The rise and fall of viticulture in the Late Antique Negev Highlands reconstructed from archaeobotanical and ceramic data

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The international scope of the Mediterranean wine trade in Late Antiquity raises important questions concerning sustainability in an ancient international economy and offers a valuable historical precedent to modern globalization. Such questions involve the role of intercontinental commerce in maintaining sustainable production within important supply regions and the vulnerability of peripheral regions believed to have been especially sensitive to environmental and political disturbances. We provide archaeobotanical evidence from trash mounds at three sites in the central Negev Desert, Israel, unraveling the rise and fall of viticulture over the second to eighth centuries of the common era (CE). Using quantitative ceramic data obtained in the same archaeological contexts, we further investigate connections between Negev viticulture and circum-Mediterranean trade. Our findings demonstrate interrelated growth in viticulture and involvement in Mediterranean trade reaching what appears to be a commercial scale in the fourth to mid-sixth centuries. Following a mid-sixth century peak, decline of this system is evident in the mid- to late sixth century, nearly a century before the Islamic conquest. These findings closely correspond with other archaeological evidence for social, economic, and urban growth in the fourth century and decline centered on the mid-sixth century. Contracting markets were a likely proximate cause for the decline; possible triggers include climate change, plague, and wider sociopolitical developments. In long-term historical perspective, the unprecedented commercial florescence of the Late Antique Negev appears to have been unsustainable, reverting to an age-old pattern of smaller-scale settlement and survival–subsistence strategies within a time frame of about two centuries.

Negev | Byzantine Empire | archaeobotany | protoglobalization | economic archaeology

Cultivated for millennia as part of the Mediterranean triad of food staples together with cereals and olives, grapes, and their products have diffused far beyond their original center of domestication (1, 2). Research on the Roman–Byzantine* wine trade is important for understanding economies of classical antiquity, including the roles of markets and states in organizing production and distribution, with relevance to the primitivist–modernist debate over the nature and scale of private enterprise in premodern economies (3–5). In the Roman and Byzantine Empires, the vine yielded some of the highest profits among Mediterranean crops (6, 7), setting the stage for development of an empire-wide wine trade. Vineyards were planted throughout the empire, with viticulture extending to the semiarid and arid regions of the Levant and North Africa (8). Wine produced in provincial and marginal regions was traded throughout the Mediterranean (8–13), providing an ancient example of "food globalization" (14, 15).

The degree to which this interconnected economy of antiquity was sustainable can best be gauged by its effects in arid and environmentally sensitive regions, which became integrated into the increasingly globalizing system of Byzantine commerce (16). We present archaeobotanical and ceramic data from the Negev Highlands in southern Israel, providing direct empirical evidence for commercial-scale viticulture in this desert region. We employ this combined dataset as a microregional test case for the local effects of Byzantine globalization and for investigating issues of sustainable agricultural production in an arid environment vis-à-vis the role of long-distance exchange over time.

Viticulture on the Margins of the Byzantine Empire

Extensive historical research has been conducted on viticulture in the Roman and Byzantine Empires (e.g., refs. 5, 6, 8, 17, and 18). One iconic symbol of international wine trade in antiquity was the famed *vinum Gazetum* (Gaza wine), mentioned by various contemporary writers (9, 12, 19). In the fourth to seventh

Significance

Commercial production of luxury "Gaza wine" was long assumed to be the economic basis of Late Antique settlement in the Negev Desert. We present empirical evidence for local viticulture of scale and its connection to Mediterranean trade. Offering unprecedented testimony to the globalization of an ancient production economy in a marginal environment, our archaeobotanical and ceramic dataset illuminates the rise and fall of local viticulture in the fourth to sixth centuries of the common era (CE). Decline likely resulted from market contraction triggered by plague and climate change rather than Islamic conquest, exposing systemic vulnerabilities of Negev agricultural commercialization. In millennial-scale Negev history, the Late Antique commercial florescence is anomalous, lasting about two centuries before reverting to smaller settlement and survival–subsistence strategies.

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*In what follows, the Byzantine period refers to that spanning the rise of Christian rule under Constantine to its demise during the Islamic conquests, rounded to 300 to 650 CE, in line with Levantine archaeological convention. The Byzantine Empire refers to the eastern Roman Empire during this period.

centuries of the common era (CE), this apparently sweet white wine was exported from the ports of Gaza and Ashkelon throughout the Mediterranean region. "Gaza jars"—the local amphorae used to package and market a range of agricultural export products, mainly wine, hence also known as "Gaza wine jars"—have been found as far afield as Germany, France, Britain, and Yemen (9–12, 20–22). Meanwhile, not very far from Gaza (50 to 100 km), the Negev Highlands (Fig. 1) were long suggested as one of the supply regions involved in production of Gaza wine (8, 9, 12, 23). As such, viticulture was considered the primary source of local wealth, which led to the tremendous growth in the Negev settlements and development of their agricultural hinterland; the ruins of which still bear testimony to this great endeavor. This has indicated to some that the decline and abandonment of these sites were also related to the decline of Mediterranean trade in the seventh century, with the fall of Christian–Byzantine hegemony in the region to Islamic rule, and the subsequent geographic reorientation of local production and markets (9, 11, 24).

Previous evidence for local viticulture in the Late Antique Negev includes monastic texts (especially fourth to sixth centuries CE), the Nessana papyri (sixth to seventh centuries CE), and several large Byzantine winepresses (9, 24, 25). Grape pip finds have also been reported in archaeobotanical assemblages from Nessana and the dovecotes of Shivta (23, 26–28). Recent large-scale excavation of midden deposits at the sites of Elusa—the Byzantine urban center of the Negev, Nessana, and Shivta (Figs. 2 and 3), has yielded rich archaeobotanical assemblages (29–32). The unprecedented quantities of grape pips and cereal grains (Fig. 4) deriving from multiple chronological phases (second to eighth centuries CE) at these sites allow comparative, quantitative analysis of viticulture in the Negev.

Local investment in infrastructure was based on an intimate understanding of local ecosystem function. This is exemplified by the ingenious agricultural system of the Byzantine Negev, encompassing extensive areas covered by cereal fields and vineyards, fed by numerous rainwater collection channels and check dams, and fertilized by high-quality pigeon manure collected in local dovecotes (26, 33–38). The intensive agricultural system of the Byzantine Negev—a high-input, high-output system—would have necessitated appreciable investments of labor for ongoing maintenance and repair. This includes annual restoration and reconstruction of check dams damaged by heavy flash floods; removal of stones along wadi slopes to enhance rainwater runoff and its diversion into human-made conduits; and construction of dovecotes followed by seasonal removal and distribution of enormous quantities of pigeon droppings in fields (36, 38–41). Massive anthropogenic transformation of this arid landscape would have inevitably caused various ecological feedback effects reverberating through the entire ecosystem, as exemplified by changes in the presence of wild/synanthropic species (42, 43). By tracing decadal- to centennial-scale fluctuations in one of the main agricultural outputs of this system—grapes—we gain crucial insights into its long-term stability and the issue of sustainable production.

The Sites and Their Context

This study focuses on 11 middens from three sites in the Negev, which reached their peak during the Byzantine period (fourth to seventh centuries CE): Elusa, Shivta, and Nessana (44). These sites are located in a climatically arid region, where mean annual precipitation ranges from 50 to 150 mm, and precipitation to evapotranspiration is as low as 0.20 to 0.05 (45). This climatic regime would have precluded standard dry farming in antiquity. Organized collection of rainwater runoff was necessary to maintain agriculture, especially at the scale that enabled the growth of the Negev population and settlement in the Byzantine period (23, 33, 46). Yet, significant multiannual climatic fluctuation is also characteristic of the region and may have affected this system's long-term stability (33, 41, 47).

Recent research of trash mounds in Negev settlements has shown that their very existence, distribution, chronology, and contents provide excellent proxies for local social and economic changes (28, 30, 32, 48). Byzantine-period middens were identified and excavated on the immediate outskirts of each of the three sites, whereas Early Islamic (seventh to eighth centuries

Fig. 1. Map showing the study sites in their Mediterranean context.

