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Thesis

MODELING AGROPASTORAL LANDSCAPES IN THE MARMARA LAKE BASIN, WESTERN ANATOLIA

by

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MODELING AGROPASTORAL LANDSCAPES IN THE MARMARA LAKE BASIN, WESTERN ANATOLIA

Nicolas Gauthier

Abstract

This study examines the development of agropastoralism in the Marmara Lake Basin in western Anatolia. It investigates how the interrelationships between geomorphology, hydrology, climate, and vegetation in and around the lake basin might have influenced the distribution of this form of land use across the landscape. It employs a combination of spatially explicit GIS-based environmental models and qualitative models of pastoral land use derived from the ethnographic, historical, and archaeological records. These landscape models serve to maximize the heuristic potential of limited archaeological datasets. The results of such research are not explicit reconstructions of prehistoric land-use systems, but rather a series of testable hypotheses to guide future research. These models suggest that climatic stability during the Early Holocene would have favored wetland agriculture and localized sheep herding, and that a shift to a highly variable climate during the Middle Holocene might have been met with increased dryland farming and extensive goat herding.

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Chapter 1: Introduction

Village-based agropastoralism is a robust subsistence strategy that has been continuously practiced by Near Eastern societies for thousands of years. Agropastoral settlements – where the economy depends on a mix of farming and animal husbandry – have larger catchments than purely agricultural settlements of similar size because the reliance on grazing animals allows herders to exploit areas of the landscape otherwise unfit for agriculture. But in contrast to the high mobility of fully nomadic pastoralists, herding activity in agropastoral contexts is still rooted in space to sedentary settlement systems.

The flexibility of mixed agropastoral subsistence strategies is highly adaptive in the face of environmental uncertainty. Having diverse food sources, as well as potential trade goods in the form secondary products such as wool and dairy, buffers against the risks of crop failure, overgrazing, and other unpredictable shocks with environmental underpinnings (Barfield 1993, 10; Danti 2000; Marston 2011). But both farming and herding activities also alter the natural environments in which they occur – most directly by striping away vegetation cover as a result of grazing and plowing (Butzer 1982: 123).

The constrained spatial character of this economic strategy and its nonlinear relationship to environmental change makes agropastoral land use an ideal context within which to approach questions of human-environment interactions on the landscape scale. Despite the similarities in the basic economic and ecological underpinnings of agropastoral land use, the archaeologically attested coevolution of crop cultivation and animal husbandry has followed multiple historical trajectories in different regions (Frachetti 2008: 21; Conolly et al. 2011). Modeling specific agropastoral landscapes – which both shape and are shaped by long-term land-use practices – is a useful method for generating hypotheses that connect regional environmental factors to contingent developments in agropastoral land use. This study isolates one landscape for analysis – the Marmara Lake Basin and Gediz Valley of western Anatolia (Figure 1) – and models how the particular manifestations of prehistoric agropastoral land use in that region might relate to the structure of the local geomorphology, vegetation, and climate.

Study Area

The Gediz Valley is well known in guidebooks and monographs alike as the site of the ancient metropolis of Sardis. Sardis first rose to prominence some 3,000 years ago as the capital of the Lydian Kingdom. Its citizens were famed in the ancient world as the inventors of coinage and builders of burial mounds that rivaled in size the pyramids at Giza (Luke

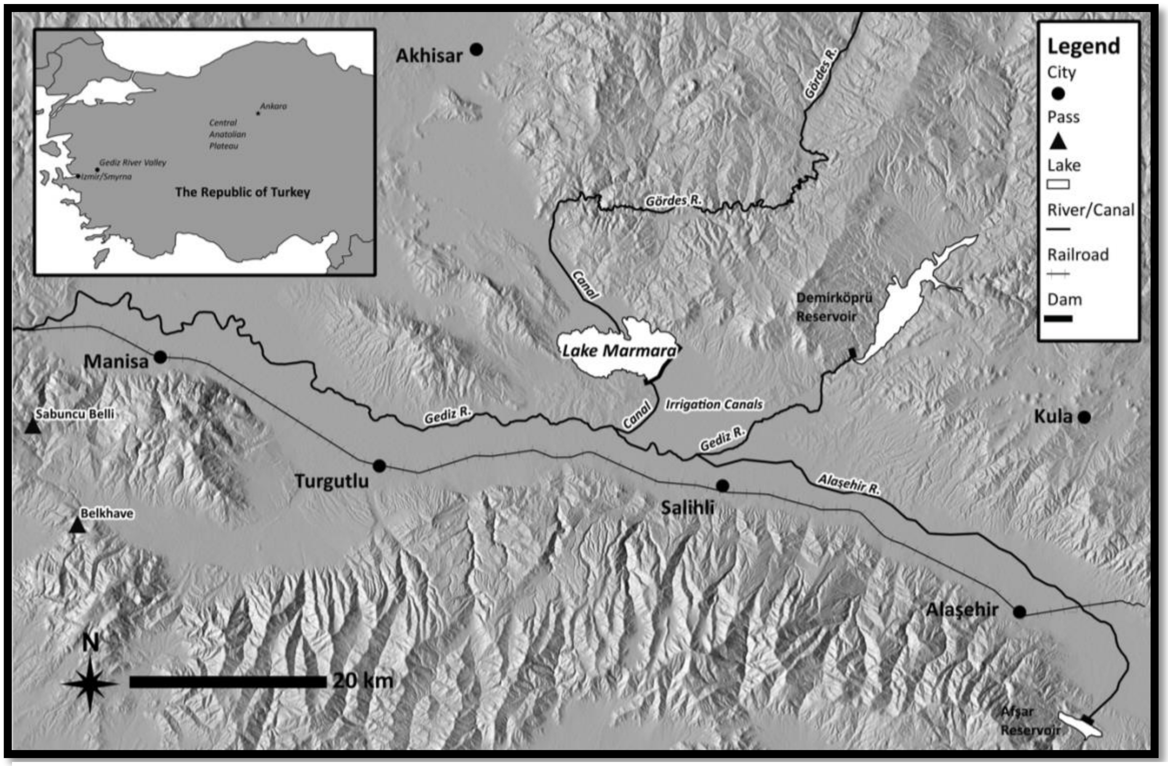

Figure 1 Map of the Gediz Valley with modern cities and watercourses.

Figure 2 View south across the Gediz Valley. Foreground: Monumental burial mounds. Midground: Acroplis (left) and necroplis (right) of Sardis. Background: Boz Dağ Mountains.

and Roosevelt 2009). The Lydians controlled movement through the Gediz Valley, which connects the Aegean Sea in the west with the Anatolian Plateau and points further east, from the lofty acropolis at Sardis (Figure 2). Their civilization acted as a key node in the network of cultural and economic interactions that connected the burgeoning East Greek city-states of the Anatolian coast with the Neo-Assyrians and other established empires of the Near East. This prime location, and the trade wealth that arose from it, helped Sardis to remain a major regional capital and cultural melting pot throughout successive waves of Persian, Macedonian, Roman, Byzantine, and Turkic armies.

Many archaeological and historical treatments of this region focus understandably on this “east meets west” facet of cultural development in the Gediz Valley. Yet an emphasis on international connections risks overshadowing an equally impressive process of autochthonous social development in the valley that stretches back even further into prehistory than the foundations of Sardis. Nearly a decade of work by the Central Lydia Archaeological Survey (CLAS) in the Gediz Valley has shown that the landscape around Lake Marmara, on the northern rim of the Gediz Valley 10km distant from Sardis, played a primary role in the pre-Lydian history of the region.

CLAS archaeologists have detected traces of human activity in the Marmara Lake Basin as early as 50,000 years ago (Çilingiroğlu et al. Forthcoming). Some 4,000 years ago during the Bronze Age– a full millennium before the florescence of Sardis – the hills and plains around Lake Marmara underwent a rapid period of urbanization that witnessed the construction of massive hilltop citadels, on a scale that surpassed all known contemporary sites in western Anatolia (Luke and Roosevelt 2009). Only faint echoes of this remarkable period are found in later eras: Lake Marmara is the easternmost point in Asia referred to in Homer's record of the Trojan War, and the kings at Sardis chose its shore as the site for their most impressive burial mounds.

Research by CLAS is expanding the archaeological understanding of the Gediz Valley beyond luxury goods and monumental architecture to include the activities of the everyday farmers and herders. Such quotidian practices often leave only ephemeral material traces on the face of the landscape. The surface archaeological record is only a time-averaged proxy of those practices, that itself has undergone millennia of post-depositional transformation by a host of social and natural processes. The primary material correlates of agropastoral land use around Lake Marmara – scatters of broken pottery corresponding to prehistoric settlements and fields systems – at first may seem more banal than the towering tumuli of the Lydian kings. But these data provide a unique window onto the interactions between the landscape and its inhabitants. The goal of the landscape modeling approach adopted in this study is to provide a clearly stated analytical framework in which to interpret these data.

