mesopotamia. Bal and Pişkin (2024) analyze the plant and animal remains from western Anatolia, observing an increase in barley, glume wheats, drought-resistant pulses, and a greater dependence on goats and wild animals, indicating strategic adaptations in provisions rather than complete failure of the societies. This variety emphasizes that while some regions exhibit indications of population or economic stress, others have responded the environmental stress through modifications in agropastoral practices.

1.2. 3.2 ka BP event

The 3.2 ka BP event coincided with the transition period from the Late Bronze Age to the Early Iron Age in the Near East. It began around 1200 BCE and lasted for nearly 300 years (Kaniewski et al., 2013). This climatic anomaly was marked by cooler and drier conditions as was the case for 4.2 BP event. As in the case of 4.2 ka BP event, the 3.2 ka BP event was also associated with several societal crises across the world. At the end of the Late Bronze Age, Greece, Anatolia, Mesopotamia, and Egypt witnessed a succession of abandonments and destructions and these downfall was associated with the climate change in several studies (Drake, 2012; Finné et al., 2017; Kaniewski et al., 2015, 2013, 2010; Kaniewski and Van Campo, 2017; Knapp and Manning, 2016; Langgut et al., 2013; Neumann and Parpola, 1987; Weiberg and Finné, 2018; Weiss, 1982). Kaniewski et al. (2010) identified drier conditions in coastal Syria from the late 13th/early 12th centuries BCE, lasting until the 9th century BCE while Kaniewski et al. (2013) identified a significant anomaly in annual precipitation based on various proxy data, including pollen records, paleo-shorelines, lake sediments, and d^{18}O speleothem scores from a large number of sampling locations in Syria, the Nile Delta, Israel, the Dead Sea, the Eastern Mediterranean, and Cyprus. More arid conditions were also identified in the Jableh Plain of northwest Syria based on pollen record. While between 1100 and 800 BCE, the region's flora consisted of warm-steppe plants. However, starting around 900 BCE, when aridification was at its peak, pollen data indicated a biome dominated by hot desert plants Kaniewski et al. (2008).

This period also witnessed the much-debated "invasion" of the Mediterranean, Levant, Mesopotamia, and Egypt by the so-called "Sea People" whose identity, origin and motivation remain unclear. The case is evidence that there was an intense movement of populations in the region (Cline, 2012). The Sea People's attacks on settlements were proposed as the last step of a bigger, climate-induced crisis (Kaniewski et al., 2015). Egyptian records indicate Ugarit's destruction between 1194 and 1175 BCE, suggesting a possible causal link between drought and the regional instability. Recently, Manning et al. (2023) identified a dry period around 1198–1196 BCE (±3) coincided with the collapse of the Hittite Empire, probably acting as a trigger that overwhelmed their risk mitigation systems. According to other written texts found in Egyptian, Ugaritic and Hittite archives, it has been argued that Hittites were heavily dependent on the grain imported from Egypt and the Levant in the late 13th century BCE due to famine experienced in the mainland (Divon, 2008; Halayqa, 2011; Klengel, 2011; Knapp and Manning, 2016; Singer, 1999; Warburton, 2003). A letter from Hittite king Arnuwanda III mentions a severe famine in Anatolia experienced by his father, citing the drought as the only cause of the food scarcity (Kaniewski et al., 2015). These records suggest that food insecurity linked to climate variability significantly affected sociopolitical stability in the region.

This climatic anomaly during this period was further supported by the environmental proxies from inland Anatolia where lake sediments and isotopic records also point to drier conditions (Kuzucuoğlu et al., 2011; Manning et al., 2023; Roberts et al., 2001). The eastern Mediterranean climate during this time was also characterized by colder temperatures (Finné et al., 2011), consistent with findings by Avşar et al. (2019) which used ITRAX micro-XRF analysis of sediment cores from Tell Atchana and Tell Tayinat to identify anomalous Ca/Ti levels between 1200 and 900 BCE. These records further underscore the extent of drought stress in both coastal and inland areas.

This climatic and political turbulence appears to have affected agricultural production as well, particularly in rainfed systems. Archaeobotanical evidence from Tell Tweini in coastal Syria shows that, despite destruction in the early 12th century BCE, urban life, agricultural activity, and trade resumed in the Iron Age (Fuller et al., 2024). In Southwest Asian sites, the olive and grape seed and charcoal assemblages point to a decline in the cultivation of these drought-sensitive perennials during and shortly after the 3.2 ka BP event which highlights their vulnerability to prolonged arid conditions (Deckers et al., 2024). Yet, similar to 4.2 ka BP event, the impact of the 3.2 ka BP event on societies and agriculture was not uniform across the region, as Hazell et al. (2022) point out. While aridity appears to correlate with societal "collapse" in parts of the northern Levant, archaeological and paleoclimate records are inconsistent in the southern Levant, and it prevents the region-wide conclusions for this area. Furthermore, for Anatolia and Southeast Europe, the paleoclimate evidence is differential.

1.3. The occupational history of Toprakhisar Höyük and Tell Atchana (Alalakh)

The environmental geography of the Amuq plain, in which the two sites are located, extends to an area of nearly 900 km^2. The plain is surrounded by the Amanus Mountains to the west, uplands to the east and south, and hills to the southwest. It is fed by three rivers: Orontes, Afrin, and Kara Su (Casana and Wilkinson, 2005). The Amuq Plain and its surroundings experience a Mediterranean climate, characterized by hot, dry summers and mild, rainy winters. Annual precipitation in the region varies between 505 and 1,078 mm (Özşahin and Kaymaz, 2014).

The plain and its surroundings have been crucial historically due to their strategic location connecting various geographical and cultural zones, namely Anatolian, eastern Mediterranean, Levantine-Palestine, and northern Syro-Mesopotamian regions (Yener et al., 2000) (Fig. 1). The Amuq plain, a conjoint point for multiple cultures, may have influenced different responses to catastrophic events such as drought-induced famine. The availability of water resources, especially the Orontes River, may have facilitated different adaptations, particularly in response to climate anomalies, resulting in unique local adaptations.

1.3.1. Toprakhisar Höyük

Toprakhisar Höyük, located in the Altınözü district of Hatay, covers an area of at least 2 ha, although the exact size remains undetermined due to the destruction caused by the Yarseli Dam and the expansion of the modern Toprakhisar village (Fig. 2). The site is situated along the narrow Beyazçay Valley, a tributary of the Orontes River that originates in the Yayladağ Mountains and flows through the Altınözü district. Surrounded by low hills, the valley forms a natural corridor linking the Amuq Plain with Toprakhisar village. The surrounding hills are currently covered with olive trees, and olive oil production constitutes the primary economic activity in the region (Akar and Kara, 2018).

Toprakhisar Höyük was identified as one of the rural periphery settlements under the control of the urban site of Alalakh in the 2nd millennium BC, which is nearly 15 km from Toprakhisar (Akar and Kara, 2018). Akar & Kara (2018) suggested that Toprakhisar might have been one of the places that specialized in olive oil production mentioned in the Alalakh texts. Indeed, the MBA administrative building (Building 2) at Toprakhisar provides archaeological evidence for the organized production of olive oil. The presence of grapes and olive remains in the archaeobotanical samples analyzed in this study has also been documented. However, a comprehensive discussion of all botanical taxa is beyond the scope of this article. Future research may address additional plant remains to provide a broader perspective on agricultural diversity in the region. The rescue excavations started by the Hatay Archaeology Museum in 2016 (Akar & Kara, 2018) and recent excavations exposed a chronological sequence from 2100 to 1900 BCE (EBIVB to MBI).

1.3.2. Tell Atchana

Tell Atchana, covering approximately 22 ha, is situated on the Amuq Plain of Hatay, adjacent to the Orontes River which is the largest water source in the region (Fig. 2). Historically, the plain also featured the Lake of Antioch, which likely began expanding from second to first millennia BC (Yener, 2005) but was drained in the 1970 s due to government policies (Varnacı, 2008). Today, the primary agricultural products of the Amuq Plain include wheat, cotton, and sunflower.