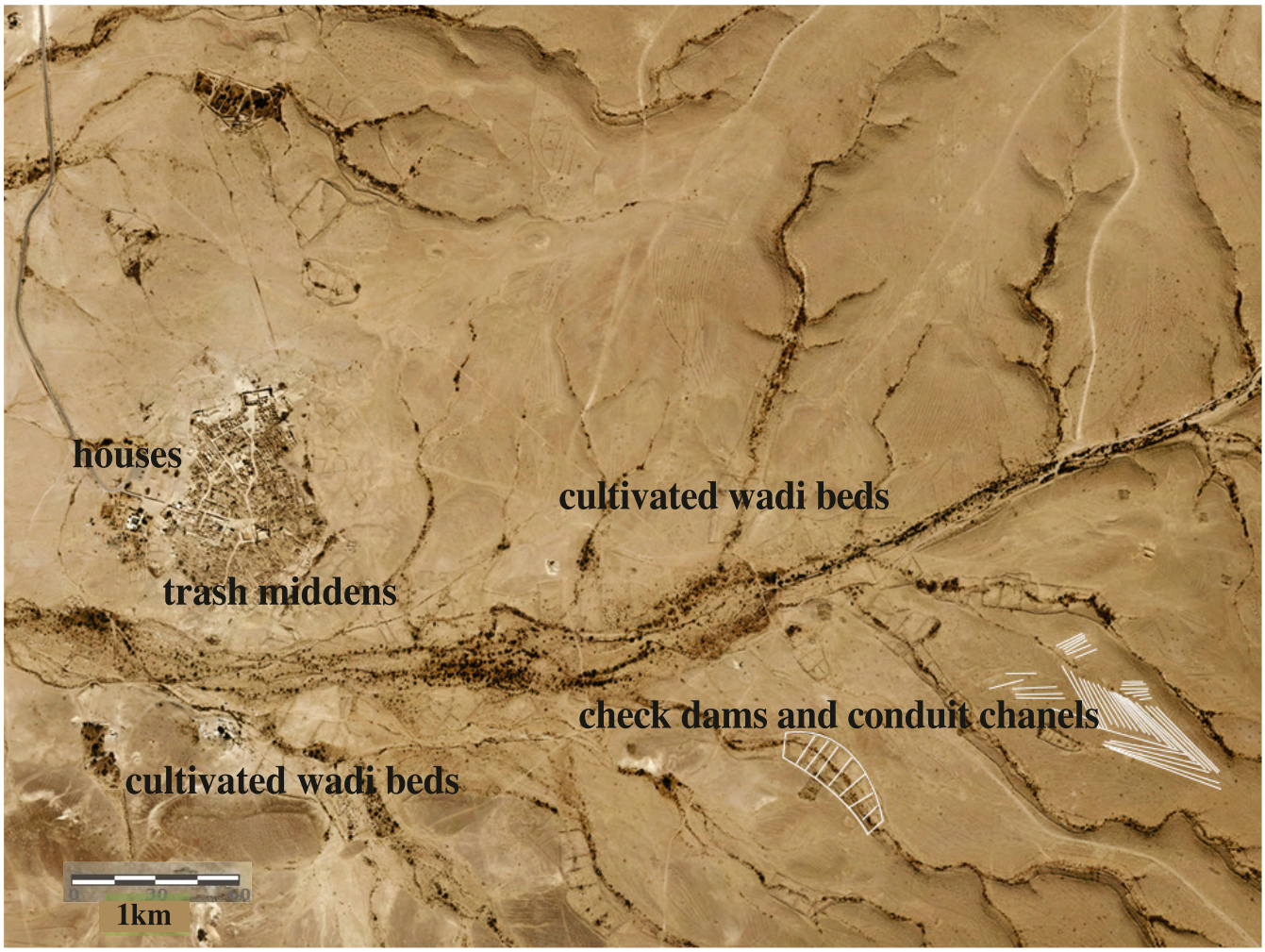

Fig. 2. Aerial map of Shivta and vicinity, showing the site, trash mounds, and salient agricultural features. This archaeological landscape is typical of Late Antique Negev villages.

CE) middens were identified and excavated inside abandoned Byzantine houses within Shivta and on the immediate outskirts of Nessana (Fig. 3). A single Roman-period (first to third centuries CE) midden outside Shivta was also investigated. Large volumes of excavated trash mound sediments, and careful systematic retrieval methods consistently applied through all of the study sites, enabled application of the comparative method to the analysis of their contents.

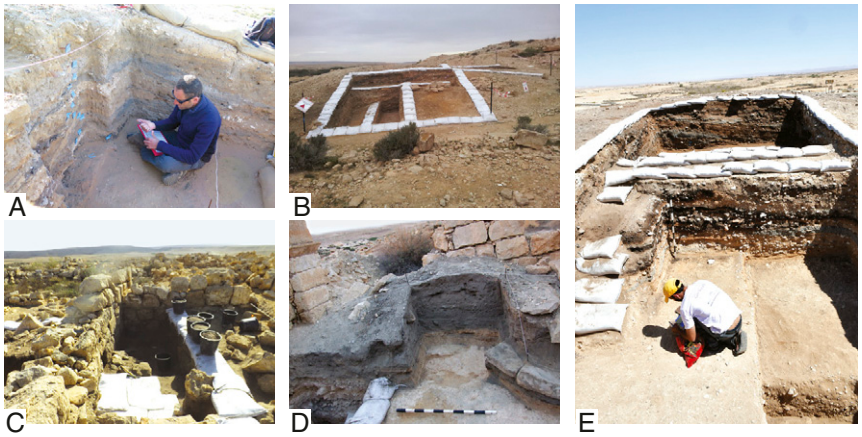

Fig. 3. Trash mounds on the immediate outskirts of Elusa (*A*), Shivta (*B*), and Nessana (*E*), and inside Shivta (*C* and *D*). (*E*) Image credit: Ari Levy (University of Haifa, Haifa, Israel).

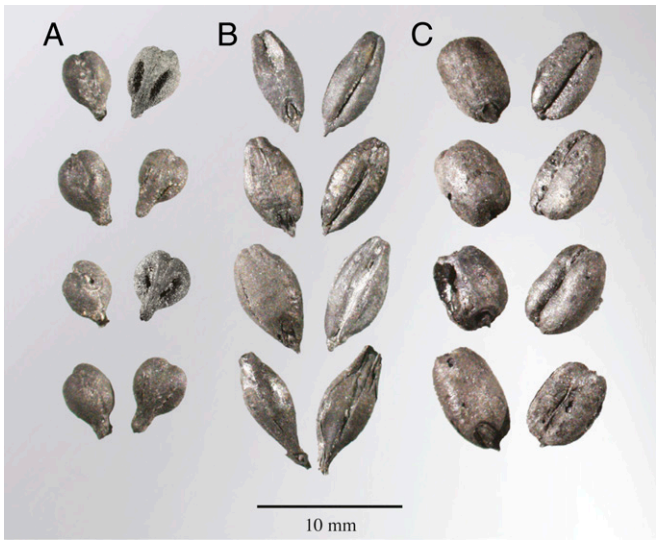

Fig. 4. Grape pips (*A*), barley grains (*B*), and wheat grains (*C*) represent the three most numerous and ubiquitous crop plants in the Negev middens.

Ceramic assemblages obtained from these trash mounds combined with radiocarbon dates allowed identification of three local subphases within the Byzantine period (*SI Appendix*, Table S1) (30): Early Byzantine (ca. 300 to 450), Middle Byzantine (ca. 450 to 550), and Late Byzantine (ca. 550 to 650). The chronological ranges of midden deposits analyzed in this study provide a long temporal sequence, while also showing partial overlaps, making synchronic comparisons possible as well. At Elusa, the middens spanned the Early to Middle Byzantine periods, with a halt of deposition around 550 CE (30). At Nessana, the two excavated middens represent the transitional Late Byzantine to Early Islamic period. Additional middens from Shivta allow for well-controlled comparisons over the critical transition periods, first for the Middle Byzantine period (Shivta/Elusa) and second for the Late Byzantine to Early Islamic periods (Shivta/Nessana). Our quantitative analysis is thus based on between-sample independence, a multiperiod perspective, and a large sample size (*SI Appendix* has further details).

All excavated trash mounds contained household waste with high concentrations of pottery and organic remains, including rich seed assemblages, while some contained small amounts of construction debris (29–32, 49). Thus, the middens' contents reflect everyday life in each of the sites, which can be subjected to comparative analysis of economic activities between sites and periods. Differential concentrations of this waste in the middens should not affect changes observed in relative frequencies of their contents over time, making the latter a useful economic proxy for comparison within and between sites.

Tracing the Rise and Fall of Negev Viticulture through Seed Ratios

Reconstruction of economic trends based on important food crops is a fundamental approach in archaeobotanical research (50, 51). Tracking the relative frequencies of specimens with high numerical abundance is a particularly productive method for teasing apart their changing economic roles (51–54). Unlike absolute quantities, which may be variably influenced by unknown sources of bias in different archaeological contexts, crop ratios enable comparisons across contexts, controlling for different sources of behavioral and taphonomic bias (52, 55–57). In the present study, such biases may include plant usage—cereal grains are eaten, whereas grape pips are not—and differential concentrations of plant remains at large in different midden contexts. We use an index of grape pip:cereal grain (barley, wheat) frequencies, as these are by far the most ubiquitous and numerous seeds found in our samples from the Negev middens (Fig. 4). Historical accounts have shown that in regions where wine grapes could be grown, grapes were a much more valuable, and hence a much more likely, cash crop than cereals (6, 7). Therefore, changes in the overall abundance of grapes relative to that of cereals should reflect the extent to which grapes were a cash crop in different periods.

Connecting Negev Viticulture to Mediterranean Trade via Pottery Remains

We conducted pottery analysis of material obtained within the same archaeological contexts as the archaeobotanical remains, in order to gain information on the chronology of these contexts as well as the presence and relative importance of vessels used in the wine trade. Gaza jars and bag-shaped jars (Fig. 5) were two local forms of storage amphorae used for transporting different food products, among them wine, in local and trans-Mediterranean trade (10, 12, 13, 21, 58). The standard Gaza jars and bag-shaped jars were produced in the western Negev and the southern coastal plain (59–61). It has been argued that the design of the Gaza jar was better suited for camelback transport and maritime cargo loading (12, 13). This is supported by depictions in ancient figurines and mosaics where these long, thin amphorae are shown strapped to camels' backs (Fig. 6). Gaza amphorae may thus be considered an indicator of involvement in Mediterranean export trade based from the hub port of Gaza. By contrast, the more bulky bag-shaped jar would have been efficient for bulk storage but less suitable for camel-pack transport. The frequencies of Gaza jars and of bag-shaped jars in the total pottery assemblage are, therefore, an important index of the intensity of overland transportation to port cities for long-distance trade.

As distinct functional types, both Gaza jars and bag-shaped jars span several centuries of use covering the period discussed here, with several different forms and variations for each. The bag-shaped jar is found in southern Palestine and Egypt throughout most of the first millennium CE and has been

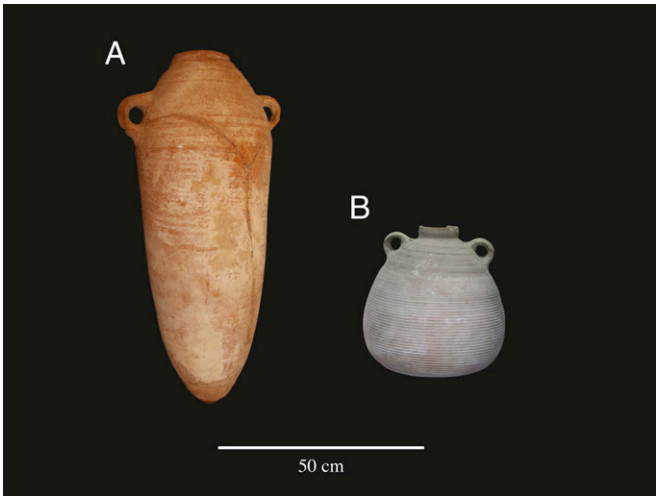

Fig. 5. Gaza jar (*A*) and bag-shaped jar (*B*). Sherds of these functional types are the most numerous and ubiquitous ceramic finds in the Negev middens. Collection of the Israel Antiquities Authority. (*A*) Image credit: Davida Eisenberg-Degen (Israel Antiquities Authority, Omer, Israel). (*B*) Image credit: Itamar Taxel (Israel Antiquities Authority, Jerusalem, Israel) and Oren Tal (Tel Aviv University, Tel Aviv, Israel).