The Utility of Simple Models

The models of the landscape used in this study are all purposeful abstractions of complex real-world phenomena. The simplicity of these models – each involving only a few variables and parameters – is beneficial for exploratory research. Developing complex models too early in a research program, in an attempt to recreate reality more precisely (e.g. Wilkinson et al. 2007), results in models as difficult to understand as the actual phenomenon being modeled (Boyd and Richerson 1985: 25). Simple, computational models can aid in untangling complex webs of cause and effect in agropastoral systems by helping to define robust characteristics of different subsystems and determine the kinds of feedbacks drive their interactions (Barton et. al 2010b).

Generalized and easily interpretable models of diachronic agropastoral landscapes in the Marmara Lake Basin can be applied to multiple time periods and used to highlight potential axes of variability for future investigation. Once one of the various small-scale processes of agropastoral land use is better understood within the context of a simple model, it can be iteratively combined with computational models of related processes to build increasingly complex, yet still precise, hypotheses concerning the larger emergent system and its long-term historical development (see Ayala and French 2005; Bolten et al. 2006; Barton et al. 2010a; Barton et al. 2010b; Barton et al. 2012; Ullah 2011; Arıkan 2012; Harrower, et al.2012).

This region of western Anatolia provides an ideal context for such a study for three reasons: 1) there are several freely-available environmental datasets from the area in the form of GIS maps, satellite imagery, and climate time series from weather stations; 2) the environmental heterogeneity in the area surrounding the lake basin allows these environmental data to be approached at first as independent variables against which to compare social phenomena; and 3) the relatively sparse evidence for prehistoric agropastoral land use in the Marmara Lake Basin allows realistic but unbiased models to be developed that are independent of, yet testable against, any future archaeological discoveries by CLAS researchers.

Studies using the approach adopted in this thesis, where ubiquitous GIS data are used to contextualize a variable and equivocal archaeological record, can potentially lead to environmentally deterministic explanations of past societies (Gaffney and Van Leusen 1995). But even though societies are clearly able to develop beyond the bounds set by their environments, it does not follow that an explicit study of environmental dynamics, such as climate change and landscape evolution, cannot shed light on cultural dynamics like population growth and cultural innovation. The potential significance of environmental factors is especially great for agropastoral systems, where the environment can set very tangible limits on the productivity of herds, farmland, and pastures (Wilkinson 1997; Danti 2000; Miller and Marston 2012).

Isolating environmental dynamics and developing parsimonious models of how cultures would have been expected to function if they were solely passive victims of their environments allows for discontinuities to be isolated and identified as areas where non-environmental factors were at play. This information can potentially be used to confirm or deny causal links between potential environmental and cultural changes, which can be established only after the 1) changes are shown not to reflect internal system dynamics; 2) the correlations in question are shown to covary strongly in time or space; and 3) potential nonlinearities and feedbacks have been fully explored (Coombes and Barber 2005). If employed purposefully, and interpreted carefully, this “environmental determinism as null hypothesis” approach can add much intellectual rigor to a complex research question and.

Structure of the Thesis

In the successive chapters, the particular environmental characteristics of the study area will be described and modeled, and the results interpreted in light of their relationship to diachronic agropastoral land use. Table 1 outlines the different subsystems that will be investigated and the models used to represent them.

Chapter 2 of this study provides a qualitative background of the natural environment and cultural landscape of the present-day Marmara Lake Basin. Chapter 3 addresses the archaeological evidence for agropastoral land use in the Marmara Lake Basin and elsewhere in Anatolia. Chapter 4 discusses how the features of the landscape described in Chapter 2 can be quantified as GIS data layers, while Chapter 5 builds on these data using GIS-based surface and cellular-automata models to determine how the configuration of the physical landscape might influence the spatial patterning of agropastoral land use across time. Chapter 6 uses statistical models to characterize the relationship between climate, topography, and vegetation in the study area, focusing on determining both the environmental niches of certain vegetation and land use types and the past climatic variability in those niches. Chapter 7 concludes this study by assessing critically both the accuracy and precision of these models, and discusses how knowledge of their flaws can assist in developing more complex models and targeted fieldwork programs.

Table 1 Models used in this study.

Modeled Subsystem	Input Variables	Models	Results
Geomorphology and Hydrology	DEM	GIS (Hammond Landform Classification, HED Erosion Model, Flow Accumulation Models)	Geographic regions, restrictions on movement and accumulation of water, sediment, and people
Climate	30yr Weather station data, Worldclim Climate Layers	Spline Interpolation, Macrophysical Climate Model	Topographic controls on modern and past climatic change
Land Cover	CORINNE Land Cover Map, Worldclim Climate Layers	Maximum Entropy Model	Topographic and climatic controls on vegetation growth
Agropastoral Land Use	Archaeological data, Ethnographic studies, Isotopic analysis, Textual evidence	Qualitative	Axes of variability in agropastoral land use over time

Chapter 2: Geography and Environment of the Marmara Lake Basin

Lake Marmara lies along the northern edge of the Gediz Valley, a wide intermontane depression connecting the Aegean coast with the highlands of central Anatolia (Figure 3). A hilly limestone ridge known as Bin Tepe separates Lake Marmara from the rest of the valley, while foothills and low-lying mountains (200–600 m asl) enclose the rest of the lake. Flat valleys filled with thick alluvium cut through the basin from the northwest and southeast. Agropastoral land use has been attested in every one of these regions in the modern and early-modern eras (Sullivan 1989: 51; Roosevelt 2009: 49;

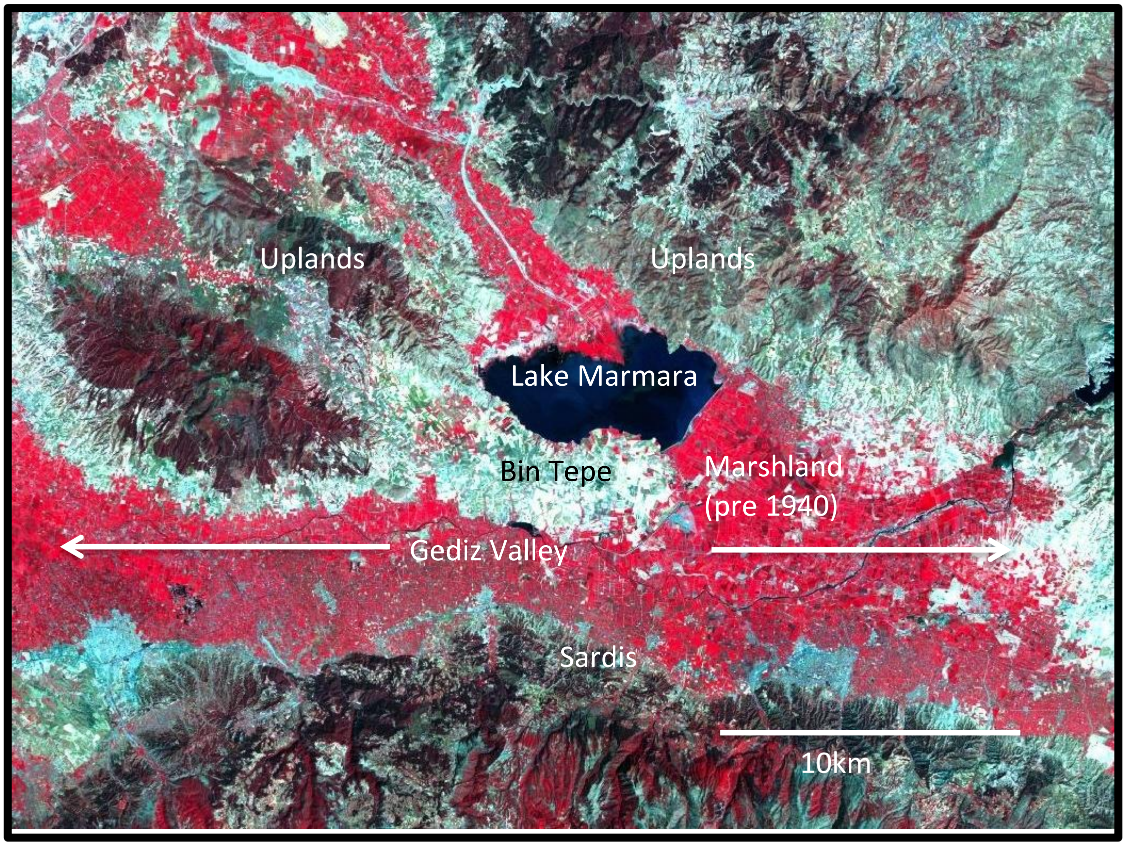

Figure 3 False color Landsat ETM+ imagery of the Marmara Lake Basin and Gediz Valley. Color changes reflect distribution of major land-use zones, with red corresponding to the irrigated valley floor, white to the dry farming on alluvial fans, and green/brown different maquis and oak woodlands.

