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Modeling vegetation dynamics in the Southern Levant through the Bronze Age

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ABSTRACT

We integrate modern spatial distributions of plant geographical regions with paleoclimatic trends to model vegetation change in the Southern Levant over the course of the mid-Holocene. This timespan witnessed the rise, collapse and redevelopment of urbanized society and settlement during the Bronze Age. This study applies GIS and statistical modeling tools (MAXENT) to vegetation data from 1696 historical and modern observation points across the region to chart potential vegetation for the present and at 100-year intervals between 5500 and 3000 calibrated years BP. A macrophysical climate model is used to create vegetation maps based on regional temperature and precipitation data. Environmental dynamics tracked over this time period, including past vegetation, temperature and precipitation, are applied to the interpretation of Bronze Age settlement and social change. Our results reveal a general trend of Mediterranean forest contraction through the Bronze Age. The "4.2 event" (ca. 4200 calibrated years BP) potentially links regional desiccation and urban collapse, and constitutes the last element in a trajectory of reduced potential forest vegetation through the Early Bronze Age. Rapid woodland expansion correlates with abrupt cooling and reurbanization at the outset of the Middle Bronze Age. Modeled vegetation shows minimum forest and maximum desert coverage consistent with a Late Bronze Age "crisis" ca. 3000 calibrated years BP. In comparison to the Bronze Age, modern potential vegetation includes the broadest extent of steppe.

1. Introduction

The Southern Levant experienced the advent, abandonment and renewal of urbanized settlement over the course of the Bronze Age. Configurations of towns and villages shifted repeatedly across a landscape molded by a long legacy of climatic change and human modification. A series of publications over the last three decades has reoriented the discussion of Bronze Age societal transitions by emphasizing mid-Holocene climate change (e.g., Roberts et al., 2011; Rosen, 2007), with particular emphasis on the potential linkage of climatic deterioration with social collapse (e.g., Barker et al., 2007; Deckers and Pessin, 2010; Issar, 2003; Kaniewski et al., 2012; Staubwasser and Weiss, 2006, 2001; Weiss et al., 1993; Whitelaw, 2000). In particular, archaeological interpretation of Bronze Age society in the Southern Levant now features prominent discussion of drought as a major contributor to the pervasive abandonment of towns at the end of the Early Bronze Age (e.g., Cullen et al., 2000; DeMenocal, 2001; Hunt et al., 2007; Issar and Zohar, 2004; Weninger et al., 2009).

We chart the environmental dynamics of the Southern Levant during this era of dramatic social variation by modeling and mapping plant geographical regions for the present and at 100-year intervals between 5500 and 3000 calibrated years BP (hereafter cal BP), from the Chalcolithic/Early Bronze Age transition until the beginning of the Iron Age. We utilize machine-based species distribution modeling (SDM), which is applied increasingly for mapping spatial distributions of plant and animal species on the basis of GIS analysis and statistical testing (e.g., Banks et al., 2008; Fløjgaard et al., 2009; Kremen et al., 2007; Lobo et al., 2010; McDonald and Bryson, 2010; VanDerWal et al., 2009; Varela et al., 2010).

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This study poses the following interrelated research questions: (1) How do cultural changes through the Bronze Age relate to environmental change? (2) Specifically, how do trajectories of vegetation change relate to the rise of Early Bronze Age town life, urban collapse toward the end of the Early Bronze Age ca. 4200 cal BP (the "4.2 event"), Middle Bronze Age re-urbanization, and a Late Bronze Age "crisis" ca. 3200 cal BP? (3) How does modern modeled vegetation compare to vegetation and underlying environmental conditions in the past?

2. Study area

The Southern Levant supported a mosaic of ancient towns, villages and pastoral encampments situated between the urban heartland of Mesopotamia and the riverine kingdoms of Egypt. Limited perennial water sources and pronounced topographic relief made the region largely dependent on dry farming and particularly susceptible to the influences of environmental fluctuations. Our study area encompasses approximately 39,500 km^2 between latitude 29°30′N to 33°N and longitude 34°17′E to 36°15′E (Fig. 1). This landscape extends from the Mediterranean Sea east across the Levantine Coastal Plain to the Central Hills (up to 1200 m elevation), and then descends into the Jordan Rift. The Rift runs from the Sea of Galilee south along the Jordan Valley to the Dead Sea (−410 m), and through the Wadi Araba to the Red Sea. East of the Rift, a steep escarpment rises to the Transjordanian Plateau (max. elevations over 1700 m), which is deeply incised by wadis draining west towards the Rift.

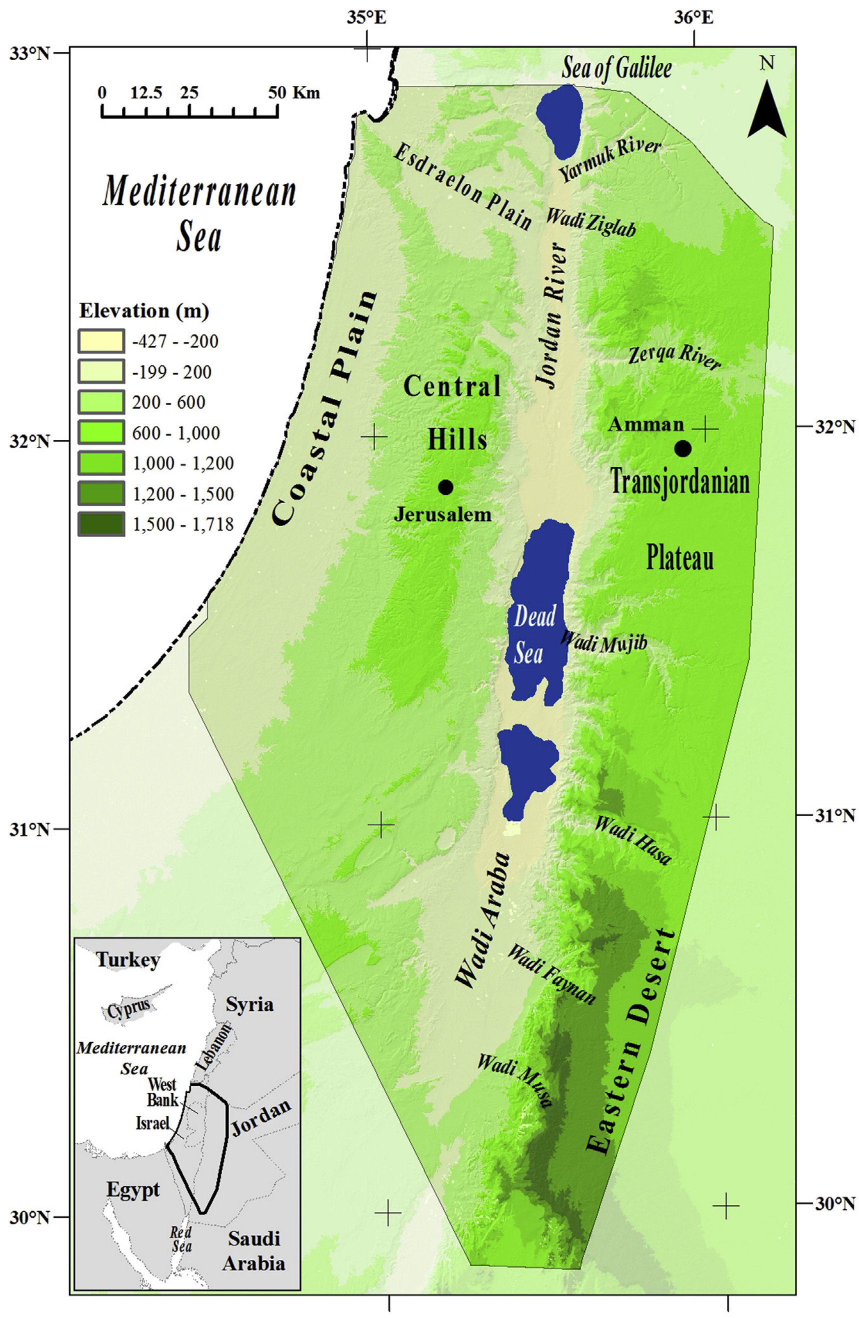

Fig. 1. Map of major topographic features and elevations of the study area in the Southern Levant; inset shows location in the eastern Mediterranean basin.

The region's Mediterranean climate is characterized by wet, cool winters and long, dry and hot summers. The coolest temperatures occur at higher elevations in the Central Hills and in the southern highlands of the Transjordanian Plateau. In sharp contrast, temperatures reach 50 °C in the lowest elevations along the Jordan Valley, around the Dead Sea and in the Wadi Araba (Al-Eisawi, 1996). Precipitation is most prevalent in winter and spring, although summer storms can deliver short intense rainfall to the arid southern portion of the study area, which may receive less than 100 mm per year. Precipitation generally decreases from west to east with increasing distance from the Mediterranean Sea, and from north to south as the influence of cyclonic storms declines. Topography also causes a gradient in which the lowest amounts of precipitation fall along the Jordan Rift and in the Eastern Desert.

