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## CLIMATOLOGY

## Climate change and water management in the biblical city of Dan

David Kaniewski,<sup>1,2,3\*</sup> Nick Marriner,<sup>4</sup> David Ilan,<sup>5</sup> Christophe Morhange,<sup>6</sup> Yifat Thareani,<sup>5</sup> Elise Van Campo<sup>1,2</sup>

Global climate change has sharpened focus on the social and economic challenges associated with water deficits, particularly in regions where anthropogenic demands exceed supply. This modern condition was also experienced by the people of ancient western Asia, where chronic water shortages were accentuated by recurrent droughts. However, human societies may react to climate change, particularly desiccation, in different ways depending on specific local conditions. Focusing on the biblical site of Tel Dan (present-day Israel), we show the effects of severe precipitation decline in an environment that was well watered and fertile even in times of drought. Such local niches of prosperity became attractive targets for predation when food resources became scarce in surrounding rain-fed areas. We propose that predation forced urban populations to either flee or adopt new subsistence strategies. Predation and abandonment, even if only partial, led to the poor maintenance of water networks in and around the city. Once stagnant water surrounded the area, water-borne disease proliferated. Our study shows how climate changes can disrupt social and political structures, cause water system management to collapse, and facilitate marshland expansion.

## INTRODUCTION

The Fertile Crescent is nowadays a water-challenged region. In the near future, predictions suggest that the largest shifts in water supply will result from a decrease in storm track activity over the Eastern Mediterranean and a resulting decline in precipitation (1–4). Although water was already a key factor in shaping the emergence of the Fertile Crescent's first true cities, some 6000 years ago, triggering and spurring urban evolution in the Mesopotamian marshes (5–7), the use of freshwater supplies as a “weapon of war” was precocious (8, 9). Urban growth and the expansion of interlacing exchange networks in the Levant and Mesopotamia (10, 11), sustained by the dominant political powers, were periodically crippled by severe declines in water availability (12), and the resulting limited water resources rapidly became an object of military conquest, a source of political leverage, and a tool and target of conflict (8, 13).

It has been suggested that the earliest, largest, and longest-lived cities were founded and grew within and on the borders of marshlands (5, 6). Marshes buffered large-scale fluctuations in precipitation or shifts in water supply. They were a permanent source of water for irrigation and a supplier of food and building materials (14). Permanent access to a source of water was key to human health and sustained food production for many thousands of years (7, 15, 16). Was this idyllic situation sustainable over several millennia?

Located at the edge of one of the most urbanized marsh areas in the Levant, the biblical city of Dan (Tell el-Qadi, “Mound of the Judge” in Arabic; Fig. 1) is mentioned more than 60 times in the Hebrew Scriptures (for example, Judges 18:29; 20:1). The term “from Dan to Beersheba” was

a stock phrase depicting the borders of the Land of Israel. Currently, the site of Tel Dan rests amid a tangle of lush greenery that emerges from the drylands of the northern Hula Valley and the Golan Heights. The ancient city lies at the source of the Dan water system, the main tributary of the Jordan River, Israel, and Jordan's primary freshwater resource, depicted in the Hebrew Bible as a fount of fertility, its valley watered like the “garden of the Lord” (Genesis 13:10). The Dan stream (annual average flow of  $2.6 \times 10^8 \text{ m}^3$ ) is fed by dozens of springs originating mainly in the rain- and snowfall that precipitate on Mount Hermon (2814 m; 2760 m above Lake Hula). The spring's discharge is known for both its annual and interannual stability (17, 18). The ancient city was also fed by Nahal Sion (average daily yield of  $1.8 \times 10^3 \text{ m}^3$ ), descending from Mount Hermon, which further contributed fresh water to the valley below. These sources have sustained human societies and urban development at Tel Dan, with a rich agricultural base since the Late Neolithic period, 7000 years ago. We have no written historical sources that recount the role of water and the impact of regional shortages at ancient Dan; however, evidence from Syria, Mesopotamia, and the southern Levant suggests that drought and changing climate patterns nurtured or hastened violent confrontation, abandonment of rain-fed plains, and migrations (12, 19–21).

It is increasingly apparent that past and present climate changes have combined with social, economic, and political factors to exacerbate vulnerabilities (22–24); severe drought events have affected western Asian societies in the recent millennia (12, 25–27). However, did permanent water resources protect some populations in the Levant and west Asia while others waned or fled in search of fertile lands? Did some cities remain completely unaffected?