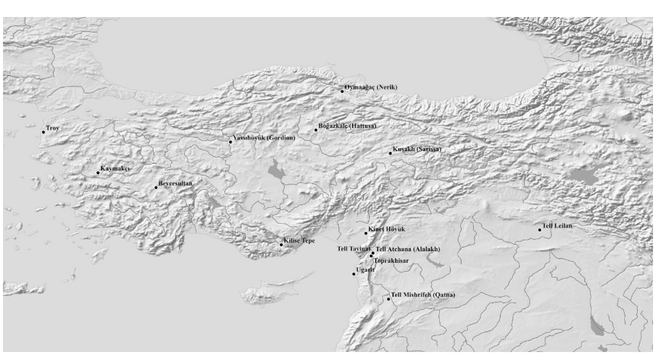

Fig. 1. The figure shows the location of Toprakhisar Höyük, Tell Atchana and other Near Eastern sites referred to in the text (map by Ebrar Sinmez).

Tell Atchana is one of the major Middle and Late Bronze Age sites in the plain (Yener et al., 2000). It was the capital city of the Late Bronze Age Kingdom of Mukish and was known as Alalakh in the 2nd millennium BC. Alalakh was a vassal state of the Yamhad Kingdom based at Aleppo during the Middle Bronze Age, followed by the Mitannian and Hittite hegemony in the region during the Late Bronze Age (Yener et al., 2000). Level VII marks the establishment of the Yarim-Lim dynasty (ca. 1750–1650 BCE) and provides the first written documents through the discovery of tablets from the palace, which was burnt at the end of the MBA possibly by Hittites. In the subsequent period, LBA I, a new Palace was constructed by King Idrimi (Level IV, ca. 1500 BCE) and the city was under the control of the Mitannian kingdom (Yener, 2013a). During the LBA, Alalakh became a target of the Hittites in their Syrian expansion policy. The Hittites first attacked Alalakh in the 17th century under the command of Hattusili I, achieving success over Alalakh's troops (Bryce, 2005). After almost a century (Level VI-V), the city regained its economic prosperity with the support of the Mitannian king Paratarna in the first half of the 15th century BCE. However, in the 14th century, another Hittites military campaign targeted the city again, leading Hittite domination (Yener and Akar, 2013). The Hittite hegemony over the Amuq Plain lasted nearly 130 years, from the last third of the 14th century BCE to the end of the 13th century BCE, during which Alalakh maintained its administrative character (De Martino and Devecchi, 2020). Towards the end of the LBA, the Mukish Kingdom, and probably Alalakh, played a crucial role in shipping grain to the Hittite mainland in central Anatolia (Cohen, 2017). Interestingly, texts from the Ugarit archives indicate that the welfare of the Amuq plain was not favorable during this period. Documents suggest that in the last quarter of the 13th century BCE and the beginning of the 12th century BCE, Alalakh and Mukish needed external help in terms of labor force to revive their agriculture (De Martino and Devecchi, 2020).

In the earlier years of excavation at the site, the lack of Iron Age evidence led researchers to believe that there was a shifting occupation between Tell Atchana and its neighboring mound, Tell Tayinat, which has Iron Age layers and was settled earlier in the Early Bronze Age. However, subsequent excavation sequences in later years established that Tell Atchana continued to be occupied in the temple area, even though its site-wide occupation ended around 1300 BCE. The site continued to be inhabited during the Iron Age around the middle of the 12th century (Yener, 2013b) In fact, Tell Atchana and Tell Tayinat together might represent a megacity throughout EBA to Iron Age (Akar et al., 2021). Even though the core of the city moved to different areas in the landscape because of the changing riverbed of the Orontes, the name of the megacity remained same throughout the time (Yener, 2005). The downfall of this megacity confirmed by the pottery evidence indicating that the temple area at Tell Atchana was still in use at the beginning of the Iron Age, although the overall occupation area of the site is thought to have declined (Montesanto and Pucci, 2019). Yener (2013b) also suggest that during the final phase of the LBA, Atchana was greatly reduced in size and ruralized. They propose that the 3.2 ka BP climate event could be the reason for this ruralization. The aridification caused by the 3.2 ka BP event was also evidenced in the sediment cores taken from the lands between the Tell Atchana and Tell Tayinat (Avşar et al., 2019) complementing the argument of Yener (2013b).

Two major factors add value to the integration of the results of these specific sites. First, the different ecosystems in which the two sites were located may have allowed or forced different solutions for these climate anomalies. The second factor, and perhaps more important in this particular case, refers to the different political/economic positions of the sites that may have determined their responses to climatic anomalies.

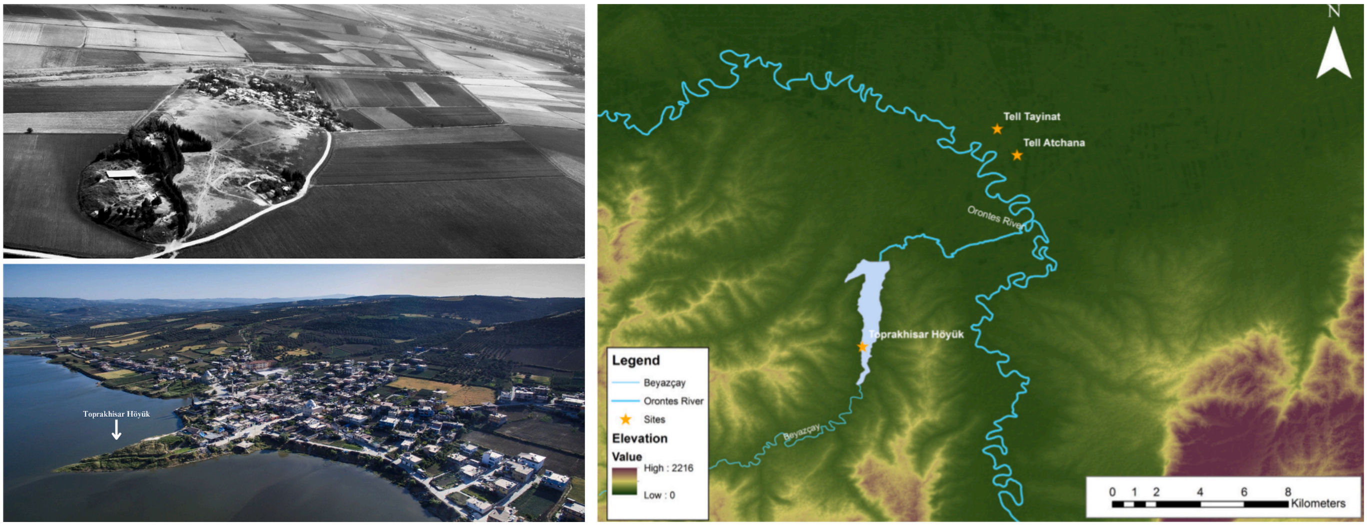

Fig. 2. The figures show the aerial views of Tell Atchana (top-left) and Toprakhisar Höyük (bottom-left) (Photos: Murat Akar), and digital elevation model of Toprakhisar Höyük, Tell Atchana and Tell Tayinat in Amuq Plain (right, Image Source: Akar & Kara, 2018).

Tell Atchana, as the capital and seat of political power, may have had many more options for provisioning its population, of which a good portion would have belonged to the elite and army, with the necessary food supplies. When there was a shortage of crops, foodstuff importations and/or taxes may have been sufficient to face the crisis. Toprakhisar on the other hand, as a rural site, may have been in starker need than the capital and may have been necessary for its inhabitants to innovate and find alternative agricultural practices. This situation allows us to build a comprehensive regional model as to how both climatic anomalies may have variously affected sites in a given area rather than if we were to study a single site or many but unconnected sites. Thus, the potential changes in agricultural practices, agricultural products, and consumption patterns caused by climatic anomalies in these mounds were investigated through macrobotanical remains comprising nearly 1000 years of the period between 2200 BCE and 1200 BCE.