Fig. 6. The mosaic of Kissufim near Gaza, depicting Orbikon the camel driver, captures the overland transport of the products of viticulture in the region during Late Antiquity. Artifactual remnants of the two main components of Orbikon's load—grapes and Gaza jars—further illuminate this phenomenon. Collection of the Israel Antiquities Authority. Mosaic image credit: The Israel Museum Jerusalem, by Elie Posner. Gaza jar image credit: Davida Eisenberg-Degen (Israel Antiquities Authority, Omer, Israel).

subdivided into no less than seven forms over this period (62). Chronologically, the production and use of bag-shaped jars outlasted the Gaza jars, but over the Byzantine period (fourth to seventh centuries CE) both abounded and have been found previously in the context of Byzantine Negev agricultural production (61). Functionally, a clear progression of Gaza jar development is evident from the heavy, barrel-shaped Form 1, typical of the first three centuries CE, to the lighter, elongated Forms 3 and 4 of the fifth to seventh centuries CE (63). These latter forms were streamlined for loading, stacking, and camel-back transport (12). Sherds of both Gaza jars and bag-shaped jars were excavated at Byzantine trading sites throughout the Mediterranean, but the former traveled farther and is found far more frequently in port sites of the Mediterranean (22, 63). This further indicates the functional specialization of these two types, suggesting that their changing relative frequencies provide an index of commercial transport vs. domestic consumption of agricultural products during their overlapping periods of use. We examine the correspondence between the indices of grape pips and those of Gaza jars as an additional independent indicator of the scale of viticulture in the Negev and its connection with Mediterranean trade. This approach offers an empirical method for testing the hypothesis that the Byzantine Negev witnessed a significant increase in viticulture and export-based trade via Gaza.

Results and Discussion

Taphonomy and the Evidence for Local Agricultural Production. Nearly 10,000 charred cereal grains and grape pips were retrieved and counted from unequivocal midden contexts at the three sites. The middens contained a variety of organic finds including other charred archaeobotanical material, archeozoological finds, dung remains, and charred wood. Cereal grains and grape pips were by far the most numerous and ubiquitous seeds of domesticated plants retrieved. Aside from some Early Islamic layers in Nessana, Area A, all macroscopic plant remains were deposited in the middens already charred. Charring likely occurred by incidental burning of cereal grain spillage, as well as intentional burning of chaff and dried dregs as fuel, and probably represents secondary or even tertiary usage, such as after collection from the uneaten leftovers of livestock fodder (31). Although differing somewhat in their sedimentary composition, the midden contents reflect the available agricultural by-products in each site. This supports our premise that, although absolute quantities of seeds have limited comparative value, changing ratios of the most common species in the different midden contexts reflect changes in local agricultural activity.

Local production and processing of both cereals and grapes are attested to not only by the quantity and ubiquity of their seeds but by the presence and variety of other plant parts associated with crop processing (64). All parts of the wheat and barley plant were identified, overwhelmingly preserved charred, including rachis segments of free-threshing hexaploid and tetraploid wheat (*Triticum aestivum*, *Triticum turgidum* s.l.) (Fig. 7*B*), and hulled six-row and two-row barley (*Hordeum vulgare* subsp. *hexastichum*, *H. vulgare* subsp. *distichum*). Cereal rhizomes, culm nodes (*SI Appendix*, Fig. S2), awn fragments, and glumes were also found. By-products of cereal cultivation and processing appear in every context for which flotation samples were processed, strengthening the appropriateness of cereal grains as an index base.

A similar variety of grape plant parts was also discovered, although not with the same ubiquity. These include charred grape pedicels and skins (Fig. 7*A* and *SI Appendix*, Fig. S1), which are indicative of grape processing (65, 66), as well as charred wood remains and pollen, which are indicative of local cultivation (57, 67). Whereas the charred wood remains, pedicels, and grape

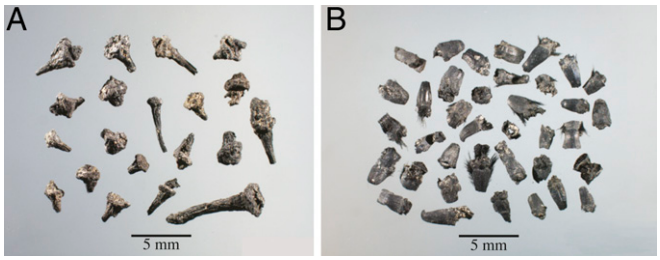

Fig. 7. Grape pedicels (*A*) and wheat rachis fragments (*B*) are among the many grape and cereal plant parts that attest to local production and processing of these crops.

skins derive from the same set of midden loci as the grape pips, pollen comes from sediment outcrops in the northern reservoir of Shivta. Table 1 combines these contexts in summarizing presence/absence of different grape plant parts by site and period.

Each category of grape plant part is affected differently by taphonomic processes, causing grape pips to be quite common among archaeobotanical assemblages of the Mediterranean region while grape skins, charred wood, and pollen are relatively rare. Hence, absence of grape skins, charred wood, and pollen in archaeological context should not be taken as evidence of absence, but the presence of any one of these is highly suggestive of local cultivation and/or processing (57, 68). For instance, grapevine remains (*Vitis* sp.) are usually underrepresented in wood–charcoal assemblages since they are characterized by low wood density of 0.40 g/cm^3 (69), and therefore, the weak constitution of lianas deteriorates easily. Due to this low density, *Vitis* timber is unsuitable for use in construction and manufacturing of wooden artifacts, while also being a poor-quality fuel material. As a result, grapevines are very rare in southern Levantine wood–charcoal assemblages (70). Likewise, grape pollen is also underrepresented in palynological spectra. Nearly all domesticated grapes are monoecious (producing both male and female flowers in the same plant) and are self-pollinated, resulting in a very low pollen dispersal efficiency. Experiments on pollen dispersal demonstrate that grape pollen abundance declines exponentially with distance from vineyards and that relative abundance of over 2% grape pollen in an assemblage is strong evidence for the presence of nearby grape plants (71).

Among the three studied sites, only Shivta provided archaeological contexts that served as an adequate pollen trap—a water reservoir that had not been previously excavated (the northern reservoir, Area H) (28). All samples that were palynologically analyzed from varied contexts at Elusa and Nessana were found to be pollen barren. At Shivta, *Vitis* pollen was recovered from eight samples from the northern reservoir, of which seven recorded relative abundances over 2%, while the eighth recorded 1.7% of the total pollen counted (more than 500 grains for each sample). Local grape cultivation at Shivta is further evidenced by the presence of charred wood, grape skins, and pedicels, in addition to abundant grape pips, in the Byzantine–Early Islamic period. At Nessana, the presence of charred *Vitis* wood in Late Byzantine–Umayyad midden layers, alongside grape skins, pedicels, and abundant grape pips in Middle Byzantine–Umayyad layers, similarly provides unequivocal evidence for local cultivation and processing during these periods. At Elusa, the small charred wood assemblage (30) may explain the absence of *Vitis* charcoal there, whereas the large samples from which numerous grape pips and cereal grains derived were not sorted by trained archaeobotanists, potentially explaining the absence of less recognizable grape skins. However, the presence of pedicels and very high relative frequencies of grape pips at Byzantine Elusa (Table 1) are still suggestive of local cultivation and processing. Overall, the grape remains provide conclusive empirical evidence for significant local grape production and processing in the Byzantine–Early Islamic Negev Highlands. This already suggests that Negev Highland agriculture in the Byzantine–Early Islamic periods was concerned with more than strict subsistence. The extent to which this may have been so over time is gauged by the grape pip:cereal grain index.

Grape Pip and Cereal Grain Proportions. The combined grain–grape relative frequencies are presented in Fig. 8, Table 2, and *SI Appendix*; raw data are in Dataset S1. In the first to third centuries CE, represented by one midden (Roman Shivta, Area P), grape pips comprise 0.5% of the cereal grain and grape total, represented by a single grape pip. In the fourth to mid-fifth centuries, represented by one midden (Early Byzantine Elusa, Area A4), grape pips increase to 14% of this total. Grape pips peak in the early sixth century, reaching between 25 and 43% in three different middens of the Middle Byzantine period (Elusa Areas A1 and B; Shivta Area M). In the mid-sixth to mid-seventh centuries, there is a sharp drop to below 15% in two different middens (14% at Late Byzantine Shivta, Area O; 4% at Mid- to Late Byzantine Nessana, Area A). Finally, in the Late Byzantine–Umayyad and Umayyad periods, similarly low ratios persist in two middens at Shivta (Areas E and K), whereas at Nessana, a relatively high proportion of grape is evident in both excavated middens (36 and 28% for Areas A and E, respectively).

Gaza Jar and Bag-Shaped Jar Sherds. Gaza jars, bag-shaped jars, other amphorae, and cooking ware comprise nearly 33,000 sherds, or about 90% of the total pottery assemblage, from the 11 middens in this study (*SI Appendix*, Table S3 and Dataset S2).