Luke and Cobb 2013).

Tectonic History

The Gediz Valley is part of tectonic formation known as the Gediz Graben, one of several east-west trending rift valleys that cover western Anatolia (Figure 4) (Sari and Şalk 2006). The extensional stress caused by continental subduction off the Aegean coast led to the alternating uplift and downfall of large pieces of the continental crust, resulting in the formation of a horst and graben structure. The Gediz Graben was initially uplifted during the late Miocene (ca. 11–7Ma) (Hakyemez et al. 1999; Purvis and Robertson 2005; Maddy et al. 2008). The valley fill contains successive layers of lacustrine, fluvial, and alluvial facies, and the youngest sediments are late Pliocene-Quaternary fluvial deposits of the

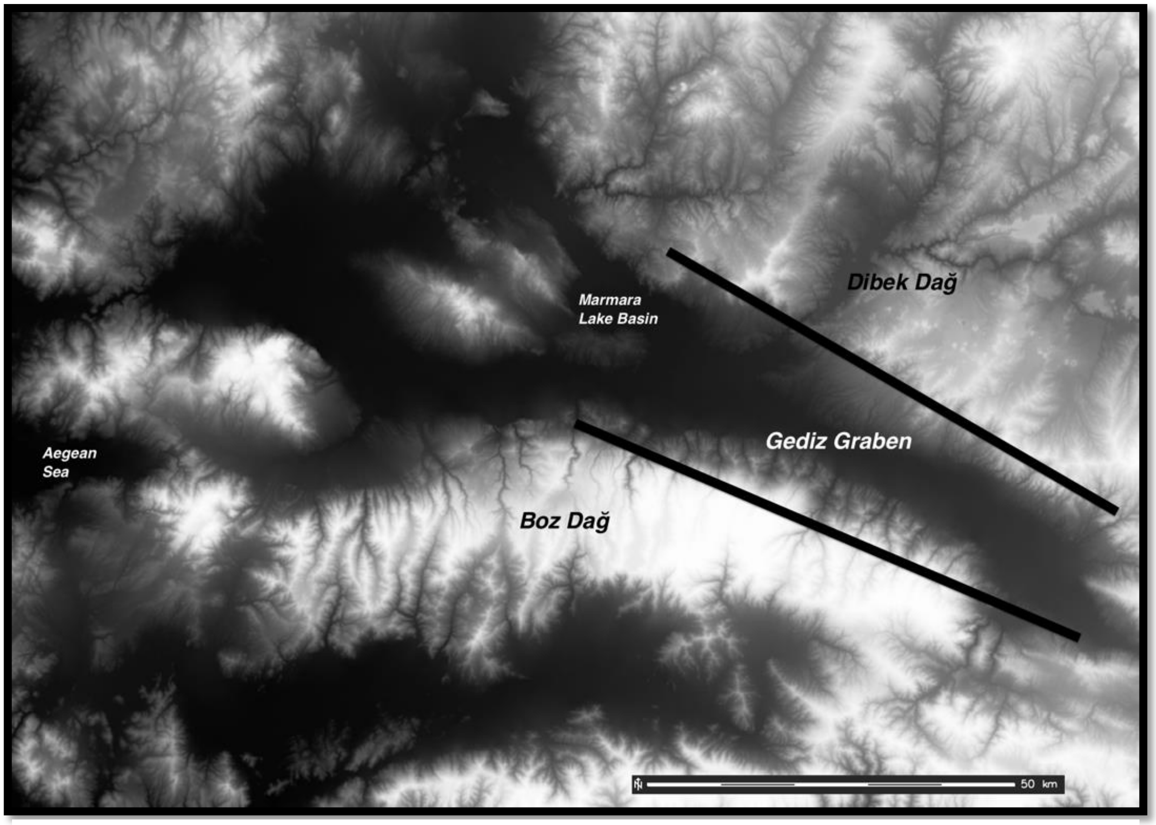

Figure 4 The Gediz Graben and central Western Anatolia

meandering rivers flowing west along the main axis of the valley floor (Hakyemez et al. 1999; Purvis and Robertson 2005). The Gediz Valley proper corresponds to the western half of the Graben, where the Gediz River descends to the Graben floor from the mountains to the north. The mountains bounding the Gediz Graben are part of the Menderes Massif, a large mass of mostly metamorphic rock underlying much of western Anatolia. Soils in these upland areas are degraded luvic leptosols (Harmonized World Soil Database 2012), developing an average of 20cm over marble, sandstone, and conglomerate bedrock, though mica-schist bedrock is also common in the immediate vicinity of the lake basin.

Despite their common tectonic origin, the northern and southern edges of the valley exhibit considerable heterogeneity. The Dibek Dağ range to the north of the Gediz Graben is composed of a series of NE trending fluvial basins separated by mountainous ridges (Bozkurt 2003). Dendritic networks of ephemeral streams, as well as larger rivers such as the Gördes and Gediz, incise these uplands. The southern rim of the graben, corresponding to the Boz Dağ mountain range, has undergone much greater uplift than the Dibek Dağ; this asymmetry means the Gediz Graben is more accurately described as a half-graben system (Purvis and Robertson 2005; Sullivan 1989). Tectonic activity in the Boz Dağ range has resulted in higher elevations, steeper slopes, and more pronounced faulting than in the comparatively stable hilly plateau of the Dibek Dağ.

Alluvial fans of various lithologies form transitional zones between the horst uplands and the valley floor. Entisols and inceptisols cover these sedimentary deposits (Olson 1981). The northern edge of Boz Dağ is a comparatively shallow dip slope dominated by highly eroded badland topography, with deep gorges cutting into coarse conglomerates that end abruptly at the valley floor, as it comes into contact with the main modern fault (Sullivan 1989; Purvis and Robertson 2005). Larger alluvial fans are found along the edge of the Dibek Dağ, composed of Pliocene limestones and sandstones interspersed with some early Quaternary alluvium (Çiftçi and Bozkurt 2009) (Figure 5). Sedimentation here is ultimately driven by regional uplift, though its intensity is moderated by climatic controls on land cover (Maddy et al. 2008).

Figure 5 Gediz Valley from Landsat ETM+ imagery. White deposits on the alluvial fans are Pliocene limestone and sandstone, redder sediments along the edge of the fans are more recent alluvium.

Lake Marmara

Hakyemez et al. (1999) have reconstructed the Quaternary history of the Marmara Lake Basin based on regional geomorphology and facies analysis. They determined that the lake had yet to form by the end of the Pleistocene; a river flowing from the northwest along the same path as the modern Gördes canal bisected the future basin before emptying into the

Gediz. Uplift of the northern plateau caused sediment influx along these paleochannels and increased deposition along the eastern rim of the modern lake basin. This prevented the stream from the northwest from emptying into the Gediz, causing it to begin inundating the shallow floodplain between Bin Tepe and Dibek Dağ by the end of the Early Holocene.

Hakyemez et al. propose that the lake has shrunk considerably in size since its initial formation, citing delta deposits to the northwest of the lake as evidence for decreasing streamflow. The origins of the northwest stream and associated delta are as yet unknown, however. Though the Gördes River – which feeds a modern canal in that location – is one possible source, its waters naturally flow to the west rather than the south after leaving the uplands, and there is no evidence suggesting it did not do so in the past as well.

Because of the lakebed's shallow profile, water depth is very sensitive to changes in supply resulting from the onset of the hot and dry summer months and, more recently, the

Figure 6 Image of the western portion of Lake Marmara during a 2008 drought (courtesy of Central Lydia Archaeological Survey).

diversion of its waters for irrigation (Figure 6). The average depth of the lake is 6m, but that can vary by as much as 2m between months, a range much greater than other large, shallow lakes in western Turkey (Beklioğlu 2013). Recent drought years have led to the total desiccation of the lake, while floodwaters have at times overrun modern flood-control infrastructure and surrounded the entirety of Bin Tepe before emptying into the Gediz. This suggests that pre-modern societies living on the lakeshore would have been even more acutely impacted by changing lake levels, especially by outbreaks of malaria from the marshes that connected Lake Marmara to the Gediz River prior to the damming of the lake's eastern shore in the past century (Elliott 1838; Yakar 2000; Luke and Roosevelt 2009).