2. Material and methods

2.1. Sampling and recording system

Both Toprakhisar Höyük and Tell Atchana excavations use the locus-lot system and employ systematic and judgmental sampling strategies for archaeobotanical data collection. From every locus, ~30 L of soil were taken for flotation (systematic sampling). Additionally, contexts that potentially contained plant remains (e.g.,ashy contexts such as hearths, or storage areas) were sampled (judgmental sampling). Flotation was conducted using an Ankara-type flotation machine, and identification on 4 mm, 2 mm, and 1 mm sized plant remains was done with a Leica S8AP0 stereo microscope. During identification, cereal grains that have embryo part were counted and recorded. For other crop plant taxa, each fragment was counted and recorded separately. The cereal identification manual of Jacomet (2006), the economic plant atlas of Neef et al. (2012), and the plant seeds and fruit identification manual of Cappers and Bekker (2013) were used for reference. Additionally, the plant reference collection of the Environmental Archaeology Laboratory of METU was benefitted.

Due to the poor state of preservation of plant remains at both Tell Atchana and Toprakhisar Höyük, the identification of cereals was constrained to broader categories. A significant proportion of grains exhibited high levels of distortion, which complicated species-level identification. Consequently, to ensure accuracy, wheat remains were classified conservatively as either free-threshing (*Triticum aestivum/durum*) or hulled (*Triticum monococcum/dicoccum*) wheat.

The proportions of the cereal species were calculated within the crop plant remains. These economic plants include domesticated legumes (Fabaceae, species not identified), grapes (*Vitis vinifera*, both pips and pedicels) and olive (*Olea europaea*) for both Atchana and Toprakhisar. The ubiquity, which means the proportion of a presence of particular taxon among all the archaeobotanical samples (Hubbard, 1980; Pearsall, 2000) were also calculated to see the depositional patterns (Marston, 2014).

2.2. Archaeobotanical materials

A total of 75 Toprakhisar samples were analyzed: 67 samples from Square 51/52.37 covering three archaeological layers (from 2100 to 1900 BCE) and 8 from Square 54.38 belonging to two different layers (from 2100 to 2000 BCE). The contexts of Square 51.37 included pits, hearths, a ceramic found on a bench, floors of different rooms and courtyards. The samples from Square 54.38 belonged to silos, a grave, and pits (for the details of the contexts, see Supplementary).

The total number of samples analyzed from Tell Atchana was 209. Of these, 120 samples come from Square 42.10, representing six distinct archaeological phases (from 1400 to 1100 BCE), and 89 samples come from Square 32.57, representing four different phases (from 1750 to 1400 BCE). In addition, morphometric measurements were taken on 22 free-threshing wheat grains from an MBA (17th century BCE) kitchen context from Tell Atchana (the context is the topic of the MA dissertation of Burgaç (2022). The contexts of the samples in Square 42.10 were very diverse including tandır ovens, room and courtyard floors, street, trash and sacrificial pits, hearths water drains, and jars. The contexts of the samples from 32.57 include pits, room fills, post-holes, silos, trash pits, hearths, kilns, ashy deposits, street floors.

The dating of the individual phases is not detailed here but is presented in the tables below (Tables 1–3). It should be noted that all the sequence presented from both sites are local phases based on the stratigraphy acquired from each excavation square and their dating is tentative.

2.3. Stable carbon isotope analysis

Stable carbon isotope analysis was carried out for free-threshing wheat, hulled wheat, and barley grains. Multiple grains were sent for analysis, when possible, to identify the intra-sample deviations. $\Delta^{13}C$ values were calculated following Farquhar et al. (1982) to calibrate $\delta^{13}C$ readings for atmospheric CO_2 variations over time. The atmospheric CO_2

Table 1
The table shows the proportion and ubiquity of plants in differentiating phases of plan-Squares 51/52.37 and 54.38 at Toprakhisar Höyük.

Square	51/52.37			54.38		51/52.37			54.38	
Local Phase	**2**	**3**	**4**	**1**	**2**	**2**	**3**	**4**	**1**	**2**
Date	2000–1900BC	2000–1900BC	2100–2000 BCE	2100–2000 BCE	2100–2000 BCE	2000–1900BC	2000–1900BC	2100–2000 BCE	2100–2000 BCE	2100–2000 BCE
Total number of cereal remains	76	282	13	28	43	76	282	13	28	43
Samples (n)	5	59	3	2	6	5	59	3	2	6
	Proportion					**Ubiquity**				
Triticum monococcum/dicoccum	4.08	2.52	0.00	6.78	0.59	40.00	13.56	0.00	50.00	16.67
Triticum durum/aestivum	8.16	4.36	0.00	0.00	1.78	100.00	25.42	0.00	0.00	50.00
Triticum sp.	20.41	22.02	4.00	11.86	4.14	80.00	44.07	33.33	100.00	66.67
Hordeum vulgare	9.18	3.44	0.00	5.08	4.14	60.00	16.95	0.00	100.00	66.67
Avena sativa	2.04	2.52	0.00	0.00	0.00	40.00	11.86	0.00	0.00	0.00
Cerealia indet.	32.65	30.05	36.00	23.73	11.24	100.00	49.15	66.67	50.00	66.67
T. monococcum spikelet fork	0.00	0.46	4.00	0.00	1.18	0.00	3.39	33.33	0.00	33.33
T. dicoccum spikelet fork	0.00	0.69	0.00	0.00	0.59	0.00	5.08	0.00	0.00	16.67
T. aestivum rachis segment	0.00	0.00	0.00	0.00	0.59	0.00	0.00	0.00	0.00	16.67
Indet. *Cerealia* rachis node	0.00	0.00	8.00	0.00	0.00	0.00	0.00	33.33	0.00	0.00
Indet. *Cerealia* rachis internode	1.02	0.00	0.00	0.00	0.00	20.00	0.00	0.00	0.00	0.00
Indet. *Cerealia* rachis segment	2.04	1.15	0.00	0.00	0.59	40.00	8.47	0.00	0.00	16.67
Indet. *Cerealia* rachis lemma/palea	0.00	0.00	0.00	0.00	0.59	0.00	0.00	0.00	0.00	16.67
Indet. Legume	12.24	18.81	44.00	3.39	7.10	20.00	30.51	66.67	50.00	50.00
Vitis vinifera fragments	5.10	8.26	0.00	3.39	8.28	60.00	27.12	0.00	50.00	33.33
Vitis vinifera pedicel	0.00	0.46	0.00	0.00	0.00	0.00	3.39	0.00	0.00	0.00
Olea europaea fragments	3.06	5.28	4.00	45.76	59.17	20.00	10.17	33.33	50.00	83.33

values presented by Ferrio et al. (2005) and Riehl et al. (2012) were used for this calibration.

For the barley grains gathered from Near Eastern mounds (including Atchana), the $\Delta^{13}C$ value ranges between 15 ‰ and 18 ‰ (Riehl et al., 2014). Below 16 ‰ represents high aridity stress. The values between 16 ‰ and 17 ‰ are considered moderate drought stress, whereas the values above 17 ‰ point to sufficient water availability (Riehl, 2020; Riehl et al., 2014). The moderate water stress range is between 15 ‰ and 16 ‰ for wheat. Because wheat is more sensitive to water shortage than barley, Ferrio et al. (2005) reported that $\Delta^{13}C$ values of wheat grains are lower in drier environments compared to barley.

3. Results

3.1. Overview of cereal assemblages

The proportion and ubiquity of the archaeobotanical assemblages are presented in Tables 1–3. When evaluating the samples from both Atchana and Toprakhisar, it was observed that free-threshing wheat increased in the transition period between 2100–2000 BCE and 2000–1900 BCE (Fig. 3). In Phase 1 of Square 54.38 (2100–2000 BCE), free-threshing wheat was absent, but appeared at the beginning of the 2nd millennium BC, reaching its highest percentages in MBA samples (Phase 4 of Square 32.57), often over 40 %. The barley proportion was very high at the end of the 3rd millennium BC, nearly or over half of the cereals, but its importance gradually decreased in the early 2nd millennium BC. Barley never became the dominant crop in the following first half of the 2nd millennium BC. Hulled wheat was present in both the 3rd and 2nd millennium BC layers but decreased in the early 2nd millennium BC.