Here, we explore the outcomes of severe climate changes on urbanized marsh areas during key periods of water stress in the Fertile Crescent through the prism of ancient Tel Dan. Climate models are now projecting widespread aridity across the Mediterranean Basin over the coming century (28, 29). This predicted growth in aridity will potentially impose exceptional stress on already limited water resources (30, 31) with substantial impacts on the environment, on society (32), and on human health (33, 34). The outcomes of severe drought events in the past may resonate with present declines in precipitation (1) in the drylands of the Middle East and prefigure their aftermaths.

<sup>1</sup>Université Paul Sabatier–Toulouse 3, EcoLab (Laboratoire d'Ecologie Fonctionnelle et Environnement), Bâtiment 4R1, 118 Route de Narbonne, 31062 Toulouse cedex 9, France. <sup>2</sup>CNRS, EcoLab (Laboratoire d'Ecologie Fonctionnelle et Environnement), 31062 Toulouse cedex 9, France. <sup>3</sup>Institut Universitaire de France, Secteur Biologie-Médecine-Santé, 103 Boulevard Saint Michel, 75005 Paris, France. <sup>4</sup>CNRS, Laboratoire Chrono-Environnement UMR6249, Université de Franche-Comté, UFR ST, 16 Route de Gray, 25030 Besançon, France. <sup>5</sup>The Nelson Glueck School of Biblical Archaeology, Hebrew Union College Jewish Institute of Religion, 13 King David Street, Jerusalem 94101, Israel. <sup>6</sup>Aix-Marseille Université, CNRS, Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement (CEREGE), UM 34, Europôle de l'Arbois BP80, 13545 Aix-en-Provence, France.

\*Corresponding author. Email: david.kaniewski@univ-tlse3.fr



**Fig. 1. Geographical location of the study area in Israel.** The study site, denoted by a yellow star, is located in the northern part of the Hula Valley, Upper Galilee. The main archaeological sites of Israel and surrounding countries for the period under consideration are displayed on the map. The original map was created by P. Pentsch (Aix-Marseille University).

## Tel Dan

The city of Dan (Fig. 2; see the Supplementary Materials), at the northernmost edge of the ancient Kingdom of Israel (35), is also referred to as Laish in the Hebrew Bible (Joshua 19:47; Judges 18:29). Laish appears in written documents from the city of Mari (Tell Hariri, Syria), located in the middle of the Euphrates trade routes, and in the Egyptian Execration texts (listing enemies of the Pharaoh), both apparently dating to the 18th century BCE (35). The imposing triple-arched mudbrick gate (~1750 BCE), one of the world's earliest preserved arched structures, dates to this period (36). The Egyptian Pharaoh Thutmose III (first regnal year 1494 to 1483 BCE) (37) named Laish as one of the cities he conquered during his military campaigns in the Levant. An Aramaic victory stela discovered in fragments among the structures at the entrance of the outer gate was erected by Hazael of Aram-Damascus (~840 BCE) (38, 39). Hazael boasts of his victory over the king of Israel (most likely Jehoram) and his ally, the king of the House of David (most likely Ahaz). The city of Dan was destroyed by an earthquake in the mid-8th century BCE, perhaps the “great noise” mentioned in the book of Amos (1:1), which would date to 762 BCE. The site was again partially destroyed in the second half of the 8th century BCE, perhaps by Tiglath-Pileser III (2 Kings 15:29), king of Assyria. Tel Dan appears to

have lost much of its grandeur and cultic importance from the Persian period onward (35, 40).