Climate

A Mediterranean climate predominates in the Gediz Valley, with hot summers giving way to mild winters where rainfall is, on average, three times greater than in the summer (Sullivan 1989: 42; Roosevelt 2009: 48). Annual precipitation in the lowlands of the valley varies between 500 and 1,000mm, while in the uplands it ranges between 1,000 and 1,500mm. More than half of this falls during December, January, and February; only 5% falls in June, July, and August, satisfying the requirement for a Mediterranean classification (Sullivan 1989: 42-45). Summer temperatures vary between 21–26°C, with average highs reaching 38°C and winter temperatures fall between 3-9°C. The dearth of weather stations in the upland zone immediately adjacent to the Gediz Valley makes estimation there difficult, but because average temperatures in the Mediterranean decrease by approximately 0.65°C with every 100m gain in elevation, average temperatures between winter and summer range from 0–20°C in the southern uplands and 2–22°C in the north (Sullivan 1989: 46). Precipitation decreases appreciably with greater distance to the north and east of the Marmara Lake Basin, but again the lack of weather stations here make this difficult to quantify (Roosevelt 2009: 48).

Paleoclimate

Because the variation in climate across time as well as space is a key factor stimulating adaptive response in both cultural and natural systems, it is also necessary to reconstruct past climate changes in the study area. Unfortunately, there is a dearth of paleoclimate proxy studies in the Gediz Valley. The nearest paleoclimate proxy record to the Gediz Valley comes from a coring campaign carried out at Lake Gölcük on the southern edge of a large alpine valley in the Boz Dağ range (Sullivan 1989). A facies and pollen analysis of the core produced a record ranging from the Early Holocene to the modern era. Though more recent climate signals are masked by human activity in the immediate area of Lake Gölcük, a clear climatic signal can be discerned that, due to circulation patterns along the northern slopes of the Boz Dağ, reflect climate changes in the lowlands as well as the uplands (Sullivan 1989: 162).

The earliest dateable stratum is a peat layer that was deposited 7400 ±230BP (cal. 6767–5772BC[1]), overlying another peat layer and a basal sandy stratum. These facies represent the dry conditions of the Early Holocene preceding the formation of Lake Gölcük, which gave way to intermittent ponding and peat formation. Above the earliest-dated layer are alternating strata of peats and lacustrine mud, indicating the onset of wetter conditions,

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[1] This and all subsequent calibrated dates were produced with the IntCal09 curve in OxCal v4.2.2 software at 95.4% confidence (Bronk Ramsey 2009).

though still drier and more variable overall than the present day. This regime continued until 3300BP (cal. 1530BC) after which was a shift towards modern conditions and less variable lake levels reached by 2850BP (cal. 1049–976BC). Much of the pollen record in these strata data reflect anthropogenic influences in the immediate area of Lake Gölcük, but a higher ratio of oak to pine and variable aquatic pollen record during the Early to Middle Holocene does support the overall trend of dryer conditions and fluctuating lake levels suggested by the sedimentary record (Sullivan 1989:169). Both lines of evidence suggest that modern moisture conditions were reached around 3000BP (cal 1220–1250 BC).

Modern Vegetation and Agropastoral Land Use

Non-agricultural land in the Gediz Valley is largely covered by grasses and dense shrubs, known as maquis, and falls into the Eu-Mediterranean vegetation zone (Sullivan 1989: 47). Maquis consists of low and closely packed oak, pine, myrtle, and pistachio trees along with smaller grasses and thorny shrubs, all of which are adapted to hot, arid climates. Sheep mainly graze on grasses and wheat stubble in the foothill zone, while goats browse the dense maquis at slightly higher elevations (Sullivan 1989: 51). At higher elevations (c.a. 300m) or with greater proximity to water in riparian zones, this vegetation begins grading into sparse woodland with larger oaks and pines (Sullivan 1989: 50). Pine and juniper become larger and more prevalent above 500m, and these develop into denser forests characteristic of Oro-Mediterranean vegetation above 1000m (Roosevelt 2009: 48).

The valley bottom is currently dedicated to the cultivation of wheat, grapes, and various fruits and vegetables, but the extent of arable land in this area is likely greater today than in pre-modern times, because the regular flooding of the Gediz River and Lake

Marmara prior to modern water-management regimes would have formed expansive marshlands (Roosevelt 2009: 49; Luke and Roosevelt 2009; Hanfmann and Foss 1983). Early modern travellers passing through the Gediz Valley, however, observed that these marshlands were used as winter campsites and for growing small plots of wheat for fodder by transhumant nomads (Chandler and England 1817; Elliott 1838; Allom et al. 2006).

Lakeside communities have been known to graze their flocks and plant crops temporarily in the land freed by receding lake waters during drought years, though this land can easily be re-submerged (Luke and Roosevelt 2009). Other communities in the recent past have mitigated the risks of lakeside settlement by depending on pastoral subsistence in the mountains, either with permanent settlements in the foothills or wholesale transhumance between the alluvial valleys and alpine valleys known as *yaylas* (Yakar 2000; Luke and Cobb 2013). Man-made water holes and shepherd's paths dot the landscape in the uplands and are still actively used by pastoralists from nearby villages to this day. While some larger *yaylas* can support permanent settlements that rely on the growth of cereals and tree crops, the majority function as seasonally occupied summer pastures for transhumant caprine herders from lower elevations (Sullivan 1989).

Though recent top-down economic programs have discouraged transhumant migrations, the impact of this subsistence strategy can still be seen in modern settlement systems: two upland villages, Kemer and Poyraz, are connected by two large *wadis* to lowland villages named Kemerdamları and Poyrazdamları (the suffix roughly translating to "*the stables of …*") (Roosevelt, personal communication 2012). The populations of some upland villages migrated *en masse* to the lakeshore after the establishment of more robust flood-control measures allowed for the farming of new cash crops, although they still strongly identify with their pastoral roots (Figure 7) (Luke and Cobb 2013).

Similar large-scale vertical settlement shifts in the distant past have been inferred from the archaeological record around the lake basin, which suggests that the social, economic, and environmental importance of animal husbandry and vertical transhumance is not a recent development there.

Figure 7 Top: Upland and lowland villages to the northeast of the lake. Clockwise from top left: Kemer, Poyraz, Poyrazdamları, Kemerdamları (Google Earth).

Bottom: Upland herding settlement abandoned in the past 50 years (Image courtesy of the Central Lydia Archaeological Survey).

Chapter 3: The Archaeology of Prehistoric Agropastoral Land Use in the Gediz Valley and Greater Anatolia

The Development of Agropastoralism in the Gediz Valley

Several lithic artifacts found during intensive surface survey in the Marmara Lake Basin place the earliest human activity there in the Middle Paleolithic, when mobile bands of hunter-gatherers likely first came to the Gediz Valley in pursuit of fish, game, and waterfowl (Luke and Roosevelt 2010, Çilingiroğlu et al. 2013). Evidence for Neolithic settlement, however, is largely absent, although the presence of Neolithic sites from this period in the immediate vicinity of the valley suggest the area was indeed inhabited at this time. Neolithic villages were likely built directly overlooking the lake, as has been attested during this period in Greece (Karkanas et al. 2011) or have been buried by the movement of the lake or other nearby watercourses (Yakar 2000; Luke and Roosevelt 2009).

Faunal remains from the Neolithic to early Chalcolithic settlement of Ulucak Höyük, approximately 60km to the west of the Marmara Lake Basin, attest to the importance of animal husbandry in western Anatolia from 7000–5700BC (Çilingiroğlu 2011). A full 91% of the total identified specimens through the entire Neolithic are domestic animals (Çakırlar 2012). The ratio of sheep to goat in this assemblage is 3:1, and age at death patterns indicate caprines were managed to maximize meat production during the eighth and seventh centuries BC (Çakırlar 2012). More restricted kill patterns suggest a shift to herd-management strategies that minimized risk at the cost of food production as the Neolithic progressed, but with the onset of the Chalcolithic this is replaced by an intensive exploitation strategy focused on production of both meat and milk (Çakırlar 2012).

The evidence for Late Chalcolithic and Early Bronze Age habitation around Lake Marmara is much more pronounced. Biconical spindle whorls, loomweights, and a silver ram pendant found during the lakeside excavations (Mitten and Yüğrüm 1971; Spier 1983) and surface survey (Luke and Roosevelt 2010, Çilingiroğlu et al. 2013) attest to the presence of animal husbandry and the processing of secondary products in the lake basin by at least the Early Bronze Age.