At the transition to the second half of the 2nd millennium BC (Square 42.10 samples-LBA), free-threshing wheat decreased, and was less abundant than in the MBA. Barley gained importance in the LBA, and with hulled wheat species, they became the dominant crops. The importance of hulled wheat species decreased in the MBA, but increased in the LBA, especially in Phase 4 of 42.10 (1300–1200 BCE), which dated to the very end of LBA (Fig. 3).

3.2. Stable carbon isotope results

The average stable carbon isotope values of the free-threshing wheat, hulled wheat, and barley are presented in Table 4. A total of 82 grains were analyzed for their stable carbon isotope contents.

For free-threshing wheat at Tell Atchana, some grains from Phase 4 of Square 42.10 (1300–1200 BCE) exhibited the highest values of $\Delta^{13}C$. Among the seven samples from this period, none experienced severe water stress, and only one grain showed signs of moderate water stress. The remaining grains were grown in well-watered fields. Phase 4/5 transition of the same Square (1300–1200 BCE) had one grain that grew in favorable growing conditions. The $\Delta^{13}C$ values of three grains from Phase 6 (1350–1300 BCE) also indicated good growing conditions. One grain from Phase 7 (1450–1350 BCE) showed signs of moderate water stress, but the $\Delta^{13}C$ values of the other two grains suggested they were grown in moist conditions. Samples from Phase 5 of Square 32.57 (1950–1650 BCE) showed no signs of water stress. Interestingly, among the six examined grains from Phase 3 of Square 33.32 (1900–1750 BCE), which is contemporary with Phase 5 of Square 32.57, four showed indications of moderate water stress. The lowest $\Delta^{13}C$ value was observed in the grains from this trench. At Toprakhisar, the $\Delta^{13}C$ values from Phase 3 of Square 51/52.37 (2000–1900 BCE) varied significantly. Although most grains suggested moderate water stress, the majority grew in well-watered fields. None of the three grains from Phase 2 of Square 54.38 (2100–2000 BCE) had values below 16 ‰, indicating favorable growing conditions (Fig. 4).

No clear pattern of improvement or decline in environmental conditions was observed during the LBA period at Tell Atchana, as both

Table 2
The table shows the proportion and ubiquity of plants in differentiating phases of *Square* 32.57 at Tell Atchana.

Square	32.57							
Local Phase	2	3	4	5	2	3	4	5
Date	1550–1450 BCE	1625–1550 BCE	1650–1625 BCE	1950–1650 BCE	1550–1450 BCE	1625–1550 BCE	1650–1625 BCE	1950–1650 BCE
Total number of cereal remains	121	513	132	1130	121	513	132	1130
Samples (n)	29	30	2	28	29	30	2	28
	Proportion				Ubiquity			
Triticum monococcum/dicoccum	2.05	1.09	3.85	1.27	10.34	13.33	50.00	35.71
Triticum durum/aestivum	20.90	38.58	32.42	20.43	48.28	76.67	100.00	85.71
Triticum sp.	6.15	2.19	16.48	7.62	17.24	13.33	100.00	60.71
Hordeum vulgare	13.11	18.19	8.79	10.95	27.59	63.33	50.00	85.71
Avena sativa	0.00	0.00	0.00	0.49	0.00	0.00	0.00	10.71
Cerealia indet.	7.38	8.89	0.00	2.79	17.24	33.33	0.00	10.71
Triticum dicoccum spikelet fork	0.00	0.00	1.65	0.44	0.00	0.00	50.00	21.43
Triticum monoccoum/dicoccum spikelet fork	0.00	0.00	0.00	0.05	0.00	0.00	0.00	3.57
Triticum monoccoum/dicoccum glume base	0.00	0.00	1.65	0.34	0.00	0.00	50.00	14.29
Indet. *Cerealia* chaff	0.00	1.23	0.00	1.76	0.00	23.33	0.00	32.14
Indet. *Cerealia* culm node	0.00	0.00	6.59	6.84	0.00	0.00	50.00	53.57
Indet. *Cerealia* culm node base	0.00	0.00	0.00	0.34	0.00	0.00	0.00	3.57
Triticum durum/aestivum node	0.00	0.00	0.00	0.15	0.00	0.00	0.00	3.57
Triticum durum/aestivum internode	0.00	0.00	0.00	0.34	0.00	0.00	0.00	14.29
Triticum durum internode	0.00	0.00	0.55	0.83	0.00	0.00	50.00	21.43
Triticum durum rachis	0.00	0.00	0.00	0.83	0.00	0.00	0.00	3.57
Hordeum vulgare rachis	0.00	0.00	0.55	0.24	0.00	0.00	50.00	10.71
Indet. Legume	9.84	27.91	26.92	40.81	34.48	76.67	100.00	85.71
Vitis vinifera fragments	0.00	1.78	0.00	0.44	0.00	26.67	0.00	10.71
Olea europaea fragments	40.57	0.14	0.55	2.98	6.90	3.33	50.00	25.00
Ficus carica	0.00	0.00	0.00	0.05	0.00	0.00	0.00	3.57

water-stressed and no-stressed grains were found. However, the MBA phases of Atchana exhibit contrasting trends in their $\Delta^{13}C$ values. Square 32.57 had no water-stressed grains, while the majority of grains from Square 33.32 showed moderate water stress. Conversely, the results from Toprakhisar indicated that free-threshing grains were well watered at the end of the 3rd millennium BC, but moderate water stress was observed at the beginning of the 2nd millennium BC.

For hulled wheat, at Tell Atchana, the $\Delta^{13}C$ values from Phase 4 of Square 42.10 (1300–1200 BCE) exhibited a wide range. Three grains had values exceeding 16 ‰, which may suggest favorable water availability, while one grain fell between 15 ‰ and 16 ‰, possibly reflecting moderate water stress. The grains from Phase 4/5 (1300–1200 BCE) showed mixed conditions, with some experiencing moderate water stress and others grown under good conditions. The single grain from Phase 5 (1350–1300 BCE) had a $\Delta^{13}C$ value above 16 ‰, though no broader inference can be drawn from an individual data point. In Phase 6 of Square 42.10 (1350–1300 BCE), one grain exhibited moderate water stress, while the remaining grains were grown in more favorable conditions. Two grains from Phase 5 of Square 32.57 (1950–1650 BCE) were grown under favorable conditions as indicated by their $\Delta^{13}C$ values exceeding 16 ‰. At Toprakhisar, hulled wheat grains from Phase 3 of Square 51/52.37 (2000–1900 BCE) displayed significant variation, with some grains experiencing moderate water stress and others having sufficient water intake. The sole grain from Phase 2 of Square 54.38 (2100–2000 BCE) had a $\Delta^{13}C$ value exceeding 18 ‰, marking it as the grain with the highest $\Delta^{13}C$ value among the others, although interpretations drawn from single grains are inherently limited (Fig. 4).

When evaluated according to periods, the change in the water status of hulled wheat correlated with the findings from free-threshing wheat. The MBA hulled wheat samples from Tell Atchana (1950–1650 BCE) had a similar mean value to free-threshing wheat, but with smaller range of values. All the hulled wheat samples from the MBA occupations experienced moderate water stress. In contrast to free-threshing wheat, the mean $\Delta^{13}C$ values of hulled wheat were lowest in the LBA samples. Furthermore, there were more hulled wheat samples showing moderate water stress in the LBA phases compared to free-threshing wheat. At Toprakhisar, hulled wheat exhibited signs of drier conditions during the transition to the 2nd millennium BC, similar to free-threshing wheat. The only grain dating back to the end of the 3rd millennium BC had the highest carbon isotope discrimination among all the analyzed samples, indicating well-watered fields. However, the beginning of the 2nd millennium BC was characterized by decreasing values, with some grains falling into the zone of moderate water stress.