During the Roman–Byzantine periods, Gaza jar sherd frequencies follow a similar trend to that of grape pip frequencies (Fig. 8 and Table 2). They rise steeply from a negligible proportion of total pottery sherds (<1%) within the total pottery assemblage in the first to third centuries CE (Roman Shivta, Area P) to between 24 and 52% in the mid-fifth to mid-sixth centuries (Middle Byzantine Elusa, Area B, and Middle Byzantine Shivta, Area M, respectively). Subsequently, in the mid-sixth to mid-seventh centuries, these frequencies decline to 6% (Late Byzantine Shivta, Area O), reaching below 3% in the mid-seventh to mid-eighth century assemblages (Nessana, Areas A and E; Shivta, Areas E and K). Meanwhile, the frequencies of bag-shaped jars relative to the total pottery assemblage show the opposite trend. They initially increase only slightly from negligible proportions (0.3%) in the first to third centuries (Roman Shivta, Area P) to between 1 and 7% in the mid-fifth to mid-sixth centuries (Middle Byzantine Elusa, Area B, and Shivta, Area M, respectively), but then rise to over 50% in the late sixth to mid-eighth centuries (Nessana, Areas A and E; Shivta, Areas E and K) as Gaza jar frequencies plummet. These data show clearly

Table 1. Presence/absence of grape plant parts by site and period

Site	Period	Pips	Pedicels	Grape skins	Charred wood	Pollen
Elusa	Early Byzantine	+	+	–	–	–
Elusa	Mid-Byzantine	+	+	–	–	–
Nessana	Mid- to Late Byzantine	+	+	+	–	–
Nessana	Late Byzantine to Umayyad	+	+	+	+	–
Nessana	Umayyad	+	+	–	–	–
Shivta	Roman	+	–	–	–	–
Shivta	Mid-Byzantine	+	+	+	+	+
Shivta	Late Byzantine	+	+	+	+	+
Shivta	Umayyad	+	+	+	+	–

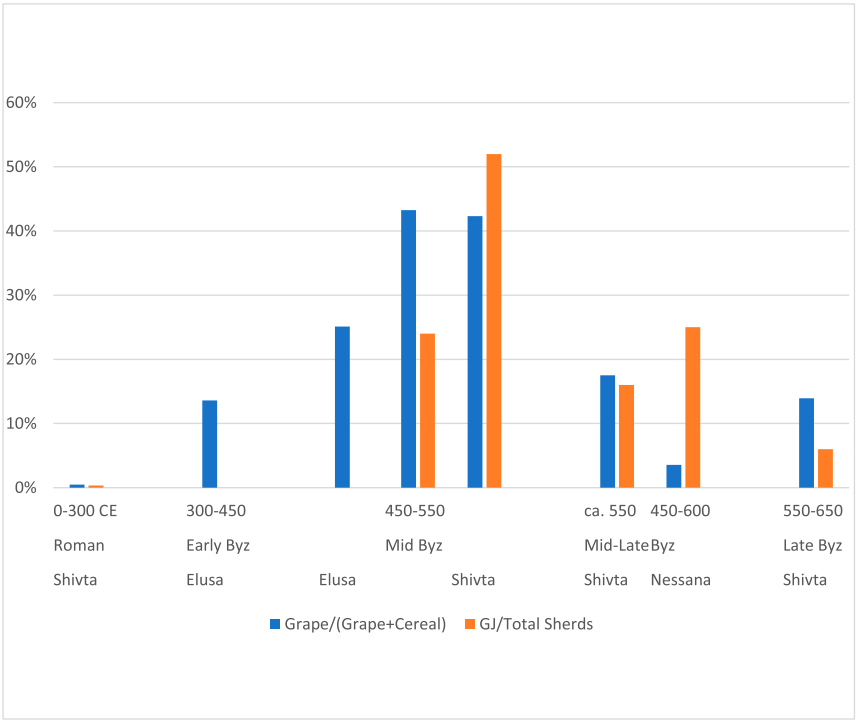

Fig. 8. The rise and fall of Negev viticulture: grape pip and Gaza jar (GJ) proportions in the Byzantine (Byz) period.

that the bag-shaped jar became the dominant amphora type as the Gaza jar phased out during the Late Byzantine period in the Negev (Table 2, *SI Appendix*, Table S3, and Dataset S2). Such trends in amphorae types contrast with the lack of chronological trends in cooking ware within the same archaeological contexts. Unlike the grape pip frequencies, there is no divergence of Gaza jar proportions by site during the transitional Late Byzantine–Umayyad and Umayyad phases (Table 2).

The Rise and Fall of Negev Highland Viticulture. Using grape–cereal proportions as an economic index of viticulture in the Negev, the data demonstrate that this industry grew from practically nothing in the third century CE to appreciable production by the fifth century. During this period, Negev agriculture developed from a system based on subsistence farming to one combining a strategy of mixed farming with what appears to be a substantial commercial orientation. By the mid-sixth century, grape production apparently rose to well above subsistence levels, conceivably becoming the primary cash crop of the Negev. However, by the mid- to late sixth century, decline is evident, with divergence by site in the seventh century.

The proportion of Gaza jars, shown to track those of grapes over the Roman–Byzantine periods and considered also to be an index of connections with long-distance trade (see above), suggests that Byzantine Negev viticulture was connected to regional and Mediterranean-wide trade. When Mayerson (9) proposed that the Negev was a source of Gaza wine, the evidence for it was inconclusive. This study provides empirical evidence for the proposed link between Negev viticulture and Mediterranean trade. The decline in Gaza jar frequency relative to bag-shaped

Table 2. Grape and Gaza jar proportions by period

Chronological order	Period	Period CE	Site	Grape/(grape + cereal), %	GJ/total sherds, %
1	Roman	0–300	Shivta	0.5	0.3
2	Early Byzantine	300–450	Elusa	14	NA
3	Mid-Byzantine	450–550	Elusa	25	NA
3	Mid-Byzantine	450–550	Elusa	43	24
3	Mid-Byzantine	450–550	Shivta	42	52
4	Mid- to Late Byzantine	Ca. 550	Shivta	18	16
4	Mid- to Late Byzantine	450–600	Nessana	4	25
5	Late Byzantine	550–650	Shivta	14	6
6	Late Byzantine to Umayyad	550–700	Nessana	36	2
6	Late Byzantine to Umayyad	550–700	Shivta	1	11
6	Late Byzantine to Umayyad	550–700	Shivta	1	0
7	Umayyad	650–750	Nessana	28	1
7	Umayyad	650–750	Shivta	19	3
7	Umayyad	650–750	Shivta	15	1
7	Umayyad	650–750	Shivta	4	2

GJ, Gaza jar.

jars suggests decreasing importance of commercial viticulture concomitant with a decline in local production evidenced by grape pip frequency relative to cereal grains. In other words, local agriculture responded to regional economic shifts. As regards the primitivist–modernist debate, this suggests that the Byzantine mercantile economy shared much with modern market economies, at its height in the fifth to mid-sixth centuries. Yet in long-term historical perspective, unprecedented commercial florescence of the Late Antique Negev was relatively short lived, reverting to an age-old pattern of smaller-scale settlement and survival–subsistence strategies.

Our findings on the growth of Negev viticulture in the Byzantine period fit well with other sources of evidence, including the beginning of major check dam construction for Negev water-harvesting systems dated by optically stimulated luminescence (OSL) to the fourth century CE (72) and peaking in the fifth to mid-sixth centuries (38); historical records such as accounts of the fourth century Christian monk, Hilarion, in Gaza and the Negev (9); major settlement expansion at sites such as Shivta in the fifth to sixth centuries CE (28); and ceramic evidence for increasing export activities through the port cities of Gaza and Ashkelon during this period, and for the increasing distribution of imported Palestinian wares appearing in European and North African sites (10, 11). The ceramic evidence for intensified international commerce is especially convincing in fifth to sixth century CE Alexandria, marked by declining quantities of local amphorae and increasing quantities of Gaza jars, among other types (73).

During the period of economic decline in the Negev Highlands, contracting viticulture around 550 CE coincides with evidence for the termination of dovecotes used as a source of fertilizer at Shivta and Sa'adon (26, 38, 40). The archaeology of Shivta also suggests Late Byzantine decline, which preceded Islamic resettlement on a much smaller scale (28, 48). At the urban center of Elusa, there is widespread evidence that large-scale organized waste disposal ceased by 550 CE, indicating the decline of urban municipal management at that time (30). Whereas Mayerson (9) and others concluded that commercial viticulture floundered in the seventh century Negev due to loss of European markets associated with the Islamic transition (24), our results indicate that the onset of decline in Negev commercial viticulture preceded the Islamic conquest by as much as a century.

During the Early Islamic (Umayyad) period, grape pip proportions remain low at Shivta but rise at Nessana. This may be due to various site-specific developments, possibly including cultural differences. Whereas a mosque was constructed at Shivta (74, 75), the persistence of an active Christian monastery at Nessana is attested to in the Nessana papyri (25). Similarly, at the site of nearby Avdat, where a Christian monastery also persisted in Umayyad times, finds from this period include substantial remains of grapes (76). While contemporary Islamic communities may have upheld religious prohibitions against the production and/or consumption of wine, pockets of viticulture apparently survived in Christian enclaves during the Early Islamic period. Still, these must have been primarily for local consumption since the Gaza jar makes no comeback in these contexts and the intensity of the early to mid-sixth century Negev agricultural settlement system did not resume (77–79).

Accounting for the Rise and Fall of Negev Viticulture. Previous scholars proposed possible social, political, economic, and environmental causes underlying the "greening of the desert," by which arid regions on the margins of the Roman and Byzantine Empires developed major population and agricultural production centers (80). Such explanations and causal mechanisms have also been integrated in discussions on the intensification and abatement of the Byzantine Negev (25, 47, 77, 81–85). We address these different factors in light of our empirical evidence for an economic connection between local Negev agricultural intensification and circum-Mediterranean trade. Our purpose is to identify factors and causal mechanisms that might have influenced the observed rise and fall of Negev viticulture.

Climate. Changes in environmental conditions, providing the boundaries within which human agency operates (86–88), could have affected the feasibility of desert agriculture, suggesting a possible role for climate change in the intensification and abatement of Byzantine Negev settlement (81–83). Successful runoff farming in the Negev depended on human-built infrastructure designed to exploit natural flash floods. Conceivably, an increase in the frequency of medium-intensity flash floods over several decades would have been a boon to Negev runoff farmers, improving their ability to buffer against subdecadal fluctuations in precipitation. By contrast, either prolonged drought or destructive high-intensity flash floods would have posed major challenges to sustainable production in this arid environment.