The five major biogeographic zones modeled in this study include the Mediterranean, Coastal Mediterranean, Irano-Turanian, Saharo-Arabian and Sudanian “plant geographical regions” after Zohary (1973) (Table 1). The modern flora of each of these regions has developed in concert with the domestication of plants and animals, and millennia of anthropogenic impacts (e.g. Cordova, 2007; Cordova et al., 2013; Fall et al., 2002, 2004; Rollefson and Kohler-Rollefson, 1992).

3. Bronze Age settlement and society

The first aggregated communities in the Southern Levant, which might be considered “proto-towns” (Falconer and Fall, 1995), appeared in the Pre-Pottery Neolithic Period (Rollefson et al., 1992). Large settlements with multi-story architecture developed at Jericho and at several locations along the eastern side of the Jordan Rift (e.g., Biernert and Gebel, 1998; Kenyon, 1960; Mahasneh, 1997; Nissen et al., 1991; Simmons and Najjar, 1999). Following the dispersal of smaller settlements in the Pottery Neolithic and Chalcolithic periods (Blackham, 2002; Bourke, 2008; Levy, 1995), the Bronze Age of the Southern Levant witnessed the coalescence of town-based polities, their dramatic collapse, and redevelopment over the centuries between 5500 and 3200 cal BP (ca. 3500 and 1200 BCE) (Table 2). Bronze Age society followed a variety of trajectories in which sedentary agrarian settlements and their populations alternately aggregated or dispersed (Falconer and Savage, 1995). Occasional fortified communities in Early Bronze I (Gophna, 1995; Joffe, 1993; Philip, 2003) preceded more nucleated settlement in the subsequent Early Bronze II and III periods, as signaled by the advent of numerous fortified towns atop mounded *tell* sites throughout the region (Gophna, 1995; Greenberg, 2002; Philip, 2003; Savage et al., 2007). By the end of Early Bronze III, these towns were abandoned across the Southern Levant, and populations shifted to farming hamlets and seasonal herding encampments for three or more centuries during Early Bronze IV (or the Intermediate Bronze Age) (Adams, 2000; Dever, 1995; Palumbo, 1990). Subsequently, walled cities reappeared rapidly atop Levantine *tells* early in the Middle Bronze Age. They grew in size, number and scale of fortification through the latter portions of this period, reaching a maximum regional population around 3600–3500 cal BP (ca. 1600–1500 BCE), which remained unsurpassed until the Roman occupation beginning about 1500 years later (e.g., Dever, 1987; Falconer, 2008; Ilan, 1995). During the Late Bronze Age, the Southern Levant experienced a recession in the size and number of towns, although the period witnessed heightened commercial and political activity throughout the Eastern Mediterranean (Bunimovitz, 1995; Strange, 2008). The subsequent Iron Age marks the appearance of state-level authority in the form of the Israelite kingdoms (Dever, 2003; Finkelstein, 1995; Finkelstein and Silberman, 2001), but with settlement and population densities that remained below those of the Middle Bronze Age. Analysis of Levantine settlement patterns, in conjunction with historical archives (most notably the Amarna Letters), suggests a fluctuating landscape of roughly 15–25 localized polities over the course of the Middle and Late Bronze ages (Falconer and Savage, 2009). During subsequent centuries, this fractious political milieu was nominally ruled as a united kingdom and subsequently as dual monarchies during the Iron Age (Finkelstein, 1995). Throughout this time span, vegetation shifts clearly were affected by regional climate change and by the interactions of agrarian communities with their immediately surrounding landscapes.

Table 1
The five major plant geographical regions modeled (after Al-Eisawi, 1985, 1996; Al-Eisawi et al., 2000; Danin, 1995, 2004; Eig, 1931/1932, 1938; Feinbrun-Dothan, 1986; Zohary, 1962, 1973; Zohary and Feinbrun-Dothan, 1966, 1972, 1978).

Plant geographical region / Vegetation description	Mean annual precipitation (mm)
Mediterranean	400–1200
Highest rainfall and coolest temperatures support *Pinus halepensis* and *Quercus ithaburensis* and *Quercus calliprinos* forests along the northern Mediterranean coast and surrounding the Sea of Galilee. Open woodlands with *Ceratonia siliqua* and *Pistacia lentiscus* grow on the Coastal Plain and Central Hills; the Transjordanian Plateau supports open woodlands of *Juniperus phoenica* and *Quercus calliprinos* with *Pistacia atlantica* trees.	
Coastal Mediterranean	250–400
A north-south precipitation gradient supports *Quercus ithaburensi* and *Pinus halepensis* along the north coast; *Pistacia lentiscus*, *Ceratonia siliqua*, and *Ziziphus spina-christi* grow in the middle; *Acacia radianna* and *Ziziphus spina-christi* are common in the more arid south. Coastal dunes support grass (*Ammophila* arenaria), shrubs (*Artemisia monosperma*, *Retama raetam*, and *Calicotome villosa*) and a few trees (*Pistacia lentiscus* and *Ceratonia siliqua*).	
Irano-Turanian	150–350
Plants withstand most extreme temperatures in this continental climate; low precipitation, hot summers and cold winters. Distinguished by steppe grasses and shrubs, with scattered *Pistacia atlantica* and *Juniperus phoenicia* trees. *Artemisia herba-alba* most common shrub species; with *Noaea mucronata*, *Salsola vermiculata* and *Anabasis syriaca*.	
Saharo-Arabian	25–150
Drought tolerant species of the Rift Valley, Negev Desert and Eastern Desert of Transjordan. Shrubs include *Zygophyllum dumosum*, *Retama raetam*, *Haloxylon articulatum*, *Anabasis articulata*, *Astragalus spinosus*, *Suaeda palaestina*, *Salsola tetrandra*, *Suaeda asphaltica*, and *Achillea fragrantissima*. *Tamarix* sp., *Phragmites sp*., *Salix sp*., *Nerium oleander*, *Populus euphratica* and *Tamarix jordanensis* grow in wadis and/or along the Jordan River.	
Sudanian	<50
High temperatures, minimal precipitation; tropical vegetation with *Acacia tortilis*, *A. albida*, *Ziziphus spina-christi*, *Balanites aegyptica*, *Moringa aptera*, *Ocradenus baccatus*, *Salvadora persica*, and *Calotropis procera*.	

Table 2
Archaeological chronology from the Chalcolithic Period to the Iron Age for the Southern Levant (after Levy and Bar-Yosef, 1995: Figs. 2 and 3); modeled ages correspond to those of plant geographical region maps (see Figs. 4–9).

Cultural period	Social organization	Age (cal yrs BP)	Age (CE/BCE)	Maps of modeled age (cal yr BP)
Modern		0	1950	0
Iron Age	Israelite kingdoms	3200–2586	1200–586	3000
Late Bronze	Urban recession	3500–3200	1500–1200	3500
Middle Bronze	Re-urbanization	4000–3500	2000–1500	4000
Early Bronze IV	Urban collapse	4300–4000	2300–2000	4200
Early Bronze I–III	Urbanization	5500–4300	3500–2300	5400
Chalcolithic	Village society	6500–5500	4500–3500	–

4. Methods

Our study models five plant geographical regions (following Zohary, 1973) characterized by shifting distributions of Mediterranean, Coastal Mediterranean, Irano-Turanian, Saharo-Arabian, and Sudanian vegetation. We model vegetation to produce a series of time specific maps of potential vegetation across the Levantine landscape. This approach integrates the effects of multiple environmental variables, especially temperature and precipitation, as expressed by potential vegetation modeled without the influences of human impact over the entire Levantine landscape.

4.1. Plant species and environmental data collection

As a foundation for modeling past and present plant geographical regions we compiled a database of individual woody plant species locations from a series of vegetation surveys of the Southern Levant (Fig. 2) conducted in the early 20th century (Eig, 1931/32, 1938, 1946; Kasapligil, 1956; Zohary, 1944, 1973) and the late 20th/early 21st centuries (Danin, 1988, 2004; Davies and Fall, 2001; Soto-Berelov, 2011). The earlier vegetation surveys (e.g., Eig, 1946; Zohary, 1973) sampled elevational (east–west) and latitudinal (north–south) transects linking portions of Palestine, Jordan and Israel. We