For barley, none of the analyzed grains showed signs of severe water stress. grains from Phase 4 of the Square 42.10 (1300–1200 BCE) indicated moderate water stress. The sole grain from Phase 5 of Square 32.57 (1950–1650 BCE) was grown in well-watered conditions. All the grains from Square 33.32 (1900–1750 BCE) had $\Delta^{13}C$ values over 17 ‰, indicating no water scarcity during growth. Similarly, none of the grains from Toprakhisar showed signs of water stress, as their $\Delta^{13}C$ values were high in both Phase 3 of 51/52.37 (2000–1900 BCE) and Phase 2 of 54.38 (2100–2000 BCE) (Fig. 4).

When the change in mean carbon isotope discrimination values of barley was evaluated according to archaeological periods, it was observed that a few grains were grown under moderate water stress during the MBA (1950–1650 BCE), but the mean value remained above 17 ‰. In contrast, all the LBA samples from Atchana fell within the moderate water stress zone. Unlike wheat species, the average $\Delta^{13}C$ value of barley grains increased during the transition from the 3rd millennium to the 2nd millennium (from 2100-2000 BCE to 2000–1900 BCE) at Toprakhisar.

4. Discussion

4.1. Crop preferences at Toprakhisar

Riehl (2008) suggests that the 4.2 ka BP event affected crop production patterns in the Near East, resulting in a decrease in drought susceptible crops from the EBA to the MBA. The samples from 2100-2000 BCE at Toprakhisar mainly contain drought-tolerant barley,

Table 3
The table shows the proportion and ubiquity of plants in differentiating phases of Square 42.10. at Tell Atchana.

Square	42.10											
Local Phase	**3**	**4**	**4/5**	**5**	**6**	**7**	**3**	**4**	**4/5**	**5**	**6**	**7**
Date	1200–1100 BCE	1300–1200 BCE	1300-1200BC	1350–1300 BCE	1350-1300 BCE	1450–1350 BCE	1200–1100 BCE	1300-1200BC	1300-1200BC	1350–1300 BCE	1350–1300 BCE	1450–1350 BCE
Total soil sediment (L)	16	357	49	75	284	1271	16	357	49	75	284	1271
Total number of cereal remains	5	210	89	11	100	492	5	210	89	11	100	492
Samples (n)	2	18	5	6	23	66	2	18	5	6	23	66
	Proportion						**Ubiquity**					
Triticum monococcum/ dicoccum	0.00	6.97	2.00	13.33	4.49	0.11	0.00	33.33	40.00	33.33	21.74	1.52
Triticum durum/aestivum	0.00	2.09	2.00	6.67	8.33	15.83	0.00	22.22	40.00	16.67	13.04	62.12
Indet. *Cerealia* chaff	0.00	0.00	0.00	0.00	0.00	2.79	0.00	0.00	0.00	0.00	0.00	19.70
Triticum sp.	12.90	32.75	44.00	26.67	29.49	15.38	50.00	72.22	80.00	33.33	56.52	59.09
Hordeum vulgare	0.00	5.23	13.00	6.67	2.56	15.83	0.00	16.67	60.00	16.67	13.04	72.73
Avena sativa	0.00	0.00	0.00	0.00	1.28	0.00	0.00	0.00	0.00	0.00	4.35	0.00
Cerealia indet.	3.23	26.13	28.00	20.00	19.23	4.91	50.00	66.67	60.00	33.33	39.13	24.24
Indet. Legume	83.87	22.65	11.00	20.00	28.21	13.27	100.00	61.11	40.00	33.33	43.48	66.67
Vitis vinifera fragments	0.00	3.83	0.00	6.67	6.41	7.69	0.00	27.78	0.00	16.67	30.43	48.48
Vitis vinifera pedicel	0.00	0.00	0.00	0.00	0.00	0.45	0.00	0.00	0.00	0.00	0.00	4.55
Olea europaea fragments	0.00	0.35	0.00	0.00	0.00	23.75	0.00	5.56	0.00	0.00	0.00	68.18

aligning with Riehl's results for the MBA and also aligning with the archaeobotanical data of terminal EBA occupation in Tell Tayinat (23rd to 22nd centuries BC (Manning et al., 2020) where barley is the most proportionate crop at the time (Karakaya, 2019). With the beginning of the 2nd millennium (2000–1900 BCE), there is a slight increase in drought susceptible free-threshing wheat.

It has been suggested that, in comparison to sites in northern Mesopotamia, Euphrates and Orontes River valleys, were less severely impacted by the proposed state and urban collapses that occurred during the transition from the EBA to MBA (Morandi Bonacossi, 2014; Schwartz, 2017). Since these collapses have often been associated with the 4.2 ka event, as mentioned above, the results from Toprakhisar contribute to these discussions by suggesting that the site may have experienced the effects of the 4.2 ka climate event more mildly than other Near Eastern sites due to its location. It has also been emphasized that these so-called crises were not simultaneous, instead, different regions experienced them at different times over several centuries (Schwartz, 2017; Massa and Şahoğlu, 2015) which is further reflected in the difficulties encountered when attempting to establish a synchronized chronology for the event. The increase in free-threshing wheat at the beginning of the 2nd millennium BC might support this notion of asynchronism, indicating that Toprakhisar could have experienced the 4.2 ka BP event a century earlier (2100–2000 BCE) than the more southern parts of Syria. The slightly higher dependence on wheat with the beginning of the 2nd millennium might be indicative of improving environmental conditions at Toprakhisar and its surroundings.

4.2. Crop preferences at Atchana

Regarding the 3.2 ka BP event, the findings from the final LBA levels at Tell Atchana indicate the increasing importance of barley at the onset of the LBA while free threshing wheat remained significant when considering their relative proportions. The results from Tell Atchana suggest that MBA and the early LBA were characterized by the consumption of free threshing wheat. This implies that agricultural production did not change rapidly when the Hittite Empire took over the region. However, as the LBA progressed at Tell Atchana, the consumption of barley and hulled wheat increased, suggesting that agricultural decision-making started to change to some degree. Karakaya and Riehl (2019) showed that in most of the southern Levant sites, while the barley was predominant crop in LBA, the preference shifted to free threshing wheat in Iron Age. Similarly, the free threshing wheat became more prominent in terms of its proportion in Iron Age levels of Tell Tayinat (Karakaya, 2019). Mishrifeh-Qatna, situated in central-western Syria and once controlled by the Hittites, demonstrates a preference for barley throughout the LBA, which maintains into the Iron Age (Peña-Chocarro and Rottoli, 2007).

Among the LBA settlements that are located in the Mediterrenean climate of Anatolia, Kilisetepe has barley prominent in both LBA and Iron Age, yet, more drought- susceptible einkorn wheat was another predominant crop throughout these periods (Bouthillier et al., 2014). Kinet Höyük (Çizer, 2006) has most dominantly free-threshing wheat. In central Anatolia, Gordion has dominantly barley during the LBA, but free-threshing wheat becomes predominant in the early Iron Age (Marston, 2017). In western Anatolia, the archaeobotanical data of 13th century BCE LBA Beycesultan shows that free-threshing wheat was more common than barley (Helbaek, 1961). On the contrary, another western Anatolian site Troy had the barley as predominant crop during the LBA (Riehl, 1999). Similar to Troy, Kaymakçı also has barley dominant assemblages in LBA (Shin et al., 2021).