A settlement shift at the end of the Early Bronze Age appears to be the inverse of that attested in the modern period and may be suggestive of some form of pastoral activity: a network of small Early Bronze Age villages and towns on the lakeshore and nearby limestone fans were replaced by several large, hilltop citadels relatively quickly during the transition to the Middle Bronze Age after the end of the third millennium BCE (Figure 8). The access to pasture

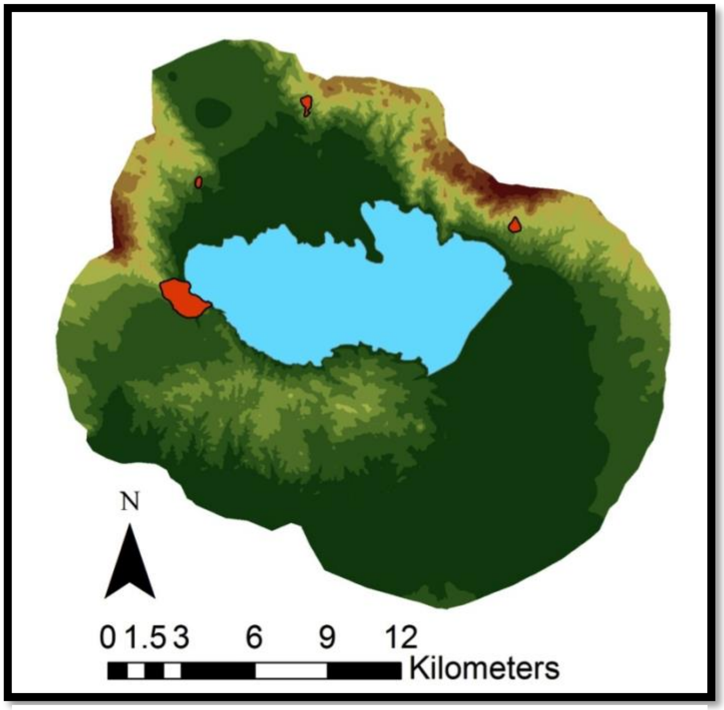

Figure 8 Middle to Late Bronze Age citadels (Data courtesy of the Central Lydia Archaeological Survey).

afforded by upland settlement may have factored in this transition, because increased reliance on animal husbandry in lands marginal for farming was a common short-term adaptation to widespread environmental changes that impacted several contemporaneous societies in the ancient Near East (Berelov 2006; Wilkinson et al. 2007; Wossink 2009)

One of these hilltop citadels, Kaymakçı, is located on a steep mountainous spur directly west of the lake and seems to have had the largest citadel in western Anatolia during this period (Luke and Roosevelt 2009). The Middle and Late Bronze Age kingdom around Lake Marmara, with its capital at Kaymakçı, has been tentatively identified with the Seha River Land that is known from historical records to be a perennial foe of the Hittite Empire in central Anatolia (Roosevelt 2009: 16). The first mention of western Anatolian kingdoms in Hittite texts describes mention of sheep and cattle being taken by tributes of war (Roosevelt 2009, 53). Because cattle and sheep were the typical prizes retrieved by victorious Hittite armies, this should not be taken as evidence for the uniqueness of herding in western Anatolia, but still confirms that this region differed little from the rest of Anatolia with respect to the importance of animal husbandry in society.

To understand herding in the lake basin beyond the limited ethnographic and archaeological material available there, sources from beyond the basin itself must be consulted. The evolution of agropastoralism at lakeside and upland settlements of western and central Anatolia has been studied in much greater detail, and provides an excellent comparative example. Limiting the archaeological comparanda to sites in nearby western and central Anatolia, rather than the greater Near East and Mediterranean, ensures that developed hypotheses will be testable against proxy records that one might reasonably expect to find as a result of future archaeological research in the Marmara Lake Basin.

Proxies for Agropastoral Land Use in Prehistoric Anatolia

The rich archaeobotanical assemblages from sites like Kumtepe and Troy in western Anatolia and Çatalhöyük in central Anatolia provide insight into the general patterns of Neolithic and Bronze Age agropastoralism. Agricultural fields were initially located in lowland alluvial zones, but by the end of the Neolithic cultivation expands to include well-drained foothill zones; principle crops throughout these periods include emmer, einkorn, barley, and a variety of pulses (Riehl 1999; Roberts and Rosen 2009). Tree crops such as olives are also exploited after the transition to the Bronze Age (Riehl and Marinova 2008).

Changes in the prevalence of certain crops over time seem to be largely contingent on cultural preferences. In contrast, reconstructions of animal management strategies, relying on the isotopic signatures or morphometric characteristics of faunal assemblages, seem to indicate that the pastoral systems more readily correlate to environmental parameters. (Riehl 2006; Henton et al. 2010; Conolly et al. 2011; Miller and Marston 2012; Çakırlar 2012). References to central Anatolian herding practices recorded in Hittite palace archives also provide some historical context to these proxies (Beckman 1988; Yakar 2000).

Oxygen, Carbon, and Nitrogen Isotopes

Isotopic analyses of caprine teeth retrieved from Neolithic and Chalcolithic sites on the central Anatolian Plateau shed light on the variability of herding strategies across space and time. Two sets of isotopes have been used in these analyses: carbon and nitrogen absorbed by the animal through the plants it eats during its entire life cycle, and oxygen fixed in the teeth from water consumed within the first year of life (Pearson et al. 2007; Henton et al.

2010). The latter thus represents more sedentary locations of herd animals, i.e., where newborn sheep were housed, while the former represents the full extent of the pasturing catchment throughout an animal's life (Henton et al. 2010; Henton 2012).

Studies of carbon/nitrogen ratios at the central Anatolian site of Aşıklı Höyük attest to an increasingly extensive management strategy between 8500 and 6000BC (Pearson et al. 2007). Sheep and goat remains from earlier levels show a marked uniformity in diet that, when interpreted in light of the distribution of age classes in that assemblage, is suggestive of single wild or proto-domestic flocks kept within close proximity to the village (Pearson et al. 2007). By the end of the Neolithic, fully-domesticated flocks show much greater variation in their diets, suggestive of more wide-ranging grazing of multiple flocks (Pearson et al. 2007).

Oxygen ratios from caprine assemblages at Neolithic Çatalhöyük suggest that the majority of sheep there were grazed at low elevations during the heat of the summer and that vertical transhumance was not practiced on a wide scale at this time (Henton 2012). Oxygen ratios suggest that those sheep that were not kept in the lowlands year round were grazed on grasses on the mid-slopes of nearby mountains during the spring and summer (Henton et al. 2010). Analysis of the wear patterns on the teeth of the same specimens from Çatalhöyük sampled for isotopic analyses suggests these sheep were fed on grasses on the outskirts of farmed plots (Henton 2012). Caprine grazing in this context was likely relegated to slightly-elevated, better drained portions of the lowlands (Roberts and Rosen 2009).

Faunal Assemblages

Early Chalcolithic animal husbandry in central Anatolia at the site of Köşk Höyük mirrors that of the Neolithic record from Ulucak Höyük. Sheep and goat carcasses with signs of butchering across a variety of age classes are common in all household refuse, suggesting the processing of meat was also carried out on a household level (Arbuckle 2012a). This pattern shifts in the Middle and Late Chalcolithic to more stratified and centralized means of production (Arbuckle 2012a). Butchering byproducts become clustered in specific structures, while animal remains in the average domestic refuse deposits become increasingly homogenous, suggesting that individual households were apportioned specific cuts of meat, but the animals themselves were managed beyond the settlement. This likely corresponds to increased mobility resulting from transhumance practices. The kill patterns of domestic sheep and goat from this period also attest to increasingly diversified exploitation of both animals including wool production (Arbuckle 2012a).

This pattern seems to bifurcate during the Middle Bronze Age, when there is evidence for an even more robust decoupling of agricultural and pastoral production (Arbuckle 2012b). The importance of wool production continues into the Bronze Age, with the central political authority becoming increasingly involved in the collection and redistribution of pastoral products. Sheep assemblages at the Bronze Age palace of Acemhöyük suggest that herds were intensively exploited for wool production, while goat assemblages suggest a management strategy focusing only on the production of meat and milk (Arbuckle 2012b). The spatial patterning of Chalcolithic butchering activity described above continues in this period, and a marked absence of younger caprine remains continues to suggest that the herds were being managed farther afield from the main settlement than in the Chalcolithic (Arbuckle 2012b). In contrast to the Chalcolithic, butchered caprine remains found within Acemhöyük are of increasingly low quality and derive from animals exploited for secondary products that have passed their peak of production (Arbuckle 2012b). These patterns in the faunal assemblage continue even after the collapse of the main settlement at Acemhöyük, suggesting that the pastoral groups creating it were part of larger regional networks and thus were buffered against the fall of a single node in that network.

Hittite Texts

The Hittite archives provide a rare glimpse of some of the social aspects of herding in Late Bronze Age Anatolia that developed in the aftermath of the Middle Bronze Age intensification and specialization of production. References to animal husbandry in the Hittite texts are found in two contexts: legal and religious (Beckman 1988). They deal generally with pasture management and ownership of flocks, while texts concerning the latter provide more abstract information on attitudes towards animal husbandry.