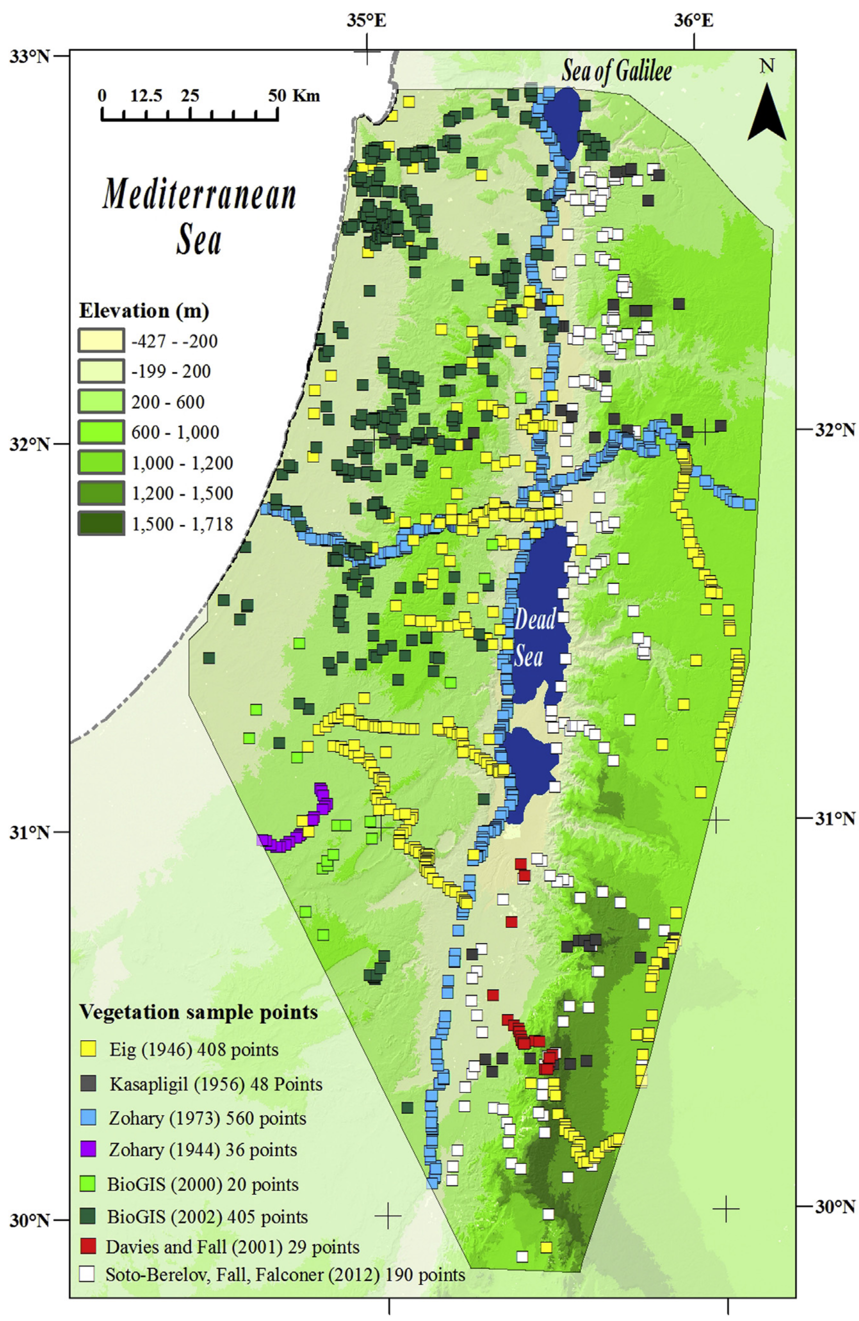

Fig. 2. Modern vegetation sample points and data sources in the study area (1696 total observations).

augmented our sample coverage west of the Rift by incorporating data from the Israel Biodiversity Information System database (BioGIS, 2000, 2002), a compendium of plant observation data from museums, herbaria and vegetation surveys. Vegetation data were collected by MSB, PLF and ER for for 219 points in Jordan (Davies and Fall, 2001; Soto-Berelov, 2011; Soto-Berelov et al., 2012) to provide systematic regional coverage along the eastern side of the Rift, including a series of altitudinal transects rising from the Rift to the Transjordanian Plateau. While the time range for these modern vegetation data represents an era of intensified agriculture and associated vegetation change, inclusion of early survey results avoids many of the sampling constraints of current Middle Eastern national borders. This method also captures potential vegetation prior to the expansion of agriculture in the late 20th century.

The locations of historic sample points were established by georeferencing and digitizing published maps (see especially Eig, 1946; Kasapligil, 1956; Zohary, 1944, 1973), and by crosschecking these locations with the distances reported between them. We excluded points whose originally published and newly digitized location or elevation differed by more than 100 m. More recent sample points were established from GPS readings taken in the field (Soto-Berelov, 2011). Our fully-assembled data set includes the modern locations of individual woody plant species at: 1) 1052 historical data points, 2) 425 data points from BioGIS (2000, 2002), and 3) 219 new data points surveyed by the authors (Davies and Fall, 2001; Soto-Berelov, 2011).

Plant species recorded at these 1696 observation points were assembled into a database of presence-only locations for the tree and shrub species associated with each of Zohary's (1973) plant geographical regions (see Supplementary materials S1). In addition to observed plant species, geographical data were incorporated into this database from 2002 Terra ASTER satellite imagery (http://asterweb.jpl.nasa.gov). A digital elevation model (DEM) with 90-m spatial resolution was resampled to 1 km to accord with the spatial resolution of our climate modeling (see below). River courses and geological substrates were digitized from a 1:200,000 geological map of Israel (Sneh et al., 1998) and a 1:750,000 geological photomap of Israel and adjacent areas (Bartov, 1994). The geological dataset was then resampled to a 1-km spatial resolution and classified according to the dominant geological substrate (see Supplementary materials S2).

4.2. Development of a macrophysical climate model

Climatic values for modeling present and past vegetation were derived through the application of a Macrophysical Climate Model (MCM) (Bryson and Bryson, 2000; Bryson and DeWall, 2007), which serves as an alternative to General Circulation Models (GCM) and provides the finer spatial (1 km) and temporal resolution appropriate for this study. Our adaptation of this MCM incorporates temperature and precipitation data recorded between 1961 and 1990 at 40 weather stations across the Southern Levant (see Fig. 3). This MCM predicts past climates based on orbital forcing, global ice volume, atmospheric conditions such as volcanic aerosols (Bryson et al., 2006), and local climatic variables including precipitation, evapotranspiration, and the location of the subtropical highs, the

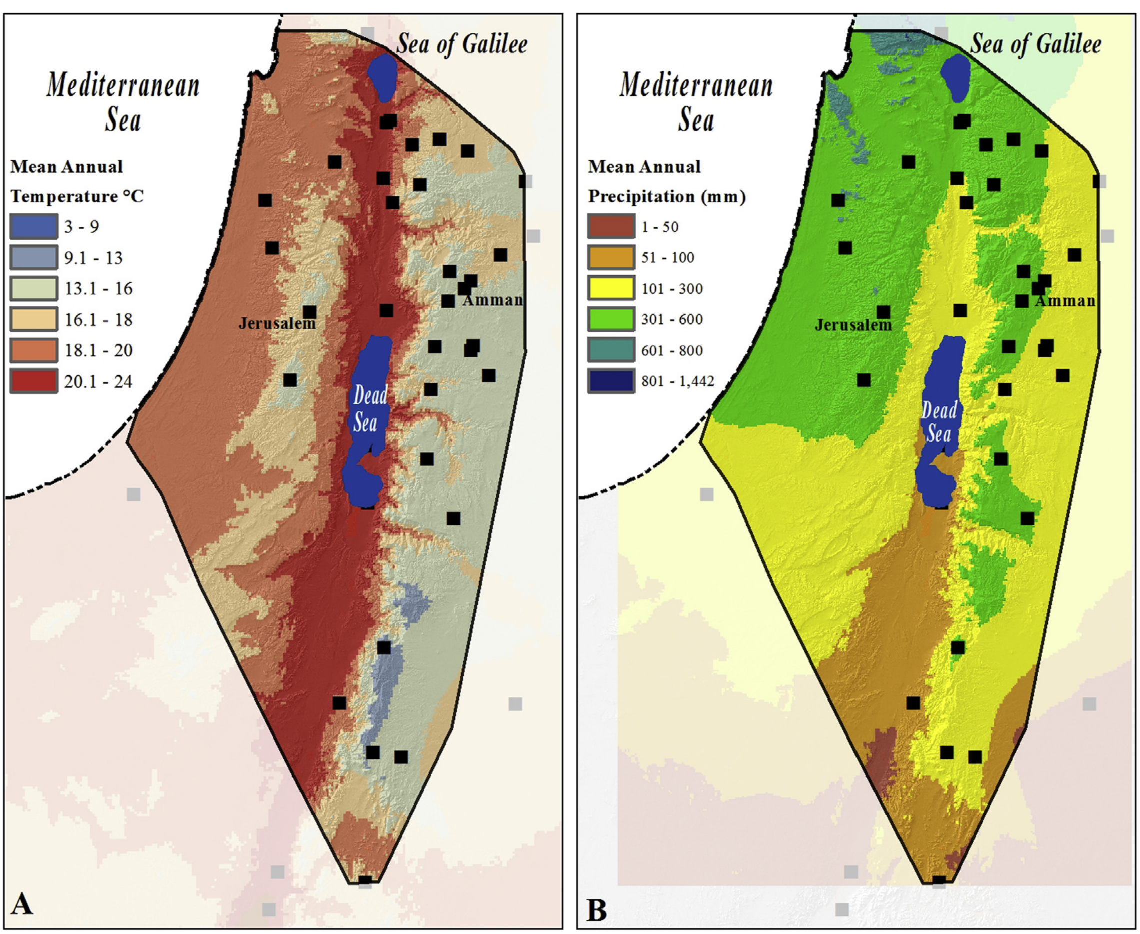

Fig. 3. Maps of modern mean annual temperature (A) and mean annual precipitation (B) in the Southern Levant (temperature and precipitation classifications from WorldClim – Global Climate Data; Hijmans et al., 2005); maps show climate stations used for our models.

jet stream, and the Intertropical Convergence Zone (Bryson and DeWall, 2007). The chronology for past climate models is based on calibrated radiocarbon dates for volcanic dust events (Bryson and DeWall, 2007). Other applications of this MCM have created climatic estimates to model Holocene environmental dynamics elsewhere in the Mediterranean Basin (Barton et al., 2010; Ullah, 2011).