Among the main Hittite sites, Boğazköy-Hattusha reveals that barley and hulled wheat were the primary crops stored in its silo complexes (Diffey et al., 2017). At Kuşaklı-Šarišša, free-threshing wheat and emmer wheat dominate the assemblage, with barley appearing only occasionally (Dörfler et al., 2011). Most recently, archaeobotanical data from Oymaağaç-Nerik indicate that barley was the most abundant crop,

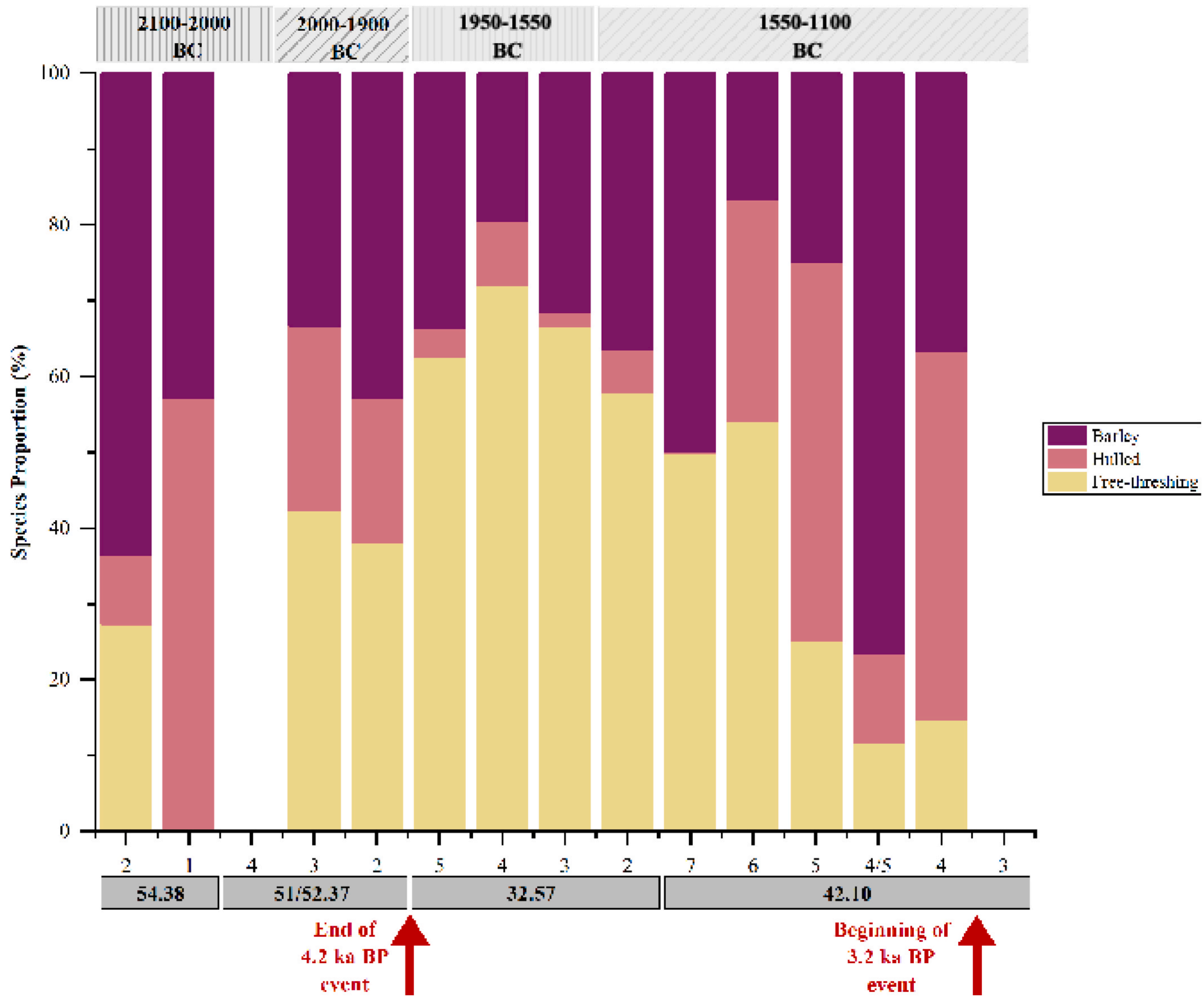

Fig. 3. The graph shows the differentiating proportions of barley, hulled wheat, and free-threshing wheat in different phases at Toprakhisar Höyük and Tell Atchana.

followed by free-threshing wheat and einkorn wheat (Rössner et al., 2025).

Based on the available data, there does not appear to be a uniform pattern in cereal preferences across Anatolia or even within sites under Hittite control. This variability is likely influenced by regional geographic and climatic differences (e.g., sites ranging from milder Mediterranean zones to the harsher conditions of central Anatolia) as well as the specific chronological context of the archaeobotanical assemblages (e.g., earlier vs. later phases of the LBA). In contrast, a more consistent trend has been identified in the southern Levant, as shown in the work of Karakaya and Riehl (2019). Based on the broader patterns observed in the southern Levant, the results of this study also suggest that the approaching 3.2 ka BP climatic event may have begun to affect Tell Atchana toward the end of the LBA. This interpretation is supported by the increasing abundance of barley at Atchana and at other southern Levantine sites during this period. However, with the onset of the Iron Age, climatic conditions may have improved, enabling the cultivation of less drought-resistant crops such as free-threshing wheat, as evidenced at Tell Tayinat and other sites in the region.

4.3. Isotope evidence for water status at Toprakhisar

The isotopic results showed that for most examined phases, the mean Δ^{13}C value of free-threshing wheat grains was above 16 ‰, indicating that neither Toprakhisar nor Atchana experienced severe water scarcity. However, there is some indication of drier conditions for free-threshing wheat at Toprakhisar at the beginning of the 2nd millennium BC (2000–1900 BCE), based on a limited number of grains. Among these, three grains from the period 2100–2000 BCE exhibit Δ^{13}C values consistent with moderate water stress, however, interpretations are necessarily cautious given the small sample size. The water stress observed at Toprakhisar during the transition from the 3rd to the 2nd millennium BC may be attributed to the increasing impact of the 4.2 ka BP event, still, the potential influence of larger samples size should not be forgotten. Although water stress was observed at Toprakhisar, it is essential to consider alternative explanations. When viewed in the context of socioeconomic and political conditions, the findings might be related to the grain import from drier areas or local production of grain in fields with varying moisture conditions rather than overall drier conditions. Even if overall drier conditions were present at the beginning of the 2nd millennium BC, they did not severely affect agriculture at Toprakhisar, which thrived politically and demographically during

Table 4
The table shows the details of the stable isotope analysis results according to sites and phases (The mean values and standard deviations are calculated for individual phases.).

	Square	Local Phase	Archaeological Period	# of Grains	*Triticum aestivum/durum* (Free-threshing wheat)				# of Grains	*Triticum monococcum/dicoccum* (Hulled wheat)				# of Grains	*Hordeum vulgare* (Barley)			
					$\delta^{13}C$ (‰)	±SD	$\Delta^{13}C$ (‰)	±SD		$\delta^{13}C$ (‰)	±SD	$\Delta^{13}C$ (‰)	±SD		$\delta^{13}C$ (‰)	±SD	$\Delta^{13}C$ (‰)	±SD
Tell Atchana	42.10	4	LBA	7	−23.69	0.95	17.61	0.99	4	−22.80	0.64	16.68	0.67	2	−22.75	0.09	16.63	0.09
	42.10	4/5	LBA	1	−22.68		16.55		2	−22.24	0.56	16.09	0.59					
	42.10	5	LBA						1	−23.29		17.19						
	42.10	6	LBA	3	−23.20	0.53	17.10	0.55	4	−22.52	0.84	16.39	0.87					
	42.10	7	LBA	3	−23.40	1.06	17.31	1.11										
	32.57	5	MBA	17	−23.38	0.59	17.29	0.61	2	−23.13	0.22	17.03	0.23	1	−23.14		17.03	
	33.32	3	MBA	6	−22.10	0.55	15.95	0.57						6	−23.77	0.58	17.70	0.60
Toprakhisar	51/52.37	3	MBA	8	−22.78	0.86	16.66	0.89	6	−22.98	0.69	16.87	0.71	3	−24.08	0.52	18.01	0.54
Höyük	54.38	2	MBA	3	−22.90	0.43	16.88	0.45	1	−24.08		18.11		1	−23.56		17.58	