## RESULTS

### Ecological shifts

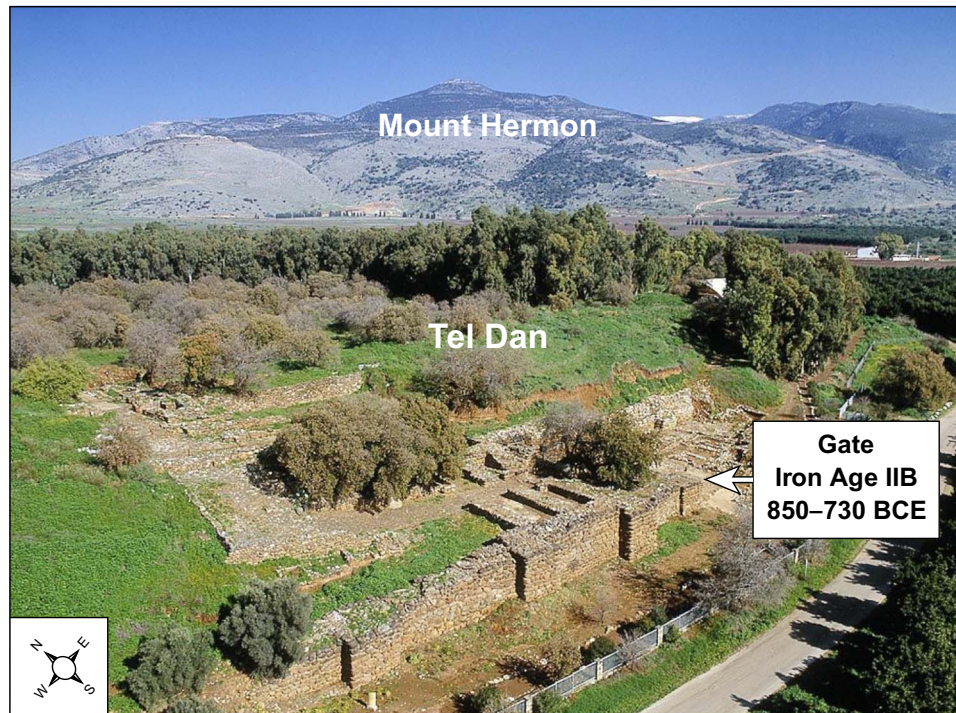
Historically, population growth has adjusted to local ecohydrological constraints (16). With this in mind, we probed the variability in freshwater supply in the marshland vicinity of Tel Dan, referencing the main ecological shifts. In the ancient Upper Galilee, key pollen-derived vegetation patterns juxtapose two different but contemporaneous environments whose dynamics characterize the major ecological changes (Fig. 3A). Over time, two environmental zones, the Transition zone and the Chaparral/oak woodland zone (figs. S1 and S2), are significantly negatively correlated ( $Lag_0 = -0.76$ ,  $P = 0.05$ ; fig. S3A) and correspond to the main loadings in the principal components analysis [PCA; all pollen-based clusters (fig. S1) account for +0.787 of the variance of PCA-Axis1 (Fig. 3A)].

Because ecosystem dynamics near urban areas may result primarily from anthropogenic factors, such as deforestation, fire, and erosion, a cross-correlation between the PCA-Axis1 scores and the cultivated species was performed (fig. S3B). A positive correlation centered on a null lag ( $Lag_0 = -0.76$ ,  $P = 0.05$ ; fig. S3B) indicates that (i) the spread of drought-resistant clusters ( $-0.68$  and  $-0.43$  of total variance on PCA-Axis1) is not an outcome of anthropogenic impacts, and (ii) cultivated crops follow the pattern of the wet vegetation types ( $Lag_0 = +0.476$ ,  $P = 0.05$ ; fig. S3C), with increased harvests during periods when cultivation was well managed.

Variations in PCA-Axis1 scores, loaded by water-fed vegetation clusters (positive values) and drought-resistant assemblages (negative scores), reflect ecological changes (fig. S2) resulting from periodic variations in water availability (Fig. 3A and fig. S1). The major shifts observed in ecosystem dynamics—trophic downgrading, community decline, and loss of ecosystem services—result from lower water inputs from Mount Hermon at ~2150 to 1950 BCE, ~1050 to 840 BCE, and ~550 to 350 BCE (Fig. 3A). The area was never dry, but probably evolved into a marsh zone, suggesting changes in water supply dynamics and disruptions in the water distribution network around the city. In the Iron Age IB to Iron Age IIA, the ecological shift in Upper Galilee also correlates with the driest phase in Egypt (41), Syria (42), Cyprus (43) (fig. S4), and Lebanon (44) (fig. S5). The wavelet analysis also shows that the PCA-Axis1 is defined by periodicities of 550 years and a longer-term trend (1500 years, combining the 550- and 950-year cycles; fig. S6A). The ecological shifts show a key cycle of 550 years (45) driven by a decline in freshwater supplies, a finding that is underlined by both spectral (white noise) and REDFIT (red noise) analyses. The 550-year pacemaker seems to be an intermediary cycle that may be a derived mode stemming from a rectification of the signal generated by a superposition of the fundamental solar modes (46, 47). This intermediary cycle could also be a manifestation of the rectified responses of the Atlantic thermohaline circulation to external solar modulation and pacing (48). Changes in water supply in the ancient Upper Galilee therefore seem to be mediated by an internal threshold response of the global thermohaline circulation to solar forcing.