We assessed the climatic variables used in our modeling of modern vegetation for spatial autocorrelation to avoid compounding the influence of highly correlated variables (e.g., Graham et al., 2008; Heikkinen et al., 2006). For instance, mean summer and winter temperature were removed from our modeling, based on their high correlation with each other ($r > 0.97$) and with mean annual temperature ($r > 0.99$) (Table 3). Similarly, mean winter precipitation was removed on the basis of its strong correlation ($r > 0.99$) with mean annual precipitation. Thus, our modeling uses four environmental variables: mean annual temperature, mean annual precipitation, elevation and geological substrate. Mean annual precipitation and temperature were chosen also because they perform better than non-aggregated climatic variables when projecting biotic distributions into other time periods (Martínez-Meyer et al., 2004; Martínez-Meyer and Peterson, 2006; Phillips, 2010). Elevation was retained as a variable in the model because it is not correlated significantly with either temperature or precipitation (see Table 3).

4.3. Modeling of species distributions

Our species distribution models correlate the locations at which a species is observed with the environmental variables that characterize those locations. Our models of present and past plant geographical regions utilize MAXENT (version 3.3.3e; http://www.cs.princeton.edu/~schapire/MaxEnt), a species distribution modeling software package with a probabilistic framework (Phillips and Dudik, 2008; Phillips et al., 2006). MAXENT models the potential geographic distribution of a plant species by estimating a probability of maximum entropy based on the relationship between species observations and their associated environmental variables (see discussion in Galletti et al., 2013). The relationships between variables generate functions that estimate the suitability of each cell (1 km^2) for the occurrence of a plant species.

MAXENT performs better than other comparable algorithms (e.g., GLM, GARP, DOMAIN, Random Forest; Elith et al., 2006; Hernandez et al., 2006; Hijmans and Graham, 2006; Phillips et al., 2006), accommodates presence-only datasets and estimates uncertainty under conditions different from those used for model training (Elith et al., 2010, 2011; Hernandez et al., 2006; Hijmans and Graham, 2006; VanDerWal et al., 2009). MAXENT produces a continuous surface as an output, in which a value for each cell indicates the likelihood of species presence. We create binary maps of the cells in which a species is most likely to occur using an optimal predictive threshold, as indicated by a Receiver Operating Curve (ROC) (Freeman and Moisen, 2008; Manel et al., 2001; see discussion in Galletti et al., 2013).

Modern plant geographical regions are modeled on the basis of the predicted distributions of indicator species (see Supplementary materials S1) and combined into a single map of the Southern Levant. Locations of overlap between two regions are classified as transitional. Past models of plant geographical regions (from 5500 through 3000 cal BP) are trained with modern species observations and environmental values (see split sample approach in Fielding and Bell, 1997), and then projected into past scenarios using 1 km grids of climatic values generated by the MCM for each of the modeled dates (provided as KML files in Supplemental material). These SDMs are evaluated with a one-tailed binomial or chi-square test to determine the probability of obtaining each model's observed omission rate by chance or sampling error (Table 4; Anderson et al., 2002; Elith, 2008). The area under the curve (AUC), derived from the ROC, provides a second means of evaluation (Fielding and Bell, 1997; Hanley and McNeil, 1982) by indicating how well each model discriminates between locations of species presence and those of absence. Values for AUC range from 0 to 1; an AUC of 0.5 indicates a model's discriminative performance to be equivalent to random chance, while 1.0 reflects complete discriminative ability (Elith et al., 2006). In practice (e.g., Swets, 1988), AUC values are used to evaluate model accuracy as low (0.5–0.7), fair (0.7–0.8), good (0.8–0.9) or excellent (0.9–1.0). Assessments of model performance also include response curves that indicate how each environmental variable affects the logistic output (probability of presence) for each modeled modern plant geographical region (see Supplementary materials S3). Jackknife testing evaluates the relative predictive importance of each environmental variable in training the models for each modern plant geographical region (see Supplementary materials S4). Past environmental conditions differ from those of the present as shown in Supplementary materials S5.

Table 3
Correlation coefficients for environmental variables used in the Maxent models. Highly correlated variables ($r > 0.95$) shown in bold.

Variable	Elevation	MAP	MAT	MST	MWP	MWT
Elevation	1					
MAP	0.11361	1				
MAT	−0.92047	−0.36036	1			
MST	−0.90079	−0.45151	**0.99204**	1		
MWP	0.1694	**0.99446**	−0.41186	−0.49835	1	
MWT	−0.9205	−0.28431	**0.99420**	**0.97286**	−0.33889	1

MAP = mean annual precipitation; MAT = mean annual temperature; MST = mean summer temperature; MWP = mean winter precipitation; MWT = mean winter temperature.

5. Results

Our modeling produces a series of MAXENT-based maps of potential plant geographical regions for the present (Fig. 4) and at 100-year intervals between 5500 and 3000 cal BP (Figs. 5–9) (see Supplementary materials S6 and S7). Statistical assessments, especially AUC values, show “good” to “excellent” model performance (Table 4). Mean annual precipitation emerges as the most important environmental variable for modeling modern Mediterranean, Irano-Turanian and Saharo-Arabian potential vegetation (see Supplementary materials S4). The probability of Mediterranean vegetation rises with increasing mean annual precipitation, while the probability of Irano-Turanian or Saharo-Arabian vegetation peaks with much less precipitation and declines as precipitation increases further (see Supplementary materials S3). Elevation and annual temperature are the most influential variables for modeling the Sudanian and Coastal Mediterranean plant geographical regions, with increased temperature associated with a sharp rise in the logistic output for Sudanian vegetation and a steep decline in the probability of Coastal Mediterranean vegetation. While the Coastal Mediterranean plant geographical region, not surprisingly, is closely associated with elevations near sea level, the probability of Sudanian vegetation increases as elevations drop below sea level.

5.1. Levantine vegetation change in overview

Modeled plant geographical regions for temporal junctures that illustrate particularly notable changes in regional vegetation

Table 4
Summary of MAXENT model performance for the modern major (i.e., non-transitional) plant geographical regions. *P*-values pertain to one-tailed binomial tests of the probability of obtaining each model's observed omission rate (misclassified locations where a species should have been present) by chance or sampling error (Anderson et al., 2002; Elith, 2008) using the bootstrap partitioning method. Model performance ratings follow Swets (1988).

Plant geographical region	Logistic threshold[a]	Training omission rate	Test omission rate	*P*	Test AUC	SD	Performance
Mediterranean	0.315	0.105	0.118	1.348^{-19}	0.854	0.016	Good
Coastal Med	0.234	0.000	0.333	2.643^{-2}	0.938	0.025	Excellent
Irano-Turanian	0.398	0.141	0.103	3.947^{-9}	0.850	0.029	Good
Saharo-Arabian	0.403	0.164	0.222	6.539^{-6}	0.857	0.029	Good
Sudanian	0.202	0.074	0.043	1.038^{-17}	0.948	0.017	Excellent

[a] Maximum training sensitivity plus specificity; logistic value at which threshold in Table 4 was met.