Most pastureland was nominally under control of the Hittite king, and he delegated the day-to-day management of the land to his bureaucracy (Beckman 1988). Herdsmen themselves were considered lower class and tended not to own their own flocks. This is especially true where transhumance was practiced, with a small number of herders moving the flocks of several wealthier individuals to summer pastures, which suggests that transhumance during this period was associated only with the seasonal movement of herds, not the settlements that owned them.

The importance of these animals relied in no small part on regular demands for sacrificial victims for festivals and cult activities, and it was the responsibility of a village's head shepherd to provide enough animals for regular quotas (Beckman 1988). This emphasis on the animals themselves rather than the pastureland could conceivably have contributed to overgrazing even when there was no food shortage. The Hittites were certainly aware of the perils of unrestricted grazing, as evidenced by a myth in which the sun god castigates some cattle for destroying a fresh meadow with their continuous eating (Beckman 1988).

Summary

When taken together, these multiple lines of evidence serve as a time- and space-averaged model of the historical trajectory of agropastoral land use in central Anatolia from the Neolithic period to the Late Bronze Age. Neolithic agriculture was focused around lowland settlements, and animal herds were grazed in nearby low foothills in order to buffer against the risks of crop failure. Animals are grazed at increasingly greater distances from settlements during the progression through the Chalcolithic to the Early Bronze Age. Animal husbandry during the Bronze Age becomes less integrated with agropastoral subsistence systems and more associated with top-down management to meet ritual and economic goals. This narrative will be useful for approaching how the same phenomenon played out in western Anatolia because it helps to isolate particular axes of variability in pastoral land use over time that can be used as a reference for interpreting the environmental models that are developed in the remaining chapters of this study.

Chapter 4: Data Collection and Preparation

While the geomorphic and environmental characteristics of the Marmara Lake Basin outlined in Chapter 2 have very likely had long-term impacts on types of agropastoral land use described in Chapter 3, the abstract nature of these environmental data precludes more precise analysis of any long-term dynamics. GIS-based surface models, in contrast, are an intuitive means of quantifying landscape-scale features of the lake basin (Conolly and Lake 2006: 101). Surface models of just a few basic physiographic parameters such as slope and elevation can be used to predict the broad spatial patterning of such diverse phenomena such as the movement of water and sediment across the earth's surface, local and regional climate regimes, and the suitability of land for certain types of vegetation or subsistence practices (Butzer 1982; Daly, Neilson, and Phillips 1994; Bolten, Bubenzer, and Darius 2006).

This chapter describes the acquisition and preparation of the basic surface models that will form the basis for the more complex models presented in later chapters. Digital elevation models (DEMs) of the study serve as the primary dataset, from which are calculated first- and second-order topographic derivatives that represent local variability in the landscape. Climate layers are then produced by combining the elevation data with climate time series from weather stations in the Gediz Valley. Finally, remotely sensed data provide the basis for a land cover and land use map of the study area.

Digital Elevation Model (DEM)

A DEM is the most basic form of surface model, in which the value of each raster grid cell represents the average elevation in that cell, and can be used to calculate topographic derivatives such as slope, aspect, and profile curvature. Only two high resolution digital elevation models (DEMs) derived from remotely sensed satellite data cover the study area: that of the Shuttle Radar Topography Mission (SRTM) and that of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). A third set of elevation data was digitized by researchers with the Central Lydia Archaeological Survey (CLAS) from Turkish 1:25,000-scale topographic maps, but the spatial extent is limited to the immediate area around Lake Marmara, making it unsuitable for regional analyses.

The SRTM DEM is the least precise of the three DEMs at 90m horizontal resolution, but the vertical resolution of the SRTM DEM is greater than the ASTER product ranging from 4 to 6 meters in flat areas and 11 to 14 in rough areas (Hirt, Filmer, and Featherstone 2010). Though the ASTER DEM has a horizontal resolution of 30m, the average vertical resolution is only 17m. GDEM2 imagery has undergone some geometric correction before release, but still contains considerable speckling, making additional post-processing necessary before successive analyses. An adaptive denoising algorithm was used to remove many of the interpolation artifacts from the ASTER DEM while minimizing data loss (Sun et al. 2007).[2]

The ASTER DEM (henceforth DEM) is the principle dataset used to calculate the geomorphic characteristics of the study area, because the resolution of the SRTM product is

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[2] This and all successive models and algorithms described in this study were executed using GRASS GIS software unless otherwise noted (GRASS Development Team, 2012. Geographic Resources Analysis Support System (GRASS) Software. Open Source Geospatial Foundation Project. http://grass.osgeo.org)

simply too low to meet the requirements for derivation of accurate slope and accumulation values (Kienzle 2004). Because of its higher accuracy, the SRTM DEM is used for models where high resolution is not a requirement, such as the regression-based models described in Chapter 6.

Both satellite DEMs lack bathymetric information and only represent the surface elevations of water bodies. The CLAS DEM, in contrast, contains bathymetric information calculated from a sonar bathymetry survey made by CLAS during the 2006 season and referenced against a series of Landsat images of the lake at different stages of desiccation (Roosevelt, pers. comm.). In order to model accurately the accumulation of water across the

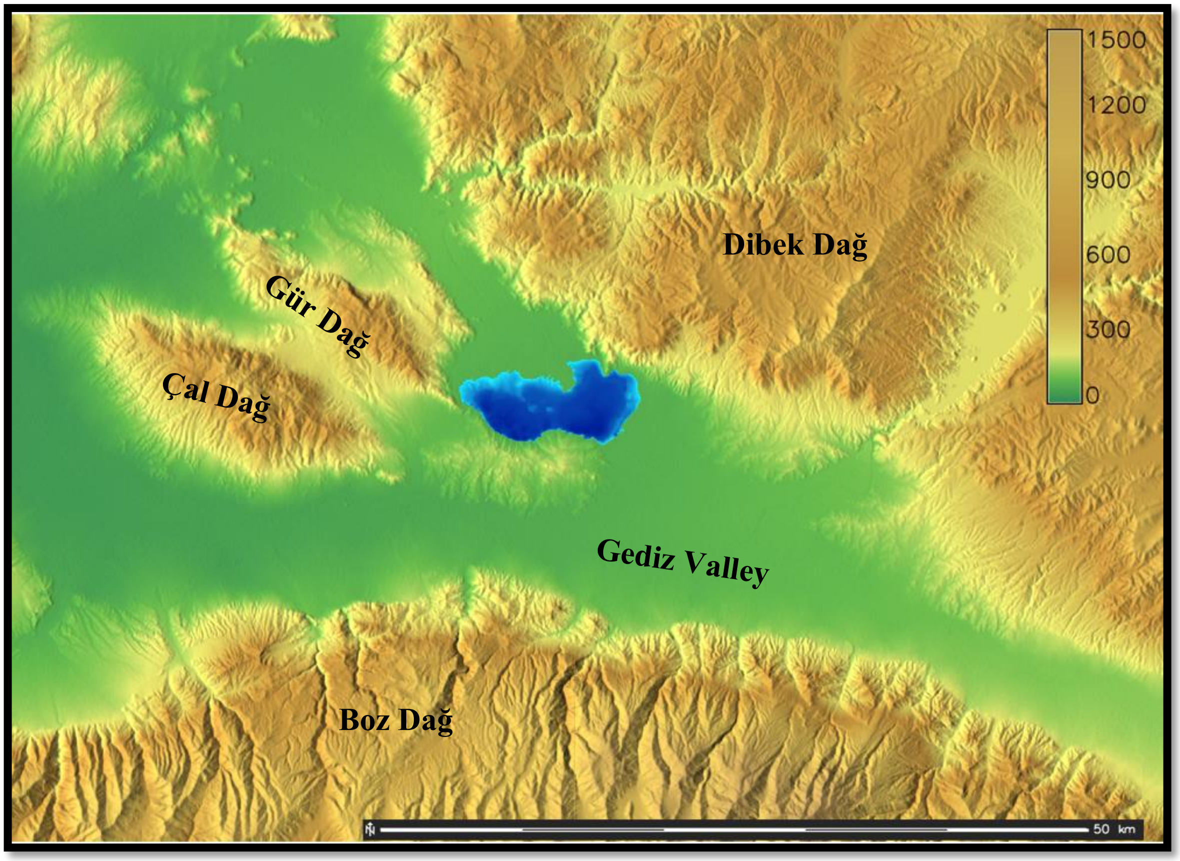

Figure 9 ASTER DEM of the Marmara Lake Basin and environs. Map coloring represents meters above sea level, save for the lake area itself where coloring corresponds to meters below surface.

landscape, the surface of Lake Marmara was first clipped from the satellite DEMs, and then filled in with elevation values from the CLAS DEM, resampled to 30m resolution. Both DEMs were clipped to an area of approximately 60x80km to include the watersheds that empty into the lake basin as well as neighboring regions such as the Gediz Valley and the surrounding Boz Dağ, Çal Dağ, Gür Dağ, and Dibek Dağ ranges (Figure 9).