Regarding the rise of Byzantine runoff farming in the Negev, paleoclimatic evidence for increased precipitation in the southern Levant during the fourth century has been garnered as an explanation for settlement growth in the Negev at that time (83). However, the supporting data reflect precipitation patterns in Mediterranean climate zones north of the Negev Desert (89, 90), while current data on Negev flash flood frequency and intensity lack chronological resolution (91). Increased precipitation in the fourth century CE could have catalyzed Byzantine agricultural intensification in the Negev, but this must not have been the only factor since a significant wet phase in the early Roman period (ca. 200 BCE to 100 CE) in the southern Levant (89, 90) did not bring about the same levels of settlement and cultivation density (78, 79, 85). It is also possible that dampened volatility in local precipitation, and hence rainwater runoff patterns, encouraged the Early to Middle Byzantine florescence in the Negev Highlands (47).

Regarding the decline, grapevines grown in experimental reconstructions of ancient runoff farming in the Negev Highlands have been demonstrated to survive individual drought years (33), which inevitably occurred over the period of peak viticulture in the fifth to mid-sixth centuries. On the other hand, current evidence does not support major long-term climate change in the Negev over the Byzantine–Umayyad period (92). However, intense decadal-scale climatic change affecting the Late Byzantine decline in the Negev Highlands is plausible. Such an event occurred globally in the decade of 536 to 545 CE and may have impacted the Negev. Recently coined the "Late Antique Little Ice Age," that decade was the coldest in Eurasia over the last 2,000 y (93, 94). The outcome for the southern Levant was conceivably increased precipitation (95). Indeed, there is evidence for detrimentally increased flash flood intensity from Jordan (96, 97), while sedimentation records throughout the Mediterranean suggest that the sixth century was a period of peak flooding (98). If the Negev was affected by this region-wide event, increased high-intensity flash floods could have hindered local farmers' ability to maintain the efficient collection of rainwater within the agricultural system. Downsizing the cultivated area and focusing on staple crops for basic survival are likely responses to such a scenario. Alternatively, a decadal-scale drought scenario could also have caused major decline in the intensity of settlement and a shift to subsistence levels of grape production relative to cereals.

Plague. The outbreak of Justinianic plague in 541 CE immediately precedes or coincides with the period of decline in commercial-scale Negev viticulture. Although the demographic effects of the plague are a matter of debate (99, 100), conservative demographic estimates suggest ~20% population decline

in the immediate aftermath of the first outbreak in Constantinople (101–103). Maximalist estimates reach 50% population decline for the period 541 to 700 CE (104). Problematic as quantitative demographic estimates may be, among the more salient political, social, and economic effects of mid-sixth century Justinianic plague were labor shortages—of peasants, soldiers, and city laborers—and religious reactions (105–107). Indeed, the most ardent plague minimalists concede that "the plague was geographically vast and caused high mortality in some cases. On a number of occasions, it had a devastating short-term effect" (108). Similarly, in the most comprehensive critical review of the evidence for, and effects of, Justinianic plague, the authors accept that "[s]ome regions may have suffered higher mortality at certain times—such as Constantinople during the first outbreak" (100). In Rome, too, a combination of war and plague caused significant depopulation in the sixth century, although Rome's population decline began much earlier (109, 110). Similar demographic effects in Alexandria could have been devastating since Alexandria was clearly involved in trade with Gaza at this time (10, 73), and current consensus supports the spread of Justinianic plague's causative agent, *Yersinia pestis*, from India via the Red Sea (107, 111, 112). The port city of the empire's breadbasket, from which Justinianic plague purportedly spread throughout the empire, Alexandria's demographic decimation during the first outbreak is described in textual testimonies (113).

Accepting only the conservative population decline estimates, a 20% depopulation in Constantinople or Alexandria during the first outbreak would have had a direct effect on demand for imported luxuries, including wine. Decline in demand for Mediterranean imports would have caused the price of such imported luxury goods to decline. After surpassing a certain price threshold, it would no longer pay to commercially cultivate grapes in the Negev. The expected archaeologically visible result would be a decline in Gaza jars relative to bag-shaped jars and a change in the extent of grape cultivation relative to cereal farming.

A contracting market for Gaza products would have detrimentally impacted the Negev economy, even while trade at nearby Gaza may have continued into the seventh century CE (9, 11, 12). If the plague reached the Negev, it could also have harmed the local production capacity and supply of agricultural products in general by inducing a shortage of agricultural laborers (102, 114). This would also have provided an impetus for farmers to change focus from commercial to subsistence production, as was shown to have taken place in the southern Anatolian city of Myra in the year 542 CE (110). While there is as yet no unequivocal evidence for a devastating plague scenario in the Negev, there are indications of local outbreak (115) and of economic repercussions in southern Palestine (116–118). Thus, both decadal-scale demand-side effects of depopulation in major trading hubs and supply-side effects of local depopulation offer explanatory mechanisms for the chronological consilience between plague outbreak in the Byzantine Empire and economic decline in the Negev Highlands.

Social–Political Developments. Unlike climate and plague, social and political forces offer a mechanistic explanation involving the direct role of human agency in the rise and fall of Negev viticulture. During the Byzantine period (fourth to seventh centuries CE), the Negev witnessed a historical peak in agricultural settlement (77), as did most of the Levant (119, 120). This peak period in population and settlement was related to various factors such as the rise of Constantinople and its trading partners, Holy Land monasticism and pilgrimage, military deployments, and political stability (121). The demographic growth may have pushed agricultural production and settlement, especially in environmentally marginal regions such as the arid Negev Desert, to the limits of local carrying capacities and sustainable production (122). The expansion and intensification of Negev runoff agriculture, manifest in local agrotechnological investment (36–40, 123) and the rise of commercial-scale viticulture, were part and parcel of this demographic process.

Previous sociopolitical explanations for the decline of Negev agriculture focused on its ultimate abandonment as a supposed result of the Islamic conquest in the mid-seventh century (124, 125), the Abbasid relocation from Damascus to Baghdad in the mid-eighth century (25, 77, 84), or significant climatic and political instability by the tenth century (126–131). In addition, the Persian conquest of Jerusalem in 614 CE represents a local climax of Sasanid–Byzantine hostilities, which weakened both empires (132, 133).

More relevant to the mid-sixth century, Sasanid incursions in 540 to 545 led to the sacking of Antioch and other Byzantine cities, while the next two decades included further skirmishes in the east alongside Justinian's program of reconquest in the west. This included a taxing war with the Goths in Italy that may have overextended the resources of the empire and foreshadowed later sixth century losses (134). According to Haldon (135), "...the state which Justinian bequeathed to his successors had only limited resources to cope with the enormous problems it now faced in its overextended imperial possessions. It was inevitable that the structure should collapse at some point" (136). One way in which Justinan's aggressive imperial policies may have affected Negev viticulture is overtaxation. If, as Procopius writes, Justinian was unrelenting in his tax policies on agricultural products, this could have caused an empire-wide fiscal crisis in the wake of labor shortages caused by plague (114).

Locally, the singular or combined effects of labor shortages, Gaza wine price decreases, an unrelenting tax policy, decadal-scale aridification, or extraordinarily destructive flash floods could have exerted a devastating effect on the ability of Negev farmers to cope with economic, social, and environmental unpredictability. Finally, social and psychological effects of the climatic catastrophes and plague pandemic may have also influenced the decline in Negev viticulture. Religious texts of the period suggest a heartfelt doomsday atmosphere (107). In times of perceived crisis, consumers may focus on survival at the expense of luxury imports. Depopulation could have negatively affected the pilgrimage economy of the Levant and, as a result, also the monastic economy, both important sources of local wealth (137). In short, indirect social factors—whether resulting from the plague and climate change or in addition to them—may have had significant economic repercussions for the viability of Negev viticulture.

Conclusion. The above discussion of different circumstances and stressors that might have influenced the rise and fall of Negev viticulture illustrates the complexity of interrelationships at the interface of social–ecological systems (87, 88, 138). While untangling cause and effect mechanisms remains a long-term challenge for interdisciplinary research, our findings suggest that contracting markets were a likely proximate cause for decline in the Late Antique Negev, whereas climate change, plague, and a range of sociopolitical developments could have acted as triggers. Whatever the precise paths and processes by which such triggers acted, the mid-sixth century has long been considered a turning point for Byzantine decline (139, 140). The archaeobotanical and ceramic evidence presented above for the rise and fall of commercial-scale viticulture and trade provides empirical evidence that, together with the termination of organized trash disposal at Elusa (30), the dovecotes at Shivta and Sa'adon (26, 40), and the runoff farming system outside of Shivta (38), paints a clear picture of mid-sixth century decline in the Negev Highlands.

Ebert et al. (141) recently proposed that the Terminal Classic Maya (750 to 1000 CE) collapse was related to specialization and

intensification of maize cultivation, which created vulnerability in the face of drought. Although involving different crops, cultures, and types of vulnerability, we propose that commercialization of viticulture in the Late Antique Negev (ca. 300 to 550 CE) similarly introduced systemic vulnerabilities. As the Negev's agricultural economy developed from an extensive, subsistence-based settlement system into an increasingly intensive, commercial economy, the more difficult it would become to adapt to new challenges while maintaining output (142). This regional intensification of production was related to increased economic specialization and scale of international trade in the eastern Mediterranean of the fifth to sixth centuries, or "Byzantine globalization" (143, 144). Environmentally marginal by virtue of a harsh climate for agriculture, the Byzantine Negev was also economically marginal by virtue of its distance from the nearest port city. The peripheral Negev Desert's transformation into an agricultural production center for a mercantile industry exemplifies the far-reaching economic and environmental impact of Byzantine globalization. Moreover, just as resilience to modern economic shocks varies regionally (145), so too shocks to the Byzantine economy must have impacted different regions variably. A Negev economy increasingly based on agricultural exports to distant markets would have become increasingly vulnerable to both market forces and environmental disasters. Hence, the very process by which the Negev became incorporated in the Byzantine orb as a production center for a global market introduced both unprecedented prosperity and vulnerability. Although successful for approximately two centuries, ultimately, commercial viticulture in the Negev proved to be unprofitable on the multicentennial scale.