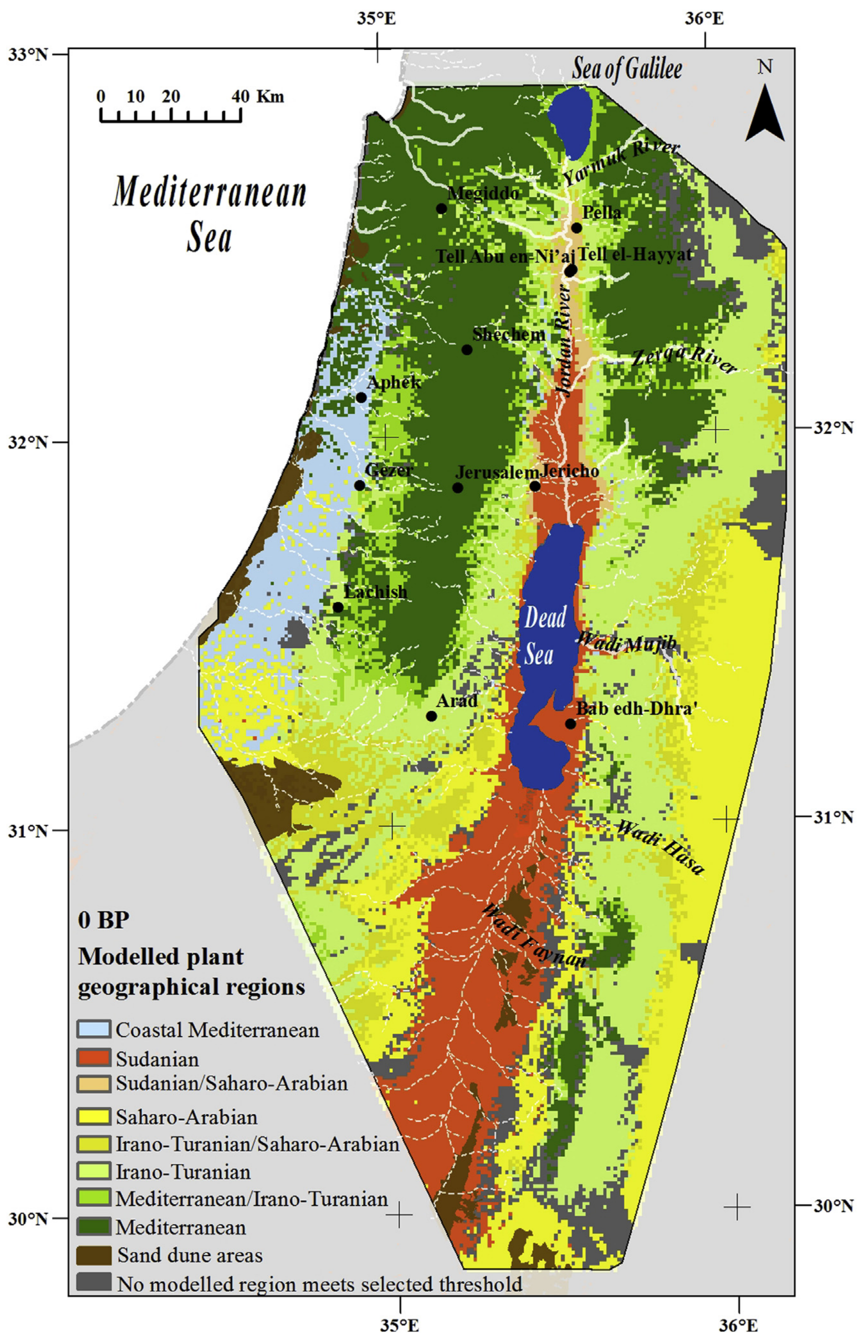

Fig. 4. Modeled potential vegetation by plant geographical regions at 0 years BP (modern vegetation).

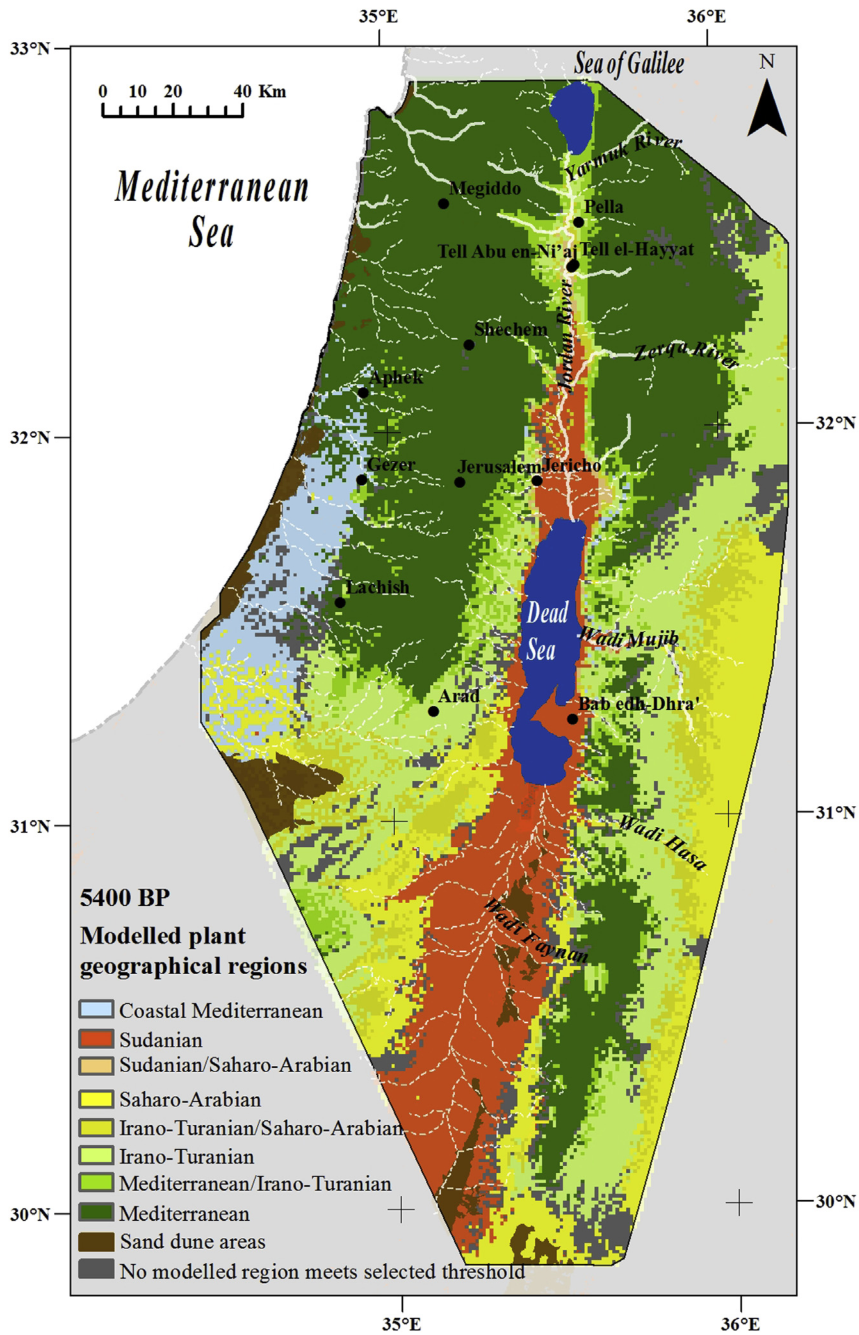

Fig. 5. Modeled potential vegetation by plant geographical regions at 5400 calibrated years BP.

dynamics through the Bronze Age are shown in Figs. 5–9. Collectively, these mapped distributions describe trajectories of increasing and decreasing coverage of Mediterranean and Coastal Mediterranean woodlands, Irano-Turanian steppe, and Sudanian and Saharo-Arabian deserts (Fig. 10).

When compared with modern potential vegetation, plant geographical regions modeled across the Bronze Age commence with greater expanses of Mediterranean and desert vegetation, and much less steppe (cf. Figs. 4 and 5). Between 5500 and 3000 cal BP, divergent overall trends are characterized by a pronounced net decrease in Mediterranean vegetation, a more gradual net increase in steppe, and intermittent change leading to a net increase in desert vegetation. Modeling of these three vegetation classes reveals two consecutive and somewhat repetitive trajectories over this 2500-year timespan, the first ca. 5400–4100 cal BP and the second ca. 4000–3000 cal BP (Fig. 10). Following its peak expanse at 5400 cal BP, Mediterranean plant cover decreases to 4100 cal BP, increases dramatically at 4100 and 4000 cal BP, and then drops more sharply by 3000 cal BP. Steppe vegetation shows a brief jump in area between 5500 and 5300 cal BP, followed by gradual increase to 4100 cal BP, another rise in area at 4000 and 3900 cal BP, after which its extent drops and remains relatively steady until 3000 cal BP. Desert vegetation drops between 5500 and 5400 cal BP, increases gradually until 4100 cal BP, drops dramatically at 4000 and 3900 cal BP, and then rises to its maximum coverage at 3000 cal BP.