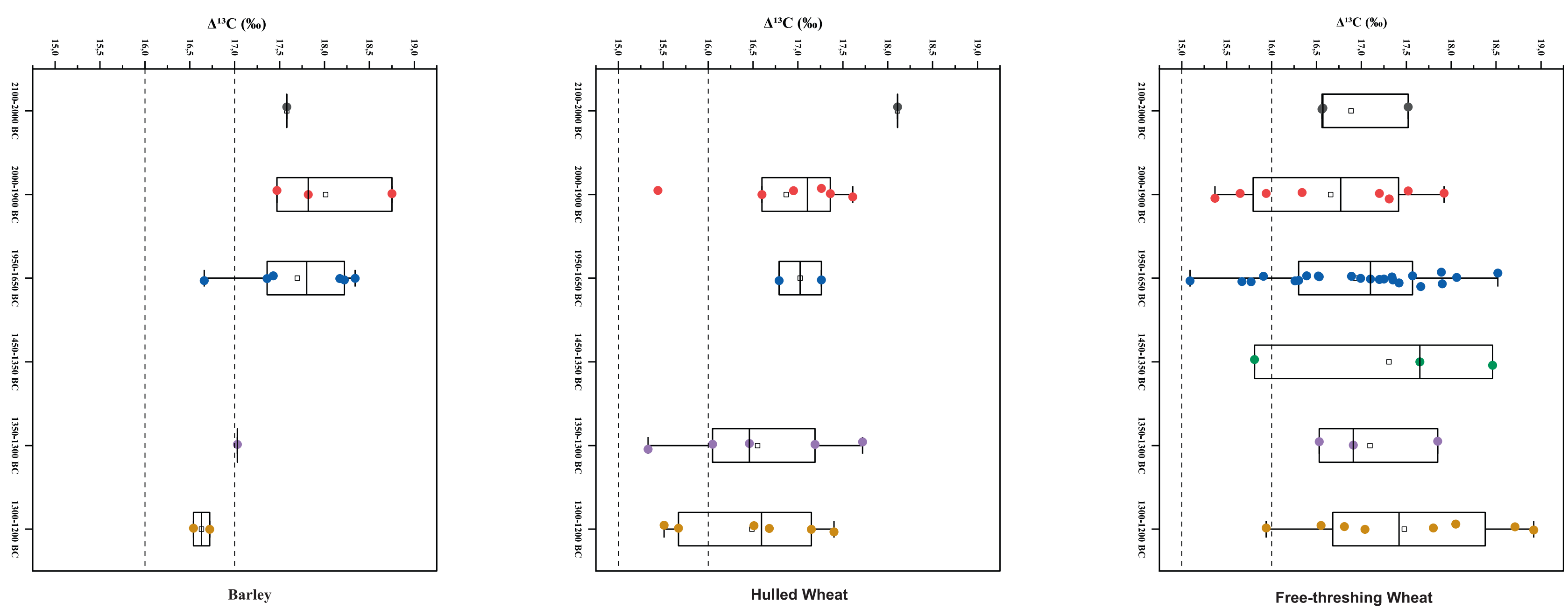

Fig. 4. $\Delta^{13}C$ (‰) values of the free-threshing wheat, hulled wheat, and barley grains separated according to the phases. The area in between dashed lines represent moderate water stress. Above the dashed lines, there is no water stress whereas the level below the dashed lines indicates severe water stress.

this period. This is evident in the significant change in settlement character of Toprakhisar during the transition from Phase 4 to Phase 3 in the Square 51/52.37. The architectural finds in this square mainly comprises of small scale domestic units dated to end of the EBA or early MBA in Phase 4 (Akar and Kara, 2020). However, at the beginning of Phase 3, it became a production center under central administration, evidenced by a monumental building (Building 2) which described as an administrative complex (Akar and Kara, 2018) which is radiocarbon dated to the early 2nd millennium BC (Akar and Kara, 2020). Akar and Kara (2018) also highlight the presence of a sizable and highly specialized surplus storage and food processing area in building 2. This facility was presumably designed to support a workforce engaged in labor-intensive tasks, such as olive and grape harvesting, as well as olive oil and wine production, under administrative oversight. Akkermans and Schwartz (2003) proposed that urban life and political power were rejuvenated in Syria at the end of the 19th century BCE, with expanded administrative control over large regions. Settlements specialized in crop production under Alalakh's control are documented in Alalakh Level VII Palace archives (Lauinger, 2015). Akar and Kara (2018) argued that resource management strategies and a network of people from nearby villages were necessary for economic growth and administrative control. It remains unclear if Toprakhisar's population increased during this period, but it is possible that this production center attracted workers from nearby villages either seasonally or permanently. To sustain a growing population, additional food sources would be required, either by expanding agricultural production into marginal lands or by importing food from other regions. Both strategies would have increased the variety of grains found in archaeobotanical samples. However, since the population dynamics of Toprakhisar are still under study, these possibilities remain unconfirmed

Overall, the effect of drought is visible, albeit weakly, in the archaeobotanical data from Toprakhisar. However, archaeological evidence suggested that Toprakhisar thrived socio-economically and became a production center during this climatic event. Therefore, even though a degree of water stress that might have created by the 4.2 ka event is traceable, it did not rigorously affect Toprakhisar's agricultural practices except for a shift in cultivated plant types in certain phases and did not cause an unmanageable agricultural production catastrophe.

4.4. Isotope evidence for water status at Atchana

Drier conditions were also evident in free-threshing wheat from MBA layers at Atchana (1950–1650 BCE, Squares 32.57 and 33.32) with four grains having Δ^{13}C values between 15 ‰ and 16 ‰ from Square 33.32. However, this might be influenced by the different contexts from which the samples were taken. The two Squares 32.57 and 33.32 from which the MBA free-threshing wheat grains of Atchana were retrieved showed opposite trends in their Δ^{13}C values. Square 32.57 had no grains with water stress sign, while most grains (4 out of 6) from Square 33.32 showed moderate water stress. Phase 5 of Square 32.57 included an apsidal building, suggesting it may have had sacred or ritualistic significance (Yener and Akar, 2013). Conversely, Square 33.32 was associated with levels below Phase VII Palace of Alalakh (Akar et al., 2021). Considering this contextual difference, one possible explanation is that the people of Alalakh selected the best crops to bring to their sacred areas, resulting in fewer water-stressed grains in Square 32.57. Alternatively, crops collected as taxes from a wide region might have included lower-quality grains from less well-watered fields and poorer villages. The presence of grains with different levels of water stress appears highlights the complexity of urban settings where crops to feed the "city" may have been come from different agricultural fields with varying water availability.

The mean Δ^{13}C values of free-threshing wheat increased in the transition from the MBA to LBA at Tell Atchana. In the LBA, there was no particular trend between phases, but the mean values of LBA phases were the highest among all the phases except for a short period (1300–1200 BCE, Phase 4/5 transition of Square 42.10) from which only one sample was taken. The sample from this phase had a smaller value than the averages of LBA phases but was still not low enough to indicate water stress. On the contrary, the Iron Age Tell Tayinat data suggest that drought stress is visible in the free-threshing wheat to some extent (Karakaya and Riehl, 2019).

At this point, it is necessary to draw attention to the existence of letters in the Ugarit archives, sent by Hittite officials, requesting assistance in the agricultural project to be carried out in the city called Alatḫa in the land of Mukish (letter RSO 23 31) (Cohen and Torrecilla, 2022) which was previously equated with Alalakh in earlier scholarship (for a recent study showing why the two sites should be different, see (Torrecilla, 2021). According to Cohen and Torrecilla (2022), the chosen area for the project was located probably near Orontes and water could be conveyed with a canal from the river (RSO 23 29). Even though the purpose of the project and the plants grown are unknown, the presence of such requests shows that irrigation was needed for various reasons and irrigation canals may have been built. Speculatively, it also raises the possibility that similar agricultural projects or irrigation canals were also initiated at Alalakh, and free-threshing wheat were cultivated under irrigation. The notably high isotope values observed in some free-threshing wheat samples, exceeding those recorded even during the MBA, may serve as a potential indicator of this irrigation practice. This interpretation is supported by recent geoarchaeological research conducted in the vicinity of Tell Atchana and Tell Tayinat (Avşar et al., 2019), which suggests arid conditions around the time of the 3.2 ka BP climatic event. Such environmental stress may have necessitated additional efforts, such as irrigation, to successfully cultivate water-demanding crops like free threshing wheat during this period.