Materials and Methods

Excavations at Elusa, Shivta, and Nessana were conducted between 2015 and 2017, as described in previous reports (28, 30, 32). Ceramic sherds were retrieved through on-site dry screening of all excavated layers using 5-mm sieves, while additional samples for small finds, among them cereal grains and grape pips, were taken from each excavated layer. Samples for small finds were processed by wet sieving, flotation, or dry sieving, which were shown to produce equivalent cereal grain:grape pip ratios (*SI Appendix*). Further details of the ceramic and archaeobotanical methodology implemented in this study may be found in the *SI Appendix* and Datasets S1 and S2.

Data Availability. All data associated with this paper appear in the manuscript, *SI Appendix*, and Datasets S1 and S2.

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1. D. Zohary, M. Hopf, E. Weiss, *Domestication of Plants in the Old World*, (Oxford University Press, Oxford, ed. 4, 2012).
2. S. M. Valamoti, "Grapes and viticulture" in *The Encyclopedia of Archaeological Sciences*, S. L. Varela, Ed. (Wiley Online Library, 2018), pp. 1–4.
3. M. I. Finley, *The Ancient Economy*, (University of California Press, Berkeley, CA, 1973).
4. M. I. Rostovtzeff, *The Social and Economic History of the Roman Empire*, (Clarendon Press, Oxford, UK, 1957).
5. T. Unwin, *Wine and the Vine: An Historical Geography of Viticulture and the Wine Trade*, (Routledge, London, UK, 2010).
6. R. Duncan-Jones, *The Economy of the Roman Empire: Quantitative Studies*, (Cambridge University Press, Cambridge, UK, 1974).
7. Z. Safrai, *The Economy of Roman Palestine*, (Routledge, New York, NY, 1994).
8. M. Decker, *Tilling the Hateful Earth: Agricultural Production and Trade in the Late Antique East*, (Oxford University Press, Oxford, UK, 2009).
9. P. Mayerson, The wine and vineyards of Gaza in the Byzantine period. *Bull. Am. Sch. Orient. Res.* **257**, 75–80 (1985).
10. S. Kingsley, "The economic impact of the Palestinian wine trade in Late Antiquity" in Economy and Exchange in the East Mediterranean during Late Antiquity: *Proceedings of a Conference at Somerville College*, S. Kingsley, M. Decker, Eds. (Oxbow, Oxford, UK, 2001), pp. 44–68.
11. M. Decker, The end of the Holy Land wine trade. *Bull. Anglo Isr. Archaeol. Soc.* **31**, 103–116 (2013).
12. M. McCormick, "Movements and markets in the first millennium: Information, containers and shipwrecks" in *Trade and Markets in Byzantium*, C. Morrisson, Ed. (Dumbarton Oaks, Washington, DC, 2012), pp. 51–98.
13. M. McCormick, Radiocarbon dating the end of urban services in a late Roman town. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 8096–8098 (2019).
14. N. Boivin, D. Q. Fuller, A. Crowther, Old World globalization and the Columbian exchange: Comparison and contrast. *World Archaeol.* **44**, 452–469 (2012).
15. M. K. Jones *et al.*, Food globalisation in prehistory: The agrarian foundations of an interconnected continent. *J Brit Acad* **4**, 73–87 (2016).
16. G. Barker, D. Gilbertson, B. Jones, D. Mattingly, Eds., *Farming the Desert: The UNESCO Libyan Valleys Archaeological Survey*, (UNESCO Publishing, Tripoli, Libya, 1996).
17. G. C. Maniatis, The Byzantine winemaking industry. *Byzantion* **83**, 229–274 (2013).
18. P. McGovern, *Ancient Wine: The Search for the Origins of Viniculture*, (Princeton University Press, Princeton, NJ, 2019).
19. S. Lantos, G. Bar-Oz, G. Gambash, Wine from the desert: Late Antique Negev viniculture and the famous Gaza Wine. *Near E. Archaeol.* **83**, 56–64 (2020).
20. J. A. Riley, The pottery from the first session of excavation in Caesarea Hippodrome. *B. Am. Sch. Orient. Res.* **218**, 25–63 (1975).
21. Y. Gadot, Y. Tepper, A late Byzantine workshop at Khirbet Baraqa. *Tel Aviv J. Inst. Archaeol. Tel Aviv Univ.* **30**, 130–162 (2003).
22. D. Pieri, *Le commerce du vin oriental à l'époque byzantine (Ve-VIIe siècles): Le témoignage des amphores en Gaule*, (Institut français du Proche-Orient, Beirut, Lebanon, 2005), Vol. 174.
23. P. Mayerson, "The ancient agricultural regime of Nessana and the Central Negeb" in *Excavations at Nessana*, D. Colt, Ed. (William Clowes & Sons, London, UK, 1962), Vol. 1, pp. 211–269.
24. G. Mazor, "Byzantine winepresses in the Negev" in *Oil and Wine Presses in Israel from the Hellenistic, Roman and Byzantine Periods*, E. Ayalon, R. Frankel, A. Kloner, Eds. (Archaeopress, Oxford, UK, 2009), pp. 399–411.
25. C. J. Kraemer, *Excavations at Nessana, Vol. 3: Non-Literary Papyri*, (Princeton University Press, Princeton, NJ, 1958).
26. Y. Hirschfeld, Y. Tepper, Columbarium towers and other structures in the environs of Shivta. *Tel Aviv J. Inst. Archaeol. Tel Aviv Univ.* **33**, 83–116 (2006).
27. J. Ramsay, For the birds: An environmental archaeological analysis of Byzantine pigeon towers at Shivta (Negev Desert, Israel). *J. Archaeol. Sci. Rep.* **9**, 718–727 (2016).
28. Y. Tepper, T. Erickson-Gini, Y. Farhi, G. Bar-Oz, Probing the Byzantine/Early Islamic transition in the Negev: The renewed Shivta excavations, 2015–2016. *Tel Aviv J. Inst. Archaeol. Tel Aviv Univ.* **45**, 120–152 (2018).
29. D. Fuks, E. Weiss, Y. Tepper, G. Bar-Oz, Seeds of collapse? Reconstructing the ancient agricultural economy at Shivta in the Negev. *Antiquity* **90** (353), e5 (2016).
30. G. Bar-Oz *et al.*, Ancient trash mounds unravel urban collapse a century before the end of Byzantine hegemony in the southern Levant. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 8239–8248 (2019).
31. Z. C. Dunseth *et al.*, Archaeobotanical proxies and archaeological interpretation: A comparative study of phytoliths, pollen and seeds in dung pellets and refuse deposits at Early Islamic Shivta, Negev, Israel. *Quat. Sci. Rev.* **211**, 166–185 (2019).
32. Y. Tepper, L. Weissbrod, T. Erickson-Gini, G. Bar-Oz, Nessana (Preliminary report). *Hadashot Archeologiyot: Excavations and Surveys in Israel* in press.
33. M. Evenari, L. Shanan, N. Tadmor, *The Negev: The Challenge of a Desert*, (Harvard University Press, Cambridge, MA, 1982).
34. A. Negev, "Sobata" in *The New Encyclopedia of Archaeological Excavations in the Holy Land*, E. Stern, Ed. (Israel Exploration Society, Jerusalem, Israel, 1993), Vol. 4, pp. 1404–1410.
35. Y. Tepper, "Soil improvement and agricultural pesticides in antiquity: Examples from archaeological research in Israel" in *Middle East Garden Traditions: Unity and Diversity. Colloquium on the History of Landscape Architecture XXXI*, M. Conan, Ed. (Dumbarton Oaks, Washington, DC, 2007), pp. 41–52.
36. Y. Tepper, G. Bar-Oz, Shivta excavation: Preliminary report. *Hadashot Arkheologiyot: Excavations and Surveys in Israel* 128, 1–6 (2016).
37. Y. Tepper, B. Rosen, A. Haber, G. Bar-Oz, Signs of soil fertigation in the desert: A pigeon tower structure near Byzantine Shivta, Israel. *J. Arid Environ.* **145**, 81–89 (2017).
38. Y. Tepper, N. Porat, G. Bar-Oz, Sustainable farming in the Roman-Byzantine period: Dating an advanced agriculture system near the site of Shivta, Negev Desert, Israel. *J. Arid Environ.* **177**, 104134 (2020).