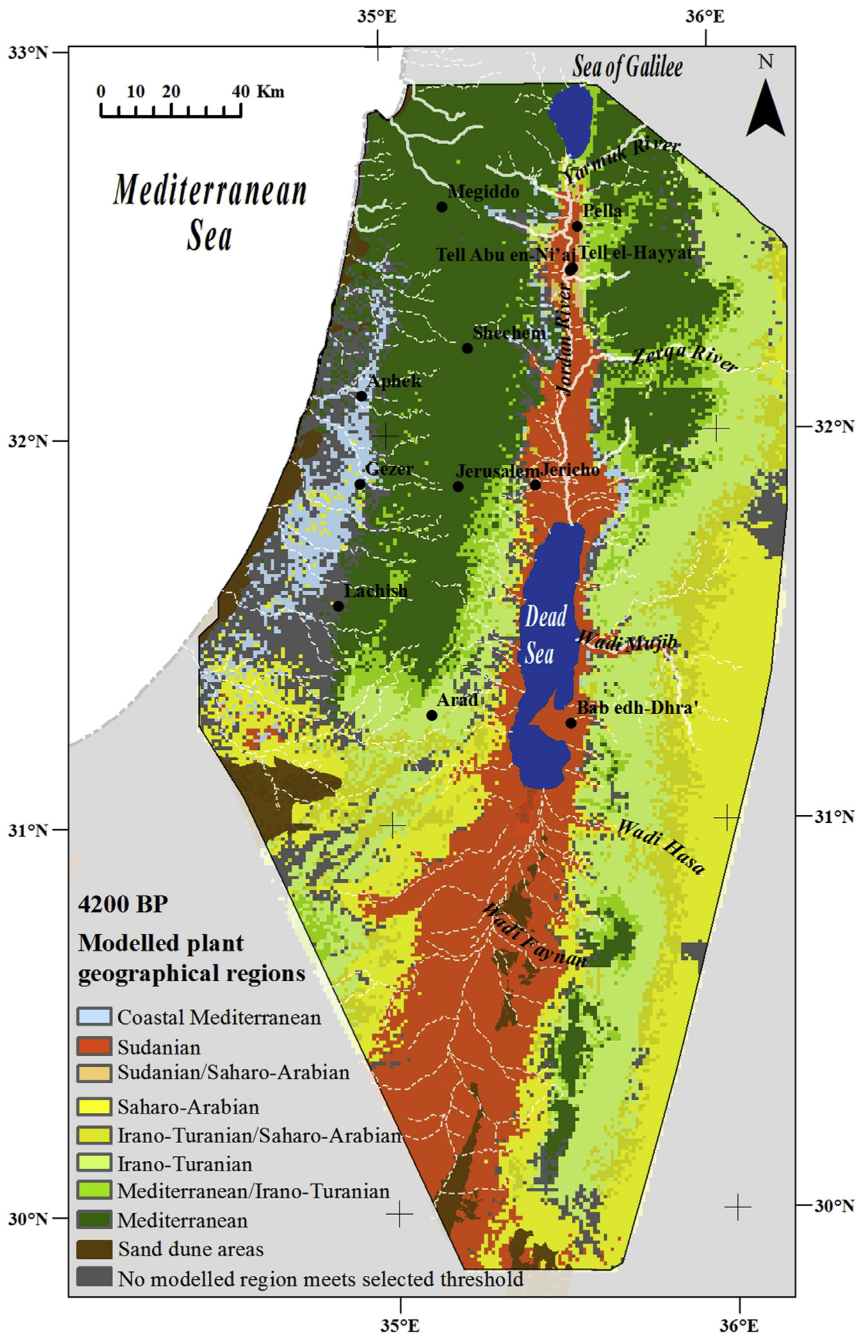

Fig. 6. Modeled potential vegetation by plant geographical regions at 4200 calibrated years BP.

Climatic variables that contribute to these potential vegetation changes may be seen in modeled temperature and precipitation trends at specific weather stations. For example, modeled climate data for Jerusalem show a long term, irregular but steady decrease in annual precipitation, dropping from a maximum value at 5400 cal BP to a minimum at 3000 cal BP (Fig. 11). Annual precipitation values modeled for 3500 cal BP and thereafter are similar to modern modeled precipitation. The most pronounced short-term precipitation increases are modeled between 5500 and 5400 cal BP, and between 4100 and 4000 cal BP. Annual temperature values modeled for Jerusalem show a gradual increase between 5300 and 4100 cal BP, bracketed by pronounced drops at 5400 and at 4000 cal BP, and then followed by a steeper increase between 3900 and 3000 cal BP. Modern temperature is comparable to minimum values modeled at 5400–5300 cal BP and 4000–3900 cal BP.

5.2. Vegetation change through the Bronze Age

In comparison to modern modeled plant geographical regions (Fig. 4), the regions modeled at 5400 cal BP (at a time of maximum precipitation and low annual temperature; Fig. 5) show the potential for much greater Mediterranean vegetation along the northern Coastal Plain, in the Central Hills covering most of the area between the Jordan Valley and the Mediterranean Sea, on the Transjordanian Plateau east of the Jordan Valley, and in the mountains of southern Jordan where it is nearly absent today. The modeled expanse of steppe vegetation at 5400 cal BP is

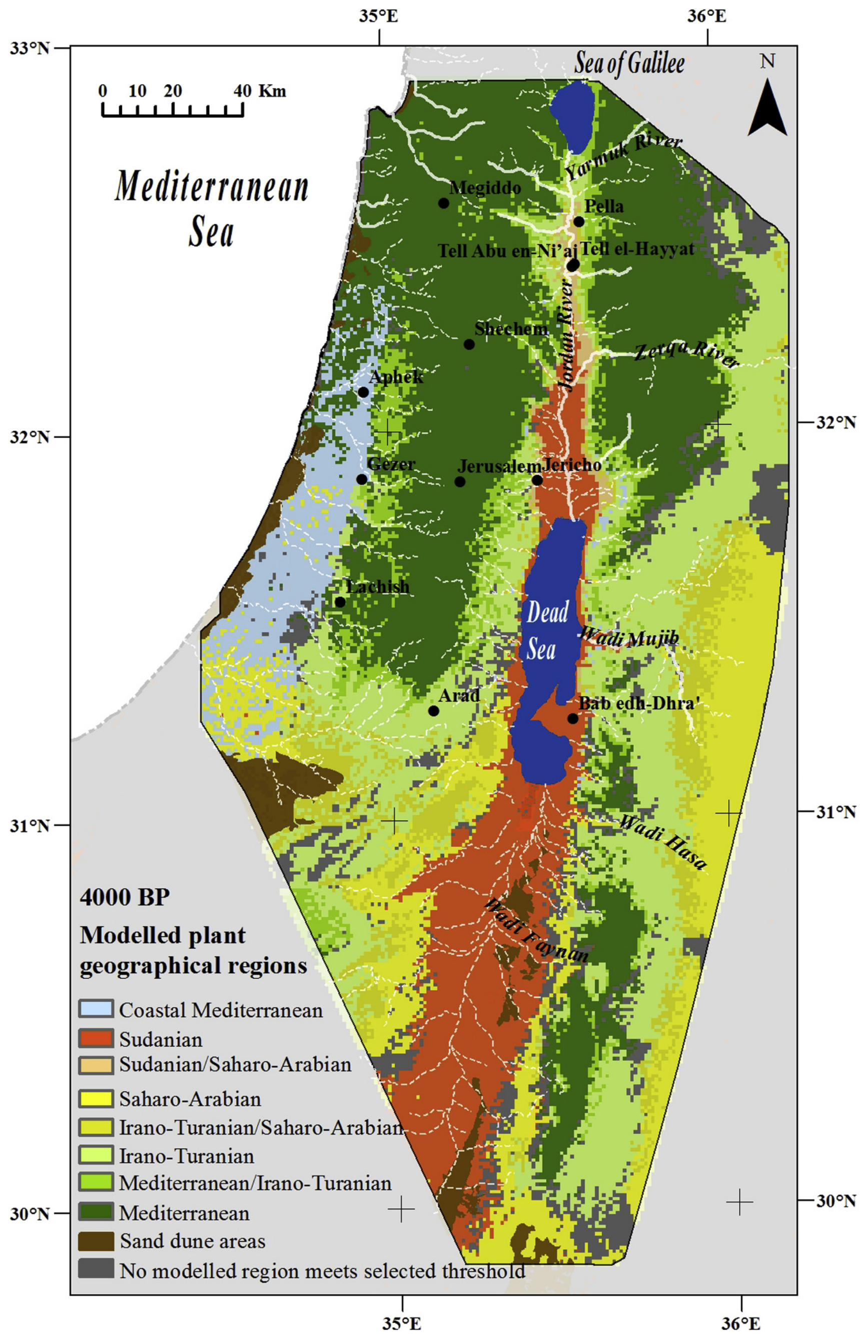

Fig. 7. Modeled potential vegetation by plant geographical regions at 4000 calibrated years BP.

correspondingly less than at present due to the wider distribution of Mediterranean vegetation, while the area modeled for desert vegetation is virtually identical to that modeled for the present (Fig. 10).

Between 5400 and 4200 cal BP, as modeled precipitation decreases following an abrupt rise in temperature (Fig. 11), the potential distribution of Mediterranean and Coastal Mediterranean vegetation diminishes along the Coastal Plain, at the southern end of the Central Hills, and especially in the highlands of the Transjordanian Plateau east of the Jordan Rift (cf. Figs. 5 and 6). The coverage of steppe vegetation differs little between 5400 and 4200 cal BP, while desert vegetation is modeled over a much larger area, which now expands along the western edge of the Wadi Araba, and especially to the eastern and western boundaries of the Jordan Valley and north nearly to the Sea of Galilee.

Plant geographical regions modeled between 4200 and 4000 cal BP change dramatically over a short time frame towards configurations that resemble those of 5400 cal BP (cf. Figs. 6 and 7), as modeled precipitation increases and temperature drops dramatically (Fig. 11). Mediterranean and Coastal Mediterranean vegetation rebounds substantially on both sides of the Rift, although they are not modeled as broadly for the Central Hills and Coastal Plain as they are at 5400 cal BP (Fig. 5). Desert vegetation recedes most noticeably along the Jordan Valley and the Wadi Araba, while steppe vegetation increases in the southern parts of the study area on both sides of the Jordan Rift.