### Settlement intensity and oleiculture

We created a settlement intensity curve (Fig. 3B) by combining two parameters, “settlement density” and “estimated settled area,” to assess whether ecological shifts, resulting from changes in freshwater supply



**Fig. 2. Aerial photograph of Tel Dan, looking east toward Mt. Hermon.** The monumental gate complexes that dominate the photo are mainly attributed to Strata III to Strata II, Iron Age IIB (~850 to 730 BCE), when the city was a national cult center of the Kingdom of Israel.

from Mount Hermon and the Golan, may have affected urban development (Fig. 4). The impact of water supply on agricultural practices and human behavior (Fig. 3C) was evaluated by tracing signs of traditional Mediterranean oleiculture around Tel Dan. Other cultivated species (cereals, vine, and walnut) and pastoral activities largely mirror the relative intensity of the olive (fig. S7).

According to the available data, the area was less densely settled during the Intermediate Bronze Age (~2500 to 1950 BCE) (49) and at the Late Bronze Age I to Late Bronze Age II boundary (~1450 to 1350 BCE), perhaps as a result of repeated Egyptian incursions, deportations, and slave taking (50), and again during the Late Iron Age IB to Iron Age IIA (~1050 to 840 BCE). Tel Dan was only sparsely populated during the Persian and Hellenistic periods (~550 to 60 BCE) when the Levant became more of an economic and political backwater (51–53). It appears that three phases of both low settlement intensity and decline in oleiculture (~2500 to 1950 BCE, ~1050 to 840 BCE, and after ~550 BCE; Fig. 3, B and C) are chronologically correlated with the lowest inputs of freshwater from Mount Hermon (Fig. 4). This correlation suggests that water supply fluctuation affected settlement density in some way, directly or indirectly. In arid regions (for example, in large parts of Syria and Turkey), the competition for increasingly scarce resources probably led to emigration toward fertile zones like Tel Dan, creating social tensions. Parts of the local population suffering from various forms of predation eventually fled the city, transforming the urban center into a low-density village (Fig. 3B).

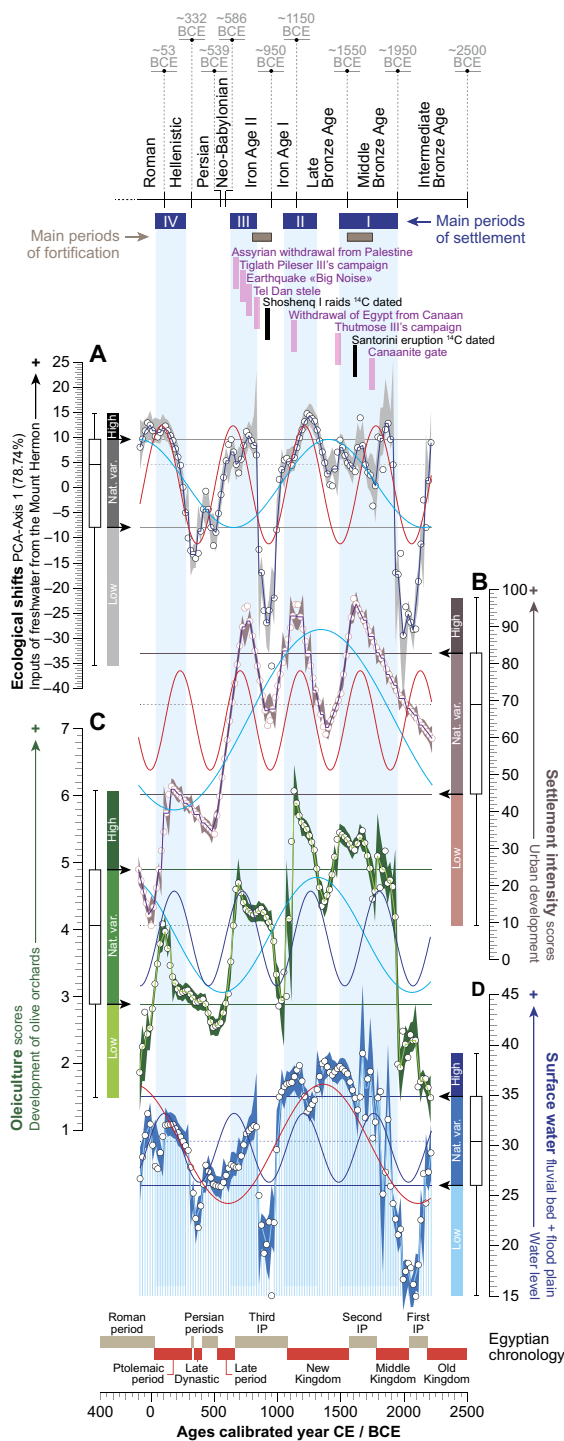
The drop in oleiculture, which started around 1100 BCE (Fig. 3C), may result not only from the decline of agricultural practices but also from a change in the phenology of the olive trees because of climate pressures. Although the olive tree is a parsimonious water consumer that is well adapted to xeric conditions, water stress can affect flowering,

resulting in low pollen production (54–56). A further pressure may correspond to the development of stagnant water in cultivated fields that would have generated root hypoxia (57).