39. Y. Avni, N. Porat, J. Plakht, G. Avni, Geomorphic changes leading to natural desertification versus anthropogenic land conservation in an arid environment, the Negev Highlands, Israel. *Geomorphology* **82**, 177–200 (2006).
40. Y. Tepper *et al*., Pigeon-raising and sustainable agriculture at the fringe of the desert: A view from the Byzantine village of Sa'adon, Negev, Israel. *Levant* **50**, 1–23 (2018).
41. H. J. Bruins, H. Bithan-Guedj, T. Svoray, GIS-based hydrological modelling to assess runoff yields in ancient-agricultural terraced wadi fields (central Negev desert). *J. Arid Environ.* **166**, 91–107 (2019).
42. T. Fried, L. Weissbrod, Y. Tepper, G. Bar-Oz, A glimpse of an ancient agricultural ecosystem based on remains of micromammals in the Byzantine Negev Desert. *R. Soc. Open Sci.* **5**, 171528 (2018).
43. N. Marom, B. Rosen, Y. Tepper, G. Bar-Oz, Pigeons at the edge of the empire: Bioarchaeological evidences for extensive management of pigeons in a Byzantine desert settlement in the southern Levant. *PLoS One* **13**, e0193206 (2018).
44. J. Shereshevski, *Byzantine Urban Settlements in the Negev Desert*, (Beer Sheva University Press, Beer Sheva, Israel, 1991).
45. H. J. Bruins, Ancient desert agriculture in the Negev and climate-zone boundary changes during average, wet and drought years. *J. Arid Environ.* **86**, 28–42 (2012).
46. Y. Kedar, Water and soil from the desert: Some ancient agricultural achievements in the central Negev. *Geogr. J.* **123**, 179–187 (1957).
47. A. M. Rosen, *Civilizing Climate: Social Responses to Climate Change in the Ancient Near East*, (AltaMira, Lanham, MD, 2007).
48. Y. Tepper, L. Weissbrod, G. Bar-Oz, Behind sealed doors: Unravelling abandonment dynamics at the Byzantine site of Shivta in the Negev Desert. *Antiquity* **89**, 1–7 (2015).
49. N. Marom *et al*., Zooarchaeology of the social and economic upheavals in the Late Antique-Early Islamic sequence of the Negev Desert. *Sci. Rep.* **9**, 6702 (2019).
50. E. Weiss, M. E. Kislev, Plant remains as a tool for reconstruction of the past environment, economy, and society: Archaeobotany in Israel. *Isr. J. Earth Sci.* **56**, 163–173 (2007).
51. D. M. Pearsall, *Paleoethnobotany: A Handbook of Procedures*, (Left Coast Press, Walnut Creek, CA, ed. 3, 2016).
52. N. Miller, "Ratios in paleoethnobotanical analysis" in *Current Paleoethnobotany: Analytical Methods and Cultural Interpretations of Archaeological Plant Remains*, C. A. Hastorf, V. S. Popper, Eds. (University of Chicago Press, Chicago, IL, 1988), pp. 72–85.
53. G. Jones, The application of present-day cereal processing studies to charred archaeobotanical remains. *Circaea* **6**, 91–96 (1990).
54. D. Q. Fuller, C. J. Stevens, "Agriculture and the development of complex societies: An archaeobotanical agenda" in *From Foragers to Farmers: Papers in Honour of Gordon C. Hillman*, A. S. Fairbairn, E. Weiss, Eds. (Oxbow Books, Oxford, UK, 2009), pp. 37–57.
55. M. Van der Veen, *Crop Husbandry Regimes: An Archaeobotanical Study of Farming in Northern England, 1000 BC–AD 500*, (J. R. Collins, Sheffield, UK, 1992).
56. J. M. Marston, "Ratios and simple statistics in paleoethnobotanical analysis: Data exploration and hypothesis testing" in *Method and Theory in Paleoethnobotany*, J. M. Marston, J. D. A. Guedes, C. Warinner, Eds. (University Press of Colorado, Boulder, CO, 2014), pp. 163–180.
57. C. White, N. F. Miller, The archaeobotany of grape and wine in Hittite Anatolia. *Die Welt Des. Orients* **48**, 209–224 (2018).
58. P. Reynolds, *Trade in the Western Mediterranean, AD 400–700: The Ceramic Evidence, BAR-IS 604*, (Tempus Reparatum, Oxford, UK, 1995).
59. Y. Israel, Survey of pottery workshops, Nahal Lakhish-Nahal Besor. *Excav. Surv. Isr.* **13**, 106–107 (1993).
60. Y. Israel, T. Erickson-Gini, Remains from the Hellenistic through the Byzantine periods at the "Third Mile Estate," Ashqelon. *Atiqot* **74**, 167–222 (2013).
61. T. Erickson-Gini, B. J. Dolinka, L. Shilov, A Late Byzantine industrial quarter and Early Islamic-period finds at Horbat Be'er Shema. *Atiqot* **83**, 209–248 (2015).
62. J. Magness, *Jerusalem Ceramic Chronology, Circa 200–800 CE*, (JSOT Press, Sheffield, UK, 1993).
63. G. Majcherek, "Gazan amphorae: Typology reconsidered, in Hellenistic and Roman pottery in the Eastern Mediterranean—advances in scientific studies" in *Acts of the II Nieborów Pottery Workshop*, H. Meyza, J. Młynarczyk, Eds. (Research Center for Mediterranean Archaeology, Polish Academy of Sciences, Warsaw, Poland, 1995), pp. 163–178.
64. G. C. Hillman, "Interpretation of archaeological plant remains: The application of ethnographic models from Turkey" in *Plants and Ancient Man: Studies in Palaeoethnobotany*, W. van Zeist, W. A. Casparie, Eds. (Balkema, Rotterdam, the Netherlands, 1984), pp. 1–41.
65. E. Margaritis, M. Jones, Beyond cereals: Crop processing and *Vitis vinifera* L. ethnography, experiment and charred grape remains from Hellenistic Greece. *J. Archaeol. Sci.* **33**, 784–805 (2006).
66. S. M. Valamoti, M. Mangafa, C. Koukouli-Chrysanthaki, D. Malamidou, Grape-pressings from northern Greece: The earliest wine in the Aegean? *Antiquity* **81**, 54–61 (2007).
67. S. Thiébault, "A note on the ancient vegetation of Baluchistan based on charcoal analysis of the latest periods from Mehrgarh, Pakistan" in *South Asian Archaeology 1985: Papers from the Eighth International Conference of the Association of South Asian Archaeologists in Western Europe*, K. Frifelt, P. Sørensen, Eds. (Curzon Press, London, UK, 1989), pp. 186–188.
68. N. F. Miller, Sweeter than wine? The use of the grape in early western Asia. *Antiquity* **82**, 937–946 (2008).
69. A. Crivellaro, F. H. Schweingruber, *Atlas of Wood, Bark and Pith Anatomy of Eastern Mediterranean Trees and Shrubs*, (Springer, Berlin, Germany, 2013).
70. M. Benzaquen, I. Finkelstein, D. Langgut, Vegetation history and human impact on the environs of Tel Megiddo in the Bronze and Iron Ages: A dendroarchaeological analysis. *Tel Aviv J. Inst. Archaeol. Tel Aviv Univ.* **46**, 42–61 (2019).
71. S. D. Turner, A. G. Brown, *Vitis* pollen dispersal in and from organic vineyards. I. Pollen trap and soil pollen data. *Rev. Palaeobot. Palynol.* **129**, 117–132 (2004).
72. G. Avni, N. Porat, Y. Avni, Byzantine–Early Islamic agricultural systems in the Negev Highlands: Stages of development as interpreted through OSL dating. *J. Field Archaeol.* **38**, 332–346 (2013).
73. G. Majcherek, "Alexandria's long-distance trade in late antiquity: The amphora evidence" in *Transport Amphorae and Trade in the Eastern Mediterranean: Acts of the International Colloquium at the Danish Institute at Athens*, J. Eiring, J. Lund, Eds. (Aarhus University Press, Aarhus, Denmark, 2004), vol. 5, pp. 229–237.
74. C. Baly, S'baita. *Palest. Explor. Fund Q. Statement* **68**, 171–181 (1935).
75. B. Moor, Mosque and church: Arabic inscriptions at Shivta in the early Islamic period. *Jerus. Stud. Arabic Islam* **40**, 73–142 (2013).
76. S. Bucking, T. Erickson-Gini, The Avdat in Late Antiquity Project: Report on the 2012 and 2016 excavations of the Area D Compound. *J. East Med. Archaeol. Herit.* **8**, 22–57 (2020).
77. S. A. Rosen, "The decline of desert agriculture: A view from the classical period Negev" in *The Archaeology of Drylands*, G. Barker, D. Gilbertson, Eds. (Routledge, London, UK, 2000), pp. 45–62.
78. S. A. Rosen, Basic instabilities? Climate and culture in the Negev over the long term. *Geoarchaeology* **32**, 6–22 (2016).
79. T. Erickson-Gini, *Nabataean Settlement and Self-Organized Economy in the Central Negev: Crisis and Renewal*, (Archaeopress, Oxford, UK, 2010).
80. G. Barker, A tale of two deserts: Contrasting desertification histories on Rome's desert frontiers. *World Archaeol.* **33**, 488–507 (2002).
81. E. Huntington, *Palestine and Its Transformation*, (Houghton Mifflin, Boston, MA, 1911).
82. R. Rubin, The debate over climate changes in the Negev, 4th–7th centuries C.E. *Palest. Explor. Q.* **121**, 71–78 (1989).
83. Y. Hirschfeld, A climatic change in the early Byzantine period? Some archaeological evidence. *Palest. Explor. Q.* **136**, 133–149 (2004).
84. G. Avni, The Byzantine–Islamic transition in the Negev: An archaeological perspective. *Jerus. Stud. Arabic Islam* **35**, 1–26 (2008).
85. M. Haiman, Dating the agricultural terraces in the southern Levantine deserts: The spatial-contextual argument. *J. Arid Environ.* **86**, 43–49 (2012).
86. C. Geertz, *Agricultural Involution: The Processes of Ecological Change in Indonesia*, (University of California Press, Berkeley, CA, 1963).
87. K. W. Butzer, *Archaeology as Human Ecology*, (Cambridge University Press, Cambridge, UK, 1982).
88. K. W. Butzer, Collapse, environment, and society. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 3632–3639 (2012).
89. R. Bookman, Y. Enzel, A. Agnon, M. Stein, Late Holocene lake-levels of the Dead Sea. *Bull. Geol. Soc. Am.* **116**, 555–571 (2004).
90. I. J. Orland, Climate deterioration in the eastern Mediterranean as revealed by ion microprobe analysis of a speleothem that grew from 2.2 to 0.9 ka in Soreq Cave, Israel. *Quat. Res.* **71**, 27–35 (2009).
91. N. Greenbaum, P. Asher, A. P. Schick, V. R. Baker, The palaeoflood record of a hyperarid catchment, Nahal Zin, Negev Desert, Israel. *Earth Surf. Process. Landf.* **25**, 951–971 (2000).
92. P. Vaiglova *et al*., Climate stability and societal decline on the margins of the Byzantine empire in the Negev Desert. *Sci. Rep.* **10**, 1512 (2020).
93. U. Büntgen *et al*., 2500 years of European climate variability and human susceptibility. *Science* **331**, 578–582 (2011).
94. U. Büntgen *et al*., Cooling and societal change during the Late Antique Little Ice Age from 536 to around 660 AD. *Nat. Geosci.* **9**, 231–236 (2016).
95. D. Fuks *et al*., Dust clouds, climate change and coins: Consiliences of palaeoclimate and economy in the Late Antique southern Levant. *Levant* **49**, 205–223 (2017).
96. B. Lucke *et al*., Questioning Transjordan's historic desertification: A critical review of the paradigm of "Empty Lands". *Levant* **44**, 101–126 (2012).
97. B. Lucke, C. Schmidt, Debris flows, soil creep and heavy rains in the Wadi Queilbeh, northern Jordan. *Z. Geomorphol. Supp.* **61**, 159–201 (2017).
98. J. Luterbacher *et al*., "A review of 2000 years of paleoclimatic evidence in the Mediterranean" in *The Climate of the Mediterranean Region: From the Past to the Future*, P. Lionello, Ed. (Elsevier, Amsterdam, the Netherlands, 2012), pp. 87–185.
99. M. Eisenberg, L. Mordechai, The Justinianic plague: An interdisciplinary review. *Byzantine Mod. Greek Stud.* **43**, 156–180 (2019).
100. L. Mordechai *et al*., The Justinianic Plague: An inconsequential pandemic? *Proc. Natl. Acad. Sci. U.S.A.* **116**, 25546–25554 (2019).
101. D. C. Stathakopoulos, The Justinianic plague revisited. *Byzantine Mod. Greek Stud.* **24**, 256–276 (2000).
102. D. C. Stathakopoulos, "Population, demography, and disease" in *The Oxford Handbook of Byzantine Studies*, R. Cormack, J. Haldon, E. Jeffreys, Eds. (Oxford University Press, Oxford, UK, 2008), pp. 309–316.
103. C. Zuckerman, *Du village à l'empire: Autour du registre fiscal d'Aphroditô (525/526)*, (Association des Amis du Centre d'Histoire et Civilisation de Byzance, Paris, France, 2004).
104. J. C. Russell, That earlier plague. *Demography* **5**, 174–184 (1968).
105. L. K. Little, "Introduction" in *Plague and the End of Antiquity: The Pandemic of 541–750*, L. K. Little, Ed. (Cambridge University Press, Cambridge, UK, 2007), pp. 3–32.
106. Ş. Pamuk, M. Shatzmiller, Plagues, wages, and economic change in the Islamic Middle East, 700–1500. *J. Econ. Hist.* **74**, 196–229 (2014).