DEM Derivatives

The raw elevation values in a DEM are used to calculate first order topographic derivatives by establishing the value of each grid cell as a function of several surrounding cells. A slope raster represents the rate of change in elevation, commonly calculated using a nine-cell window around each cell in the input DEM (Figure 10). The intensity of slope impacts the movement of sediment, water, and organisms across the surface, and as a result the potential for different varieties of land cover and land use (Bolten, Bubenzer, and Darius 2006). An aspect map represents the cardinal direction in which the steepest gradient of elevation is facing, which impacts the intensity of solar irradiation at that point and by extension the suitability of that slope for different vegetation types (Figure 11).

Second order topographic derivatives are calculated in turn as a function of the rate of change of slope (Conolly and Lake 2006: 196). Plan and profile curvature represent the curvature of a surface, and by extension, its shape (Figure 12). The convexity of a slope is shaped in part by erosion from overland flow and generally varies inversely to soil depth (Heimsath et al. 1997).

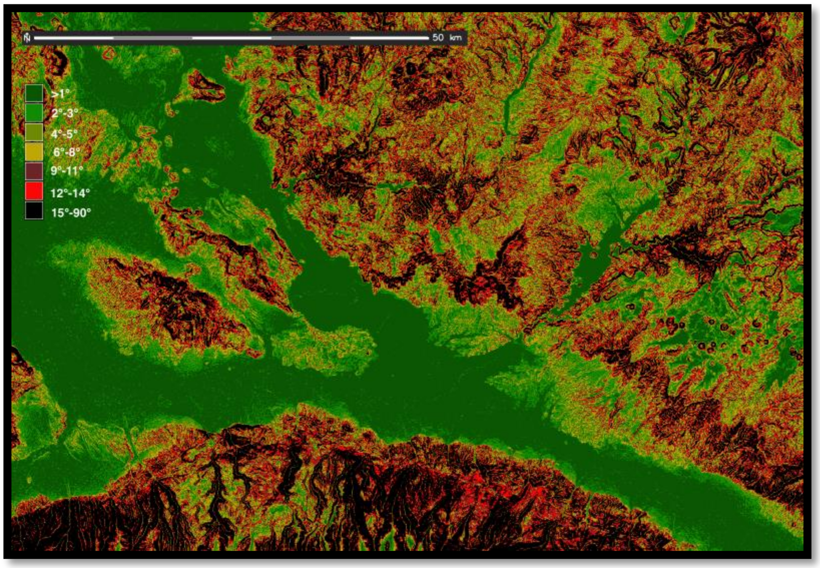

Figure 10 Slope values in degrees above the horizontal.

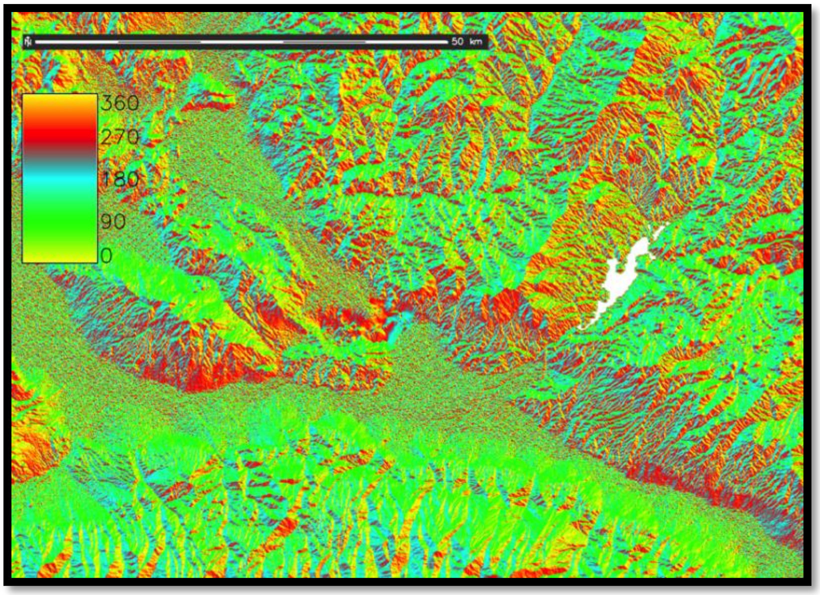

Figure 12 Aspect values in degrees clockwise from the east.

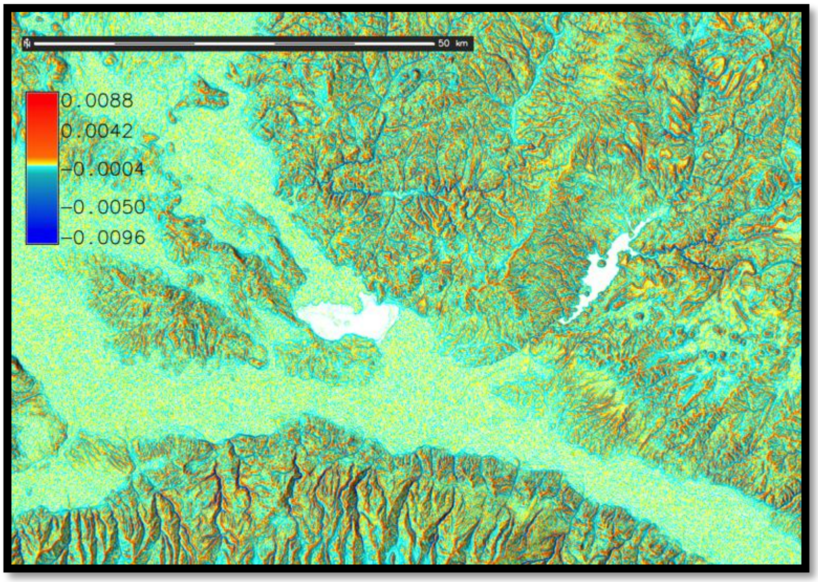

Figure 11 Profile curvature values, positive is concave, negative is convex.

Climate Maps

The Food and Agriculture Organization of the UN maintains a collection of climate data (FAOCLIM 2 World-Wide Agroclimatic Database, Version 2.01) derived from several weather stations in the region. Of these, only those in the cities of Manisa, Akhisar, Ödemiş, and Salihli have been active long enough to provide the 30-year normals representative of the overarching climate regime. There are only a few weather stations in the upland zones, and none have been in operation long enough to provide reliable climate estimates. Continuous climate maps of the study area that account for the influence of elevation were derived from the WorldClim database, which applies a volumetric spline interpolation algorithm to the FAO weather station data (Hijmans et al. 2005). The climatic