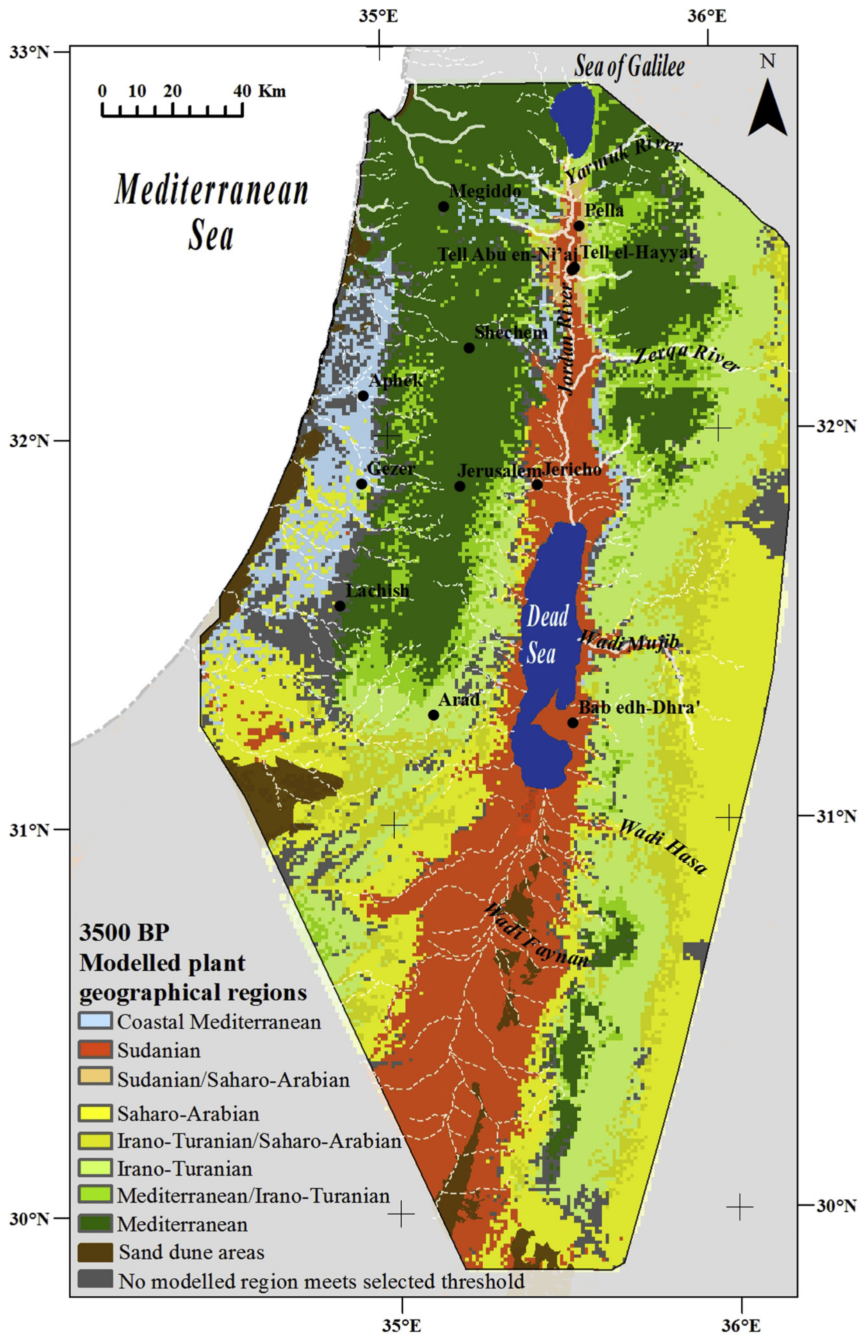

Fig. 8. Modeled potential vegetation by plant geographical regions at 3500 calibrated years BP.

Between 4000 and 3500 cal BP, under conditions of diminishing rainfall following a sharp rise in temperature, modeled desert vegetation expands again, nearly as substantially as at 4200 cal BP (cf. Figs. 6–8). Both steppe and Mediterranean vegetation are reduced in modeled area, with a clearly diminished Coastal Mediterranean plant geographical region, less continuous distribution of Mediterranean vegetation in the Central Hills, and a striking reduction of Mediterranean vegetation east of the Jordan Rift compared to 4200 cal BP.

From 3500 to 3000 cal BP, as temperature continues to rise and precipitation falls, the extent of Mediterranean vegetation contracts further in areas west of the Jordan Valley and, especially, in the highlands of Transjordan (cf. Figs. 8 and 9). Surrounding steppe areas remain similar in coverage, while Sudanian vegetation is modeled over the greatest extent seen in this study, encroaching into the Esdraelon Plain and stretching to the Sea of Galilee.

In comparison to the plant geographical regions for 3000 cal BP, modern Mediterranean vegetation is modeled (under conditions of slightly more precipitation and more drastically reduced temperature) over larger areas of the Central Hills west of the Jordan Rift and especially in the highlands of Transjordan east of the Rift (cf. Figs. 4 and 9). Steppe vegetation around the margins of these woodlands likewise covers considerably greater areas. Saharo-Arabian and Sudanian vegetation, in contrast, has retreated considerably along the edges of the Rift, but most especially along

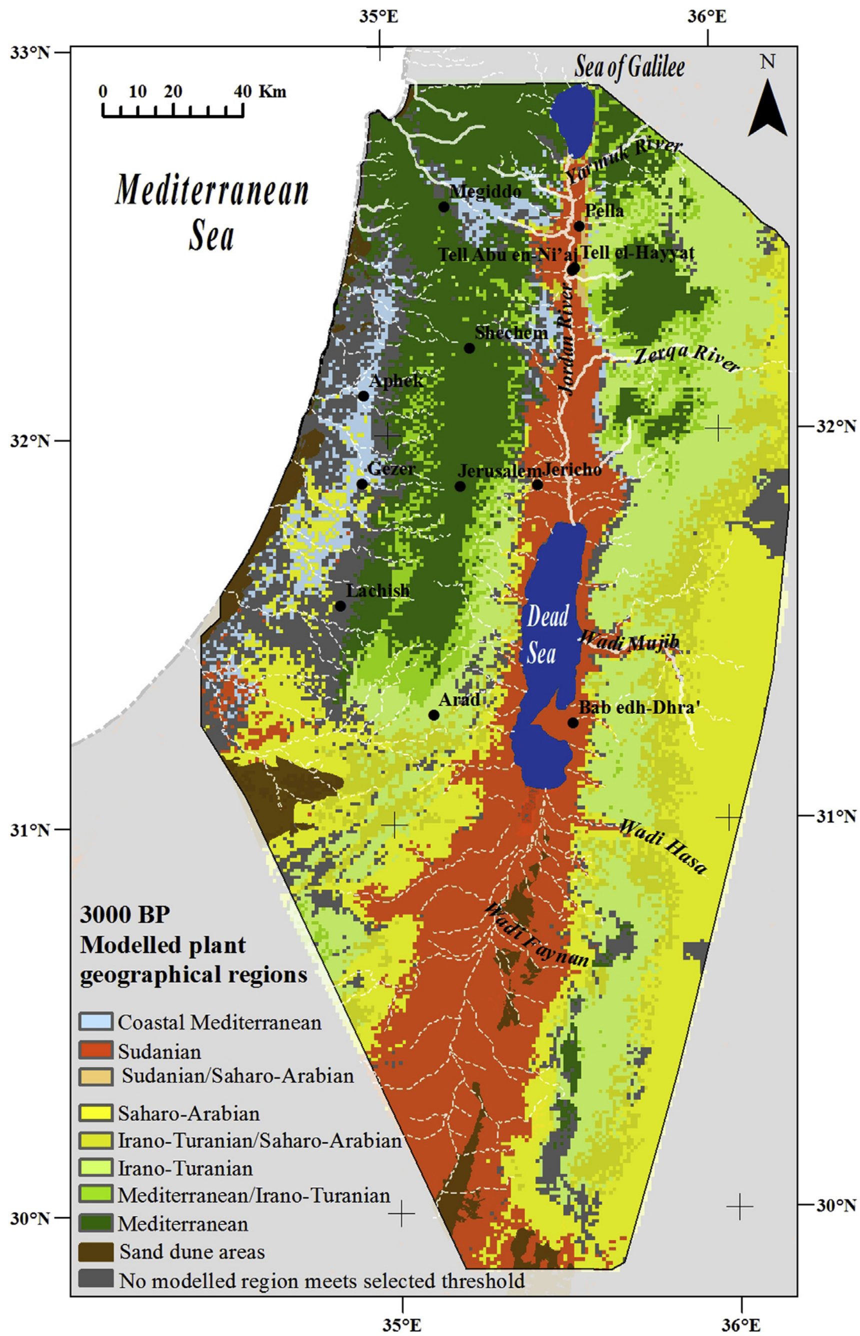

Fig. 9. Modeled potential vegetation by plant geographical regions at 3000 calibrated years BP.

the Jordan Valley, where it is modeled only halfway north from the Dead Sea toward the Sea of Galilee.

6. Discussion

The interpretation of Levantine Bronze Age cultural change traditionally draws heavily on regional historical correlations, particularly with Egypt. For example, the development of Early Bronze urbanism has been linked to the rise of the Old Kingdom state (e.g., Kantor, 1992: 17–21; Stager, 1992: 40–41), while the abandonment of Early Bronze IV Levantine towns has been attributed to the collapse of Egyptian central authority during the subsequent First Intermediate Period (e.g., Dever, 1995). A linchpin of Levantine chronology derives from the correlation of the beginning of the Middle Bronze Age with the ascension of Egypt's Twelfth Dynasty, which reestablished centralized government and commercial exchange across the Eastern Mediterranean (e.g., Weinstein, 1981). Although less explicitly linked, the Middle and Late Bronze Ages have been defined to roughly parallel the Egyptian Middle and New Kingdoms (Bunimovitz, 1995; Ilan, 1995; Weinstein, 1981).