For hulled wheat grains, lower Δ^{13}C values and an increased number of grains growing under moderate water stress during LBA phases at Atchana suggest changing agricultural approaches of Atchana farmers. LBA farmers may have preferred to cultivate free-threshing wheat in wetter (or maybe irrigated) lands, while hulled wheat was grown under more water-stressed conditions.

The stable isotope results presented here show some resemblance to Riehl's (2010a) previous work at Tell Atchana. In both studies, the mean and individual Δ^{13}C values were higher in free-threshing wheat than in barley. However, Riehl found a wider range of Δ^{13}C values in free-threshing wheat. The sample sizes in this study were not large enough to robustly determine the origin of free-threshing wheat, but Riehl's work suggests that cereals at Tell Atchana came from various fields and proposes that free-threshing wheat may have been treated differently during cultivation. Riehl suggests three possible treatments for free-threshing wheat: irrigating selected stands, growing in naturally wet soils, or importing from areas with better growing conditions. This raises the question that why the farmers treated these crops differently. The straightforward answer is that they were aware of their ecological requirements. It is also possible that the care taken for free-threshing wheat was influenced by the demands or socioeconomic power of elites who might be the primary consumers of these crops. The silos excavated in Hattusa contained mostly hulled wheat and barley (Diffey et al., 2017), which were likely brought into the city as taxes/contributions from the surrounding villages and were kept sealed as a backup for emergencies (Schachner, 2022). This might indicate that rural people and elites had different consumption patterns. However, this distinction is not clearly reflected in the data of Toprakhisar and Atchana.

The Hittite agricultural policy might have been a key driving factor for the increased cultivation of hulled wheat and barley during LBA. Textual evidence suggests that barley and emmer wheat were the principal crops in the Hittite realm (Gurney, 2016; Macqueen, 1986) which is also evident in the silo complexes found in the Hittite territory (Diffey et al., 2020, 2017). The word *halkiš*, used in Hittite tablets to denote both barley and grain (Hoffner, 1974), may also highlight the significance of barley as a staple crop. The Hittites also imported many products, notably wheat, to their capital, Hattusa (Bryce, 2005). Thus, one possibility is that the Hittite ruling elite at Atchana encouraged barley and hulled wheat farming to supply their capital even though its feasibility has been questioned previously (Klinger, 2022; Schachner, 2022; Seeher, 2023; Van De Mieroop, 2007). Rössner et al. (2025) suggests that the shift towards the production of barley is evident in the many Hittite sites at the end of the LBA, suggesting a pressure created by the Hittite hegemony to specialize in the barley production which is a resilient crop even under the unfavourable conditions. This kind of shift is also evident in the data presented here and data from Tell Atchana in general.

Castellano (2024) recently argued that the central institutions failed to adopt new and effective protective measures during the long-term and intense drought, which lead to a widespread food shortage and urgent requests for grain supplies. Also, considering the above-mentioned textual evidence that shows a request for resources for irrigational activities in the region, it seems possible that the Hittite empire would have needed to solve the agricultural crisis in its core territories, which likely caused by the drought, by implementing the solutions in its periphery. Given that southern Anatolia receives higher annual rainfall than the Hittite heartland central Anatolia according to modern references (Türkeş, 2003), systematic crop failures there could have been more easily prevented through irrigation. In this context, it seems plausible to argue that the Hittite administration employed resilience strategies to counteract agricultural difficulties that were likely more severe in central Anatolia and tried to sustain the heartland with drought resistant barley and hulled wheat which were well suited for long-term storage (Dörfler et al., 2011).

If we set aside this explanation due to the economic impracticality of large-scale grain transport within Anatolia, another possibility might be that the cultivation of barley might also be given priority to provide for the Hittite army and also administrative personnel. As suggested by Dörfler et al. (2011), a *bulgur*-like cereal product made from barley might be used as a ready-made food to increase the army's mobility and save time.

Overall, when the available information and data presented here are reconsidered holistically from the outset, three key points become more prominent. First, there appears to be an increased reliance on barley at Tell Atchana, particularly in the later phases of the LBA. Second, previous studies have proposed that the Hittite administration undertook agricultural risk mitigation strategies, both through the selection of more resilient crops and the implementation of infrastructural measures such as irrigation canals and dams. Taken together with stable isotope analyses from Tell Atchana which indicate a degree of water stress in barley –a drought-tolerant crop that typically requires minimal or no irrigation-, these findings suggest increasing environmental pressure in connection with the approaching 3.2 ka BP climatic event. Although this pressure may have been less severe in the specific case of Atchana, because of its Mediterranean climate and access to the Orontes River, it likely still influenced agricultural policy. The preference for barley cultivation and potential investment in irrigation infrastructure mentioned in the previous paragraphs may be a reflection of a precautionary approach by the Hittite authorities to buffer against the anticipated impacts of climate variability, both in Atchana and maybe also in the Hittite mainland. Such measures could have been aimed at sustaining the political system (e.g., provisioning the army and elite classes) and maintaining social stability (e.g., ensuring food security for the broader population) ultimately ensuring the stability of the established administrative and economic systems.

5. Conclusion

To understand the possible effects of Bronze Age climatic anomalies on the agricultural practices of the settlements of Atchana and Toprakhisar, changes in the proportions of wheat and barley crops were examined and isotope analysis was carried out. The archaeobotanical results suggested an increasing trend towards the usage of drought-tolerant hulled wheat and barley in the late 3rd millennium BC contexts at Toprakhisar, and especially from 1350 BCE onwards until 1200 BCE at Tell Atchana. The timing of the increase of these species at both sites suggests that changes in plant cultivation patterns might be related to climate anomalies. It is likely that both the 4.2 ka BP and 3.2 ka BP climatic events increased aridity in the region, prompting agricultural strategies to favor these more durable species. The presence of Hittite administrative influence at Atchana may have played a further role in shaping agricultural strategies aimed at reducing vulnerability to the 3.2 ka BP event.

Isotopic results showed that cereals growing under water stress and those growing with sufficient water, were present at both sites. This indicates a rather limited effect of the climatic events on the settlements under study, possibly due to specific ecological system in which they were located. The Orontes River might have been a crucial feature, helping to cope with aridity. Even so, the results present a complex picture indicating that a variety of adaptive approaches may have been employed. Both sites did not appear to have been devastated; instead, their inhabitants found ways to cope with drought by replacing some of their crops with more drought-resistant ones, relocating their fields, or carefully choosing which crops to cultivate in specific locations to achieve better yields. Perhaps some form of irrigation was also used, although there is currently no archaeological evidence for this.

Comparing these findings with other regions in the Near East affected by the 4.2 ka and 3.2 ka BP climatic events can provide a broader context and show regional variability in responses to climate anomalies. The interaction between environmental and political factors, such as the influence of Hittite hegemony, highlights how political changes might have influenced agricultural practices in the face of climatic anomalies. The potential role of technological innovations, such as irrigation or advanced storage techniques, could also explain the resilience observed in these settlements. While a full resilience framework is beyond the scope of this study, the observed responses correspond closely to theoretical models of agricultural resilience in the face of environmental variability.

Future research might focus on more detailed isotopic analyses, might explore the potential irrigation systems, or more closely examine the settlement patterns and population dynamics during these climatic events. An interdisciplinary approach combining archaeobotany, paleoecology, and climate science is essential to fully understand the complex interactions between humans and their environment.

CRediT authorship contribution statement

Ebrar Sinmez: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Evangelia Pişkin:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Murat Akar:** Writing – review & editing, Resources, Data curation, Conceptualization, Funding acquisition, Project administration. **Aurélia Hubert-Ferrari:** Writing – review & editing, Formal analysis. **Gilles Lepoint:** Formal analysis. **K. Aslıhan Yener:** Writing – review & editing, Data curation. **Ulaş Avşar:** Writing – review & editing, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Data availability

The authors do not have permission to share data.

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