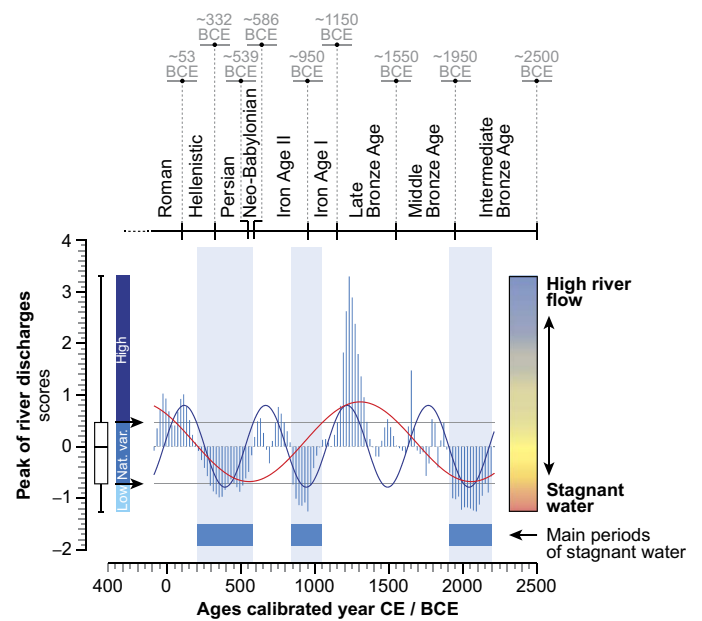
### Water discharge

Water level (Fig. 3D) and water discharge (Fig. 4), fed by Mount Hermon (fig. S8), have been reconstructed in an attempt to detect correlations with urban development. Two main phases of low water level (~2150 to 1950 BCE and ~1050 to 840 BCE; Fig. 3) are chronologically correlated with a steep decline in settlement intensity (Fig. 3B). For the period 1950 to 1050 BCE (Fig. 3D), the surroundings of the site appear to have been completely covered by water, at least during the seeding and growing seasons. The water-table level was probably sufficiently high for successful agricultural development (Fig. 3C). Conversely, the period ~840 to 300 BCE shows large variations in water inputs, with a gradual decline initiated at ~700 BCE and peaking at ~350 BCE, most probably affecting the population since ~650 BCE. This period of decline is also marked by increases in pasturing, whereas agricultural indicators dropped below the Bronze Age scores (fig. S7). The water level during the last recorded period (~300 to ~90 BCE) increases but remains around the median values. The wavelet analyses for the water level and discharges show a 550-year periodicity, similar to the one recorded by the PCA-Axis1 (fig. S6). A positive correlation centered on a null lag ( $Lag_0 = +0.791$ ,  $P = 0.05$ ; fig. S3C) also indicates that water variability is linked to ecosystem dynamics.

We suggest that the decline in wetlands flora around Tel Dan (fig. S2) was the result of habitat desiccation due to reduced freshwater inputs to the marshlands, generating large areas of stagnant water, marshy borders, and brackish puddles (Fig. 4) surrounded by xeric vegetation types (fig. S2). The human populations that occupied the site during



**Fig. 3. Reconstructed environmental dynamics at Tel Dan from the Bronze Age [2200 calibrated years (cal yr) BCE] to the Roman period (100 cal yr CE).** The PCA-Axis1, termed ecological shifts (A), settlement intensity (B), oleiculture (C), and water level (D) are all displayed as a locally weighted linear regression (LOESS) smoothing (with bootstrap and smoothing 0.05) with sinusoidal regressions (550 and 1500 years,  $P < 0.001$ ). A boxplot was added to each curve to mark the extreme scores. The curves are plotted on a linear timescale (BCE/CE). At the top, an archaeological scale is denoted. The main events at Tel Dan are indicated in purple, whereas the two external events (89, 90) are displayed in black. The shaded blue lines indicate the main periods of settlement. At the base of the graph, an Egyptian chronology has also been added. nat. var., natural variability; IP, intermediate period.