Our paleoclimatic and vegetation modeling corroborates empirically based inferences derived from a variety of data sources and locales across the Southern Levant. Most proxy records indicate that Early Bronze Age climate was generally wetter than at present, with fluctuations between wetter and drier episodes later in the

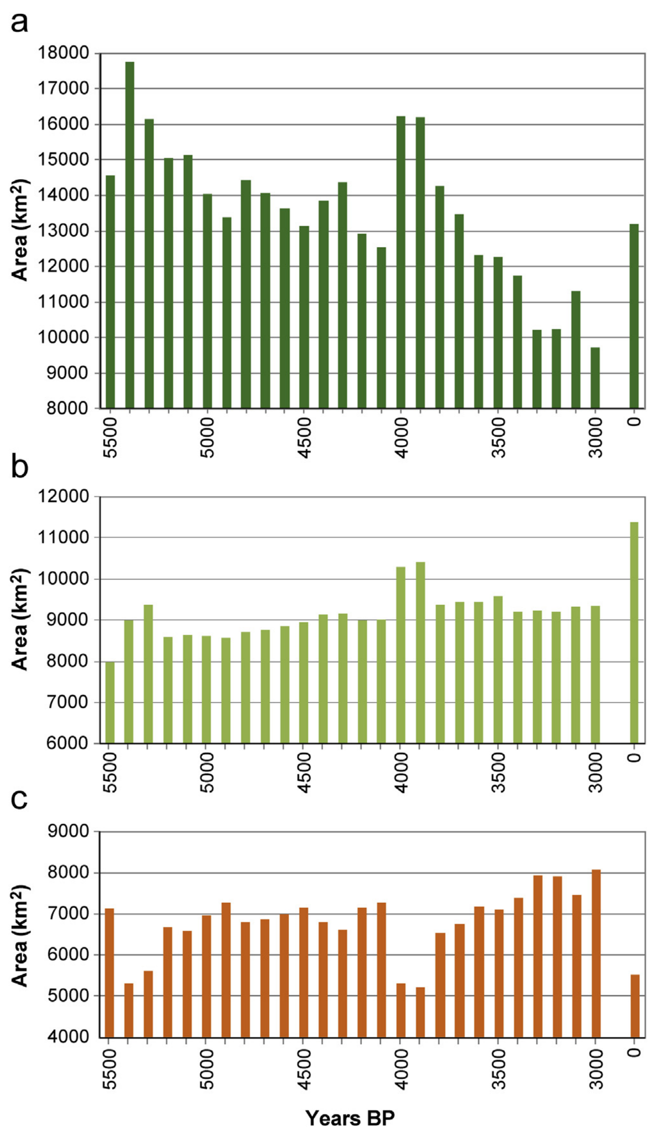

Fig. 10. Area (km^2) modeled for the main plant geographical regions, 5500–3000 calibrated years BP (at one hundred year intervals) and 0 years BP (modern): (a) Mediterranean and Coastal Mediterranean woodlands; (b) Irano-Turanian steppe; and (c) Sudanian and Saharo-Arabian deserts.

Bronze Age (Rosen, 2007). Multi-faceted paleoenvironmental evidence suggests similarly that climate dynamics drove Late Holocene fluvial geomorphic change in the Wadi Faynan on the margin of the southern Jordan Rift (Hunt et al., 2004, 2007). Our modeling suggests a peak in Mediterranean woodlands and minimal desert vegetation ca. 5400 cal BP, consistent with lower temperatures and higher precipitation. This result accords with higher Dead Sea lake levels inferred for the beginning of the Early Bronze Age from lacustrine sediments (Migowski et al., 2004) and speleothems (Bar-Matthews and Ayalon, 2011). Our portrait of decreasing Mediterranean vegetation through the Early Bronze Age parallels a subsequent increase in aridity and corresponding decline in lake levels interpreted for the Dead Sea (Bar-Matthews and Ayalon, 2011; Migowski et al., 2006).

A regional drought at the end of the Early Bronze Age, sometimes conceptualized as the "4.2 event," has been proposed on the basis of a suite of sedimentological and isotope studies (Bar-Matthews and Ayalon, 2011; Finné et al., 2011; Frumkin, 2009; Gvirtzman and Wieder, 2001; Kuzucuoğlu and Marro, 2007; Migowski et al., 2006; Riehl et al., 2008) that imply major desiccation beginning 4600–4200 cal BP and ending around 4000 cal BP. Rather than an event of sudden and pronounced drying, our results suggest that this drying episode marks the culmination of a long process of environmental change reflected in our modeling by diminishing Mediterranean and increasing desert potential vegetation. Our modeling of a pronounced increase in Mediterranean vegetation and diminished desert vegetation at the beginning of the Middle Bronze Age reflects rapid, significantly improved climatic conditions, which also are interpreted from sedimentological and palynological analyses of the Dead Sea and Hula basins ca. 4000 cal BP (Migowski et al., 2004; Neumann et al., 2007; van Zeist et al., 2009). Our modeled subsequent reduction in Mediterranean woodlands, coupled with expanding desert vegetation, accords with increasing aridity inferred for the Dead Sea Basin (Migowski et al., 2004).

We model the most dramatic reduction of Mediterranean woodlands and increase in desert vegetation during the Middle and Late Bronze ages, especially after ca. 3400 cal BP, in accordance with drying trends inferred from several proxy records (Hunt et al., 2007; Migowski et al., 2006; Neumann et al., 2007, 2010). Climatically induced forest recession would have been compounded by land clearance for pastoralism and fuel wood exploitation (e.g., in localities of intensive metallurgy; Hunt et al., 2007). Most notably, by ca. 3000 cal BP, roughly the time of the Late Bronze Age "crisis" (e.g., Kaniewski et al., 2013), the potential expanse of Mediterranean vegetation represents only 75% of the area for which it is modeled at present. Thus, Levantine potential vegetation at the end of the Bronze Age marks the culmination of two trajectories of diminishing Mediterranean vegetation and increasing desert vegetation, the first roughly paralleling the Early Bronze Age (and ending at the time normally ascribed to the "4.2 event") and the second corresponding to the Middle and Late Bronze Ages. Rather than highlighting sudden environmental deterioration, our modeling shows the most pronounced shifts in plant geographical

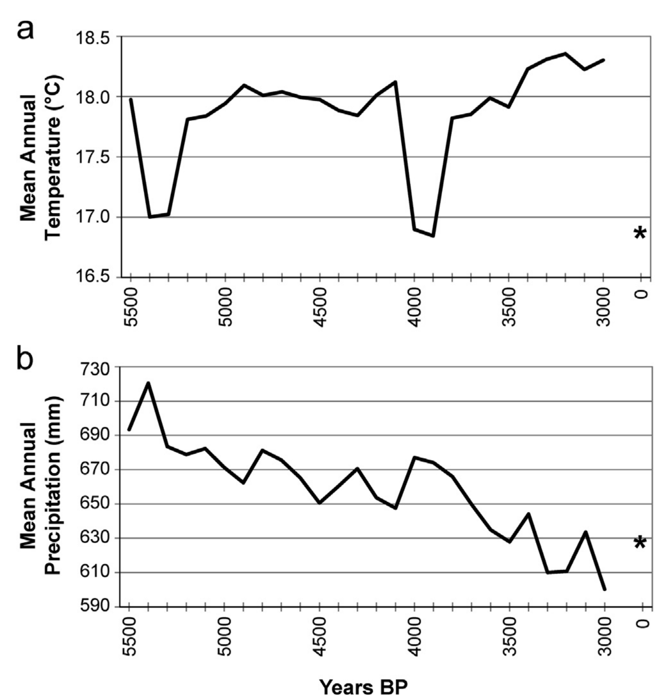

Fig. 11. Modeled mean annual temperature (a) and mean annual precipitation (b) for Jerusalem, 5500–3000 calibrated years BP (at one hundred year intervals) and 0 years BP (modern).

regions ca. 5400 cal BP and ca. 4000 cal BP stemming from sharply increased precipitation and decreased temperature.

7. Conclusions

This study integrates environmental and climatic data to model plant geographical regions over the Southern Levant at present and at 100-year intervals during the Bronze Age (5500–3000 cal BP). Our modeled long-term vegetation shifts suggest that development of Early Bronze Age towns unfolded in a regional context of diminishing potential for Mediterranean vegetation and increasing potential for desert vegetation associated with decreased precipitation and rising temperature. The time frame often ascribed to the "4.2 event" emerges as the latest portion of this long-term drying trend, rather than as a distinct episode of pronounced desiccation. The more remarkable event suggested by our modeling is the sudden expansion of Mediterranean potential vegetation at 4000 cal BP, which results from a sudden drop in mean annual temperature of more than 1 °C. Our modeling suggests further that Middle Bronze Age reurbanization followed in the wake of this pronounced climatic and vegetative amelioration. A second trajectory of more accentuated decreasing potential Mediterranean and increasing desert vegetation (associated with dropping precipitation and rising temperature) provided the backdrop for the contentious local polities of the Middle and Late Bronze Ages. At the end of our modeled sequence, the Late Bronze Age environmental crisis emerges ca. 3000 cal BP as the last element in a long-term recession of Mediterranean vegetation marked by mean annual temperature much higher than the present and the lowest precipitation modeled through the Bronze Age. In contrast to the Bronze Age, modern modeled plant geographical regions include distributions of Mediterranean vegetation comparable to those at the Middle/Late Bronze Age transition ca. 3500 cal BP and desert vegetation comparable to wetter intervals ca. 5400 cal BP or 4000 cal BP. In overview, modeled incremental changes in plant geographical communities describe multi-faceted long-term regional environmental dynamics over the course of Bronze Age social change in the Southern Levant.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2014.09.015.

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