107. K. Harper, *The Fate of Rome: Climate, Disease, and the End of an Empire*, (Princeton University Press, Princeton, NJ, 2017).
108. L. Mordechai, M. Eisenberg, Rejecting catastrophe: The case of the Justinianic plague. *Past Present* **244**, 3–50 (2019).
109. K. Twine, The city in decline: Rome in late antiquity. *Middle States Geogr.* **25**, 134–138 (1992).
110. D. C. Stathakopoulo, "To have and to have not: Supply and shortage in the centres of the late antique world" in *Material Culture and Well-Being in Byzantium (400–1453): Proceedings of the International Conference (Cambridge, 8–10 September 2001)*, M. Grünbart, E. Kislinger, A. Muthesius, D. C. Stathakopoulos, Eds. (Austrian Academy of Sciences Press, Vienna, Austria, 2007), pp. 211–217.
111. C. Tsiamis, E. Poulakou-Rebelakou, E. Petridou, The Red Sea and the port of Clysma. A possible gate of Justinian's plague. *Gesnerus* **66**, 209–217 (2009).
112. M. Keller *et al*., Ancient *Yersinia pestis* genomes provide no evidence for the origins or spread of the Justinianic Plague. bioRxiv:819698 (31 October 2019).
113. M. G. Morony, "For whom does the writer write?" The first bubonic plague pandemic according to Syriac sources" in *Plague and the End of Antiquity: The Pandemic of 541–750*, L. K. Little, Ed. (Cambridge University Press, Cambridge, UK, 2007), pp. 59–86.
114. P. Sarris, The Justinianic plague: Origins and effects. *Contin. Change* **17**, 169–182 (2002).
115. N. Benovitz, The Justinianic plague: Evidence from the dated Greek epitaphs of Byzantine Palestine and Arabia. *J. Roman Archaeol.* **27**, 487–498 (2014).
116. D. T. Ariel, The coins from the "Third Mile Estate," Ashqelon. *Atiqot* **74**, 229–239 (2013).
117. G. I. Bijovsky, *Gold Coin and Small Change: Monetary Circulation in Fifth-Seventh Century Byzantine Palestine*, (EUT Edizioni Università di Trieste, Trieste, Italy, 2012).
118. M. Meier, The "Justinianic Plague": The economic consequences of the pandemic in the eastern Roman empire and its cultural and religious effects. *Early Mediev. Eur.* **24**, 267–292 (2016).
119. Z. Safrai, "The influence of demographic stratification on the agricultural and economic structure during the Mishnaic and Talmudic periods" in *Man and Land in Eretz-Israel in Antiquity*, A. Kasher, A. Oppenheimer, U. Rappaport, Eds. (Ben-Zvi Institute, Jerusalem, Israel, 1986), pp. 20–48.
120. Y. Tsafrir, "Some notes on the settlement and demography of Palestine in the Byzantine period: The archaeological evidence" in *Retrieving the Past: Essays on Archaeological Research and Methodology in Honor of G. W. Van Beek*, J. D. Seger, Ed. (Eisenbrauns, Winona Lake, IN, 1996), pp. 269–283.
121. A. Walmsley, "Byzantine Palestine and Arabia: Urban prosperity in late antiquity" in *Towns in Transition: Urban Evolution in Late Antiquity and the Early Middle Ages*, N. Christie, S. T. Loseby, Eds. (Scolar Press, Aldershot, UK, 1996), pp. 126–158.
122. Y. Hirschfeld, Farms and villages in Byzantine Palestine. *Dumbart. Oaks Pap.* **51**, 33–71 (1997).
123. H. J. Bruins, M. Evenari, U. Nessler, Rainwater-harvesting agriculture for food production in arid zones: The challenge of the African famine. *Appl. Geogr.* **6**, 13–32 (1986).
124. H. D. Colt, Ed., *Excavations at Nessana*, (British School of Archaeology, Jerusalem, Israel, 1962), Vol. 1.
125. A. Negev, S. Gibson, Eds., *Archaeological Encyclopedia of the Holy Land*, (Continuum, New York, NY, 2001).
126. J. Magness, *The Archaeology of the Early Islamic Settlement in Palestine*, (Eisenbrauns, Winona Lake, IN, 2003).
127. A. Walmsley, Economic developments and the nature of settlement in the towns and countryside of Syria-Palestine, ca. 565–800. *Dumbart. Oaks Pap.* **61**, 319–352 (2007).
128. G. Avni, *The Byzantine–Islamic Transition in Palestine: An Archaeological Approach*, (Oxford University Press, Oxford, UK, 2014).
129. R. Ellenblum, *The Collapse of the Eastern Mediterranean: Climate Change and the Decline of the East, 950–1072*, (Cambridge University Press, Cambridge, UK, 2012).
130. S. K. Raphael, *Climate and Political Change: Environmental Disasters in the Medieval Levant*, (Brill, Leiden, the Netherlands, 2013).
131. Y. Avni, G. Avni, N. Porat, A review of the rise and fall of ancient desert runoff agriculture in the Negev Highlands: A model for the southern Levant deserts. *J. Arid Environ.* **163**, 127–137 (2019).
132. C. Foss, The Persians in Asia Minor and the end of antiquity. *Engl. Hist. Rev.* **90**, 721–747 (1975).
133. C. Foss, Syria in transition, AD 550–750: An archaeological approach. *Dumbart. Oaks Pap.* **51**, 189–269 (1997).
134. J. J. Norwich, *Byzantium: The Early Centuries*, (Viking, London, UK, 1988), Vol. 1.
135. J. F. Haldon, *Byzantium in the Seventh Century: The Transformation of a Culture*, (Cambridge University Press, Cambridge, UK, 1990).
136. P. Sarris, *Economy and Society in the Age of Justinian*, (Cambridge University Press, Cambridge, UK, 2006).
137. M. Avi-Yonah, The economics of Byzantine Palestine. *Isr. Explor. J.* **8**, 39–51 (1958).
138. J. Haldon *et al*., History meets palaeoscience: Consilience and collaboration in studying past societal responses to environmental change. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 3210–3218 (2018).
139. H. Kennedy, The last century of Byzantine Syria: A reinterpretation. *Byzantinische Forsch.* **10**, 141–184 (1985).
140. C. Morrisson, J. P. Sodini, "The sixth-century economy" in *Economic History of Byzantium*, A. E. Laiou, Ed. (Dumbarton Oaks, Washington, DC, 2002), Vol. 1, pp. 171–220.
141. C. E. Ebert, J. A. Hoggarth, J. J. Awe, B. J. Culleton, D. J. Kennett, The role of diet in resilience and vulnerability to climate change among early agricultural communities in the Maya Lowlands. *Curr. Anthropol.* **60**, 589–601 (2019).
142. J. A. Tainter, *The Collapse of Complex Societies*, (Cambridge University Press, Cambridge, UK, 1990).
143. K. Dark, "Globalizing late antiquity: Models, metaphors and the realities of long-distance trade and diplomacy" in *Incipient Globalization? Long-Distance Contacts in the Sixth Century*, A. Harris, Ed. (Archaeopress, Oxford, UK, 2007), pp. 3–14.
144. M. J. Versluys, Understanding objects in motion: An archaeological dialogue on Romanization. *Archaeol. Dialogues* **21**, 1–20 (2014).
145. R. Martin, Regional economic resilience, hysteresis and recessionary shocks. *J. Econ. Geogr.* **12**, 1–32 (2012).