**Fig. 4. River discharge to the alluvial fan of the Nahal Sion.** The curve is displayed with two sinusoidal regressions (550 years in blue and 1500 years in red,  $P < 0.001$ ). A boxplot indicates the extreme scores and the natural variability. The curve is plotted on a linear timescale and shown with an archaeological framework.

periods of low settlement density (~2500 to 1950 BCE, ~1050 to 850 BCE, and since ~550 BCE; Fig. 4) inhabited a challenging environment and were probably subjected to marsh-related disease.

### DISCUSSION

The dry events that have occurred repeatedly in the Mediterranean and west Asia during the last 4500 years (12, 27, 58–60) deeply affected ecosystems and led to environmental degradation that upset the traditional balance between habitat and socioeconomic systems (13, 61). Subsistence-based populations probably migrated from rural farming areas to the peripheries of urban centers. This outcome was witnessed in modern Syria during the 3-year drought in 2007 to 2010, which resulted in widespread crop failure and a mass migration of farming communities to urban areas (22, 62). In the same way, during phases of enduring drought in the area of Tel Dan (~2150 to 1950 BCE, ~1050 to 840 BCE, and ~550 to 350 BCE), the adaptive societal structures appear to have become extremely fragile. Abandonment of rain-fed plains and habitat tracking across hydrologically varied landscapes (riparian, paludal, and karst-fed spring zones, such as the fertile area of Tel Dan, created rivalry for resources, tensions between groups, and, finally, the semi-abandonment of the city (Fig. 3B).

Once central authority and the urban framework collapsed, the irrigation and drainage systems—those that had made the environs of Tel Dan down to the Hula Valley a highly productive system—were no longer maintained, and the valley reverted to its marshy, disease-ridden former self (Fig. 4). To understand what ensued in and around Tel Dan during these periods, a parallel can be drawn with the settlement pattern of the Hula Valley from the medieval period up until the 19th century CE (49, 63–66). Lacking a strong central authority to manage

drainage and irrigation systems after the Mongol raids (~1240 CE) (67), marshes expanded in the valley up to Tel Dan. Irrigation reservoirs, channels, and sluices were left to decay, creating a “muddy wilderness” (63) infected by water-borne diseases, mainly malaria (*Plasmodium*), spread by the mosquito genus *Anopheles* (64, 68). Since Hippocrates (5th century BCE) and, later, in the Roman Empire period, malaria has been related to marshes (69), with the disease interpreted as a miasma arising from the marshes (70). Nomad inhabitants moved out of the Hula Valley during summer time when the densities of mosquito larva and adults are higher (71) and returned for the sowing of sorghum and rice planting; however, malaria was so widespread that the disease controlled the density of Bedouin populations (67). In the 19th to 20th centuries CE, the Bedouins who lived in the Hula Valley (“Buhairat al Hula” in Arabic) only maintained their permanent settlements because of a constant but low-level influx of population. Marshes offered inhabitants only a marginal subsistence, and heat and malaria worsened the harsh and challenging conditions (72). Their subsistence lifestyle was based on resources from the marshes (for example, papyrus harvest), from animals (water buffalo and cattle), and from agriculture (maize, rice, and wheat) in and around the wetlands (64), similar to that of the Ma’Dan Marsh Arabs of the Tigris-Euphrates marshes in southern Iraq (73). Mortality rates were extremely high due to chronic disease (63) and to fecal-oral pathogens transmitted through the consumption of stagnant water (diarrheal disease or gastrointestinal illnesses).

Malaria was so alarming for populations that, between 1951 and 1958 CE, the wetland was drained not only to expand agricultural production but also to eliminate water-borne disease (64). According to our data from Tel Dan, conditions for malaria became optimal during periods when the city became a low-density village (~2500 to 1950 BCE, ~1050 to 840 BCE, and since ~550 BCE), with the abandonment of irrigation and drainage systems during periods of reduced inputs from Mount Hermon, collectively resulting in organically polluted basins, ponds, and puddles of stagnant water. Malaria, wrongly interpreted as being imported by the crusaders (63), was a well-established scourge in the Levant. Its spread is thought to have started between 10,000 and 5000 years ago in Africa and the Middle East, favored by the emergence of agriculture and early urban development (74, 75). The earliest evidence for Bronze Age malaria in the Eastern Mediterranean comes from Egypt, where genetic fingerprinting of Tutankhamun’s body has revealed traces of the disease (first regnal year 1348 to 1339 BCE) (37), as well as in Tutankhamun’s immediate lineage (76) and in mummy tissues in tomb complexes dating from the New Kingdom to the Late Period (77). Malaria was endemic to the Nile Valley at least as early as the 2nd millennium BCE (76, 78) and probably as early as the 4th millennium BCE (79). Many Egyptians would have been carriers of malaria. Egyptians were resident in the Jordan Valley at least as early as the Late Bronze Age, ~1500 BCE (80–82). They also arrived as settlers to the coastal plain of the southern Levant in the Early Bronze Age in the late 4th millennium BCE (83). It is near certain that malaria was a key factor in shaping human lifestyles in the lowlands of ancient Canaan (84). The Nile Valley and the Nile Delta were vast marshy areas and, consequently, perfect breeding grounds for *Anopheles* (76), similar to the Dan area down to the Hula Valley.

The maintenance of irrigation and drainage canals might have eased the scourge of malaria epidemics during periods of reduced freshwater inputs (Fig. 3D); however, the persistence of low population densities during these long periods (Fig. 3B) precluded effective management. The low densities may first have resulted from fear of predation, because the town had become, we hypothesize, a target for pillage or conquest.

After that, the absence of a centrally managed irrigation and drainage system left widespread stagnant water and created conditions conducive to disease, adding further disincentive to settle here.

The area from Tel Dan down to the Hula Valley serves as a model for understanding the future of marshland societies, their margins, and their proximate drylands. Ancient Tel Dan underlines the threat of water-borne disease in the current context of global climate change. Although malaria remains of great concern, the recent outbreak of Rift Valley fever in Africa and the Arabian Peninsula (33, 34, 85) would suggest that changing climate and unmanaged water systems will serve as catalysts for water-borne disease, with significant implications for the health of local populations.

## MATERIALS AND METHODS

### Core and chronology

Tel Dan is a rectangular mound (circa 20 ha) located in the northeastern reaches of the Hula valley near the foothills of Mount Hermon (Fig. 2). Terrestrial and freshwater biological indicators were extracted from a 675-cm continuous core (TD-1, 33°15′00.24″N, 35°39′13.18″E; +209 m mean sea level) drilled on the alluvial fan of the Nahal Sion (fig. S8), close to the eastern flank of Tel Dan, in an avocado orchard near the Middle Bronze Age mudbrick gate. The chronology of the core is based on nine accelerator mass spectrometry <sup>14</sup>C dates (table S1). No botanical macro-remains or secure bulk fractions were found in the middle core, leaving a floating chronology between 250- and 150-cm depth. Dated samples were calibrated (1σ and 2σ calibrations, respectively, 68 and 95% of probability) using CALIB REV 7.1 with IntCal13 (86). The average chronological resolution for the core stratigraphy is 4 years/cm<sup>-1</sup> (2.5 mm per year<sup>-1</sup>). We recognize that this average is liable to mask both more intense weather events and closely sequenced series of more extreme years of drought or high precipitation. It would then also mask some of the temporal variability in the depositional patterns of alluvium and pollen. From the point of view of a single core, this would result in a heuristic exercise of interpolation, rather than as a chronologically reliable record of changing climate. Nevertheless, when the same patterns recur in different cores from different locations in the eastern Mediterranean and western Asia (12, 19, 20, 41–44), we can consider these patterns as reflecting the temporal dimension with some degree of precision.

### Archaeological data

The archaeological data are the fruit of more than 50 years (38 field campaigns) of excavation at Tel Dan since 1966 (35, 40, 87, 88) and are summarized as a supplementary text (see the Supplementary Materials and tables S2 to S4). Estimates of population and population density are based on the measured area of habitation gleaned from excavations and surveys of the site carried out since 1966. All these estimates assume a contemporaneity of occupation of architectural units throughout the site based on the homogeneity of material culture in the identified stratigraphic horizons.

### Botanical data

Samples from core TD-1 were prepared for pollen analysis using the standard procedure for clay samples. Pollen frequencies (expressed as percentages) are based on the terrestrial pollen sum, excluding local hygrophytes and spores of nonvascular cryptogams. Aquatic taxa frequencies were calculated by adding the local hygrophytes-hydrophytes to the terrestrial pollen sum.

## Statistical analyses

All archaeological and botanical data were analyzed using the software package PAST version 2.17c. A regular interpolation (20 years) was first applied to the entire data set. Pollen data were investigated using cluster analysis (paired group as algorithm and correlation as similarity measure; fig. S1). Cluster analysis (descending type) was used to compute the lengths of tree branches, using branches as ecological distances between groups of taxa. Neighbor joining, an alternative process for hierarchical cluster analysis, was also calculated for the hygrophilous-hydrophilous components, using correlation as similarity measure and final branch as root (fig. S1). Each cluster was summed to create pollen-derived vegetation patterns.

A PCA was run to test the ordination of terrestrial ecosystems by assessing major changes in the pollen-derived vegetation patterns (Fig. 3A). The “agro-pastoral activities” and “flood plain–fluvial bed” assemblages (fig. S1) were excluded from the matrix. The main variance is loaded by the PCA-Axis1 (termed ecological shifts), which is shown as LOESS smoothing (with bootstrap and smooth 0.05) plotted on a linear age scale (Fig. 3A). A boxplot was added to demarcate the natural variability from the extreme values.

Periodicity was investigated using a sinusoidal regression (phase Free; Fig. 3A) to show the long-term trends and further examined using a wavelet analysis (wavelet transform) with Morlet as the basis function (fig. S6A). The scalograms are displayed as periods ( $\log_2$  scale) against a linear age-scale. A spectral analysis was then computed to consider the periodicity in terms of frequency/power (fig. S6A). A REDFIT analysis was added to reduce the red noise (oversampling, 1; segments, 1; and window, rectangular; fig. S6A). The potential effect of the residual on the periodicity was tested using autoregressive-moving average analysis and autocorrelation (95% confidence).

The settlement intensity curve (Fig. 3B) and the oleiculture scores (Fig. 3C) are also shown as LOESS smoothing (with bootstrap and smooth 0.05), with the outcomes of the sinusoidal regression (phase Free), and plotted on a linear age-scale. For each curve, a boxplot was also added to show the natural variability from the extreme scores.

A surface water curve (Fig. 3D) was created by adding the clusters “flood plain” and “fluvial bed” (fig. S1) and represented in the same manner as the other curves (LOESS, sinusoidal regression, and boxplot). The river discharge curve (Fig. 4) was then generated by correcting the surface water with the variability of drought-resistant ecosystems. A square root was applied to the resulting signal, and the “subtract mean” function was calculated. The outcome is displayed with a sinusoidal regression and a boxplot (Fig. 4). The periodicity of the river discharge curve (fig. S6B) and the surface water curve (fig. S6C) was examined using a wavelet analysis with Morlet as the basis function.

The relationships between clusters, the PCA-Axis1, agriculture, and the surface water were analyzed using cross-correlations ( $P = 0.05$ ). The cross-correlations assess the time alignment of two time series by means of the correlation coefficient. The series have been cross-correlated to ascertain the best temporal match and the potential lag between two selected variables. The correlation coefficient was then plotted as a function of the alignment position (fig. S3). Positive and negative correlation coefficients were considered, focusing on the  $Lag_0$  value (with +0.50 and –0.50 as significant thresholds).

## SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/3/11/e1700954/DC1>

Supplementary text. Tel Dan—Summary of the archaeological data

fig. S1. Pollen-based ecological clusters detected in the Upper Galilee from the Bronze Age to the Roman period.

fig. S2. Pollen diagram showing the dynamics of vegetation assemblages from the Bronze Age to the Roman period.

fig. S3. Correlations between the clusters, the PCA-Axis1, agriculture, and surface water.

fig. S4. Ecological shifts recorded at Tel Dan compared with records from Syria (Tell Tweini) and Cyprus (Hala Sultan Tekke).

fig. S5. The chronology of ecological shifts recorded at Tel Dan compared with Jeita Cave ( $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ ), Lebanon.

fig. S6. Periodicity of ecological shifts in the Upper Galilee from the Bronze Age (2200 cal yr BCE) to the Roman period (100 cal yr CE).

fig. S7. Agriculture and pastoral activities in and around Tel Dan from the Bronze Age (2200 BCE) to the Roman period (100 CE).

fig. S8. Map of the Tel Dan area showing Mount Hermon, the Golan Heights, the Nahal Sion, and the Dan springs.

table S1. Details of the  $^{14}\text{C}$  age determinations for the core TD-1.

table S2. The strata of Tel Dan and their salient characteristics.

table S3. Estimated settled area and settlement density at Tel Dan by stratum.

table S4. Selected radiocarbon dates from sites linked to Tel Dan by ceramic horizons and by period. Source data

References (91–116)

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David Kaniewski, Nick Marriner, David Ilan, Christophe Morhange, Yifat Thareani and Elise Van Campo

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