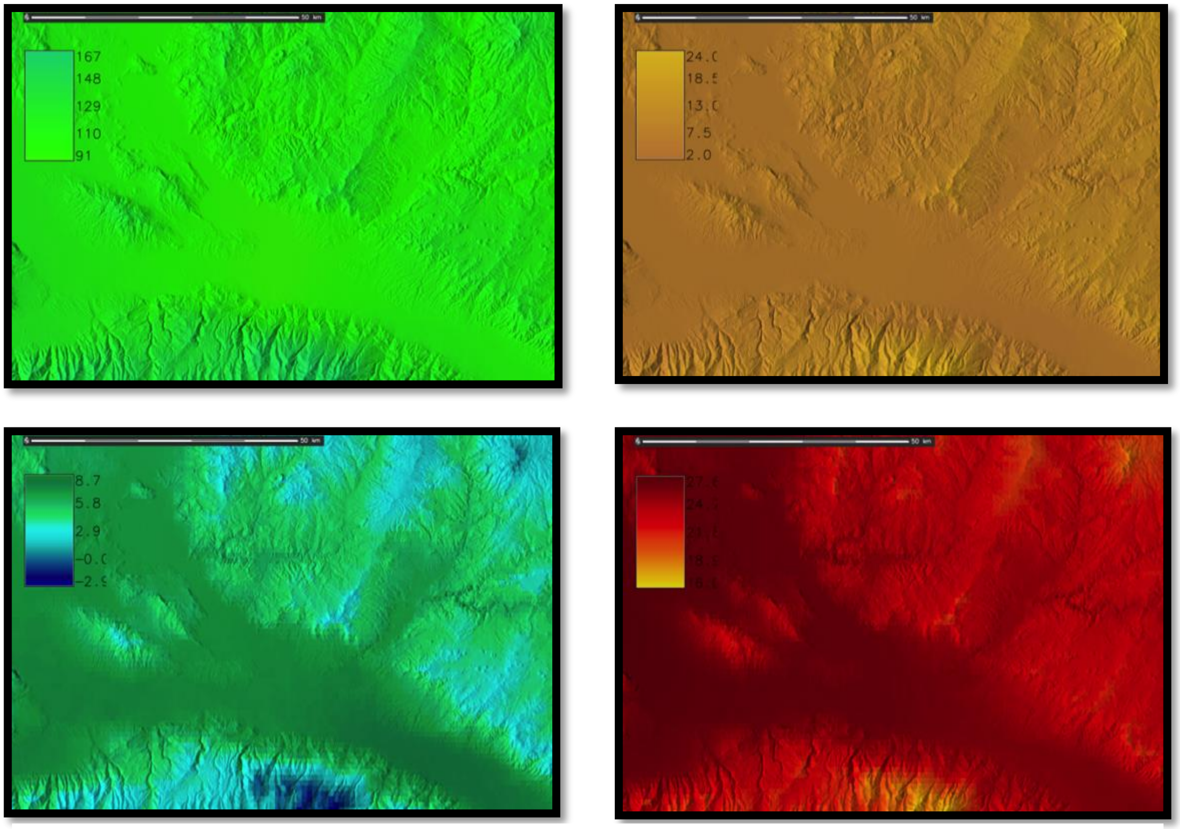

Figure 13 Interpolated climate maps. Moving clockwise from top left: January precipitation, July precipitation, July temperature, January temperature.

variables used in this study were average precipitation and temperature values for July and January, intended to cover the full scale of annual climatic variability in the region (Figure 13).

Land Cover Data

A map of modern land-cover patterns was derived from 2006 Corine land cover (CLC2006) raster maps produced by the European Environment Agency at 100m resolution from remotely sensed imagery. The dataset contains 50 different classes representing a variety of both natural and anthropogenic features, of which less than half were represented in the region of western Turkey surrounding the study area. The CLC2006 map was reclassified into a simpler map in order to highlight the broad vegetation groups that underlie more socially and historically contingent patterns of modern land use. The classes corresponding to artificial land cover such as cities, mines, and roads in the CLC2006 dataset were aggregated into a single “urban” category that was masked from successive analyses. CLC2006 classes representing specific crop types were combined on the basis of the irrigation requirements. “Grass” and “maquis” classes were used to define potential grazing land, with the former defined as natural grassland and manmade pasture, and the latter defined as a combination of sclerophyllous vegetation, woodland scrub, and heathland. Other potentially relevant land cover classes were left as-is from the CLC2006 data. The resulting vegetation map includes nine land-cover categories: urban, irrigated arable, non-irrigated arable, grass, maquis, broadleaf forest, coniferous forest, sparse vegetation, and transitional (i.e. complex combination of farming and natural vegetation) (Figure 14).

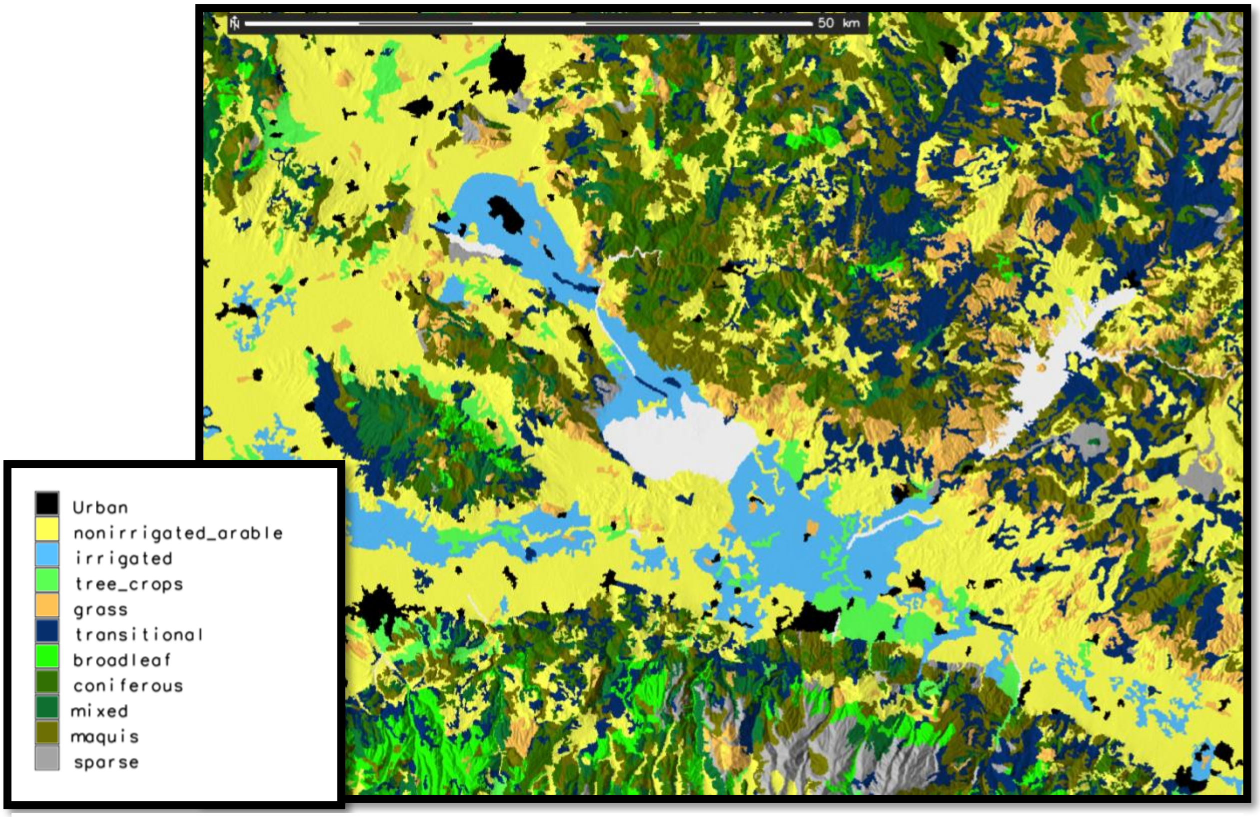

Figure 14 Reclassified land cover and vegetation data.

Chapter 5: Modeling Topography and Surface Processes in GIS

The geomorphology of a landscape defines the essential structure on which regional-scale social and natural processes operate. Quantifying the spatial variability in geomorphology can aid in identifying subtler relationships between these variables and broader socioecological systems of agropastoral land use. This chapter uses geomorphic and process-based models to quantify structural features of the landscape and the impacts of these structures on the movement and accumulation of water and sediment across the landscape, respectively. The DEM derivatives calculated in Chapter 4 are first integrated into geomorphic landform classifications, providing a more intuitive means of understanding surface structure on a regional scale. The derivatives are then used as inputs into process-based hydrology and erosion models, which help to isolate areas of the landscape that are especially sensitive to changes in the environmental system. For agropastoral landscapes in particular, these analyses can provide insight into the dynamic physical constraints on the location of fields and the movement of shepherds and their flocks (see Bolten, Bubenzer, and Darius 2006; Frachetti 2008; Ullah 2011).

Landform Classification

Because the DEM derivatives described above are calculated on a pixel-by-pixel basis, local heterogeneity can often mask larger-scale regional patterns. A semi-automated GIS implementation of Dikau's version of the Hammond Landform Classification system (Morgan and Lesh 2005) is thus applied to the DEM of the Gediz Valley in order to determine how continuous landscape zones emerge from the complex covariance of physiographic parameters across the landscape. Landform classification results in surface models that are more readily interpretable and culturally significant while remaining objectively rooted in the physical structure of the landscape (Verhagen and Drăguţ 2012).

The Hammond system uses five major divisions: plains, tablelands, plains with hills and mountains, open hills and mountains, and hills and mountains (Gallant, Brown, and Hoffer 2005). These classes are then subdivided further based on the degree of relief (e.g. smooth plains, open high hills) for a total of approximately 40 classes. Each class represents a unique combination of three parameters – slope, curvature, and relief (the range of elevation within a discrete area) – as integrated through an iterative series of map algebra calculations in GIS. Each step in the classification routine is carried out after smoothing the input layers by setting the value of each pixel to a function of all surrounding pixels within a defined computational window. Morgan and Lesh (2005) experimented with a variety of moving-window configurations and compared the results to empirical data, determining that a window of a 20 pixel-radius circle results in the optimal classification of landforms in a 30m DEM. The resulting regions (Figure 15) are useful not only for inputting spatially explicit morphometric parameters into other models but also for simplifying analyses and interpreting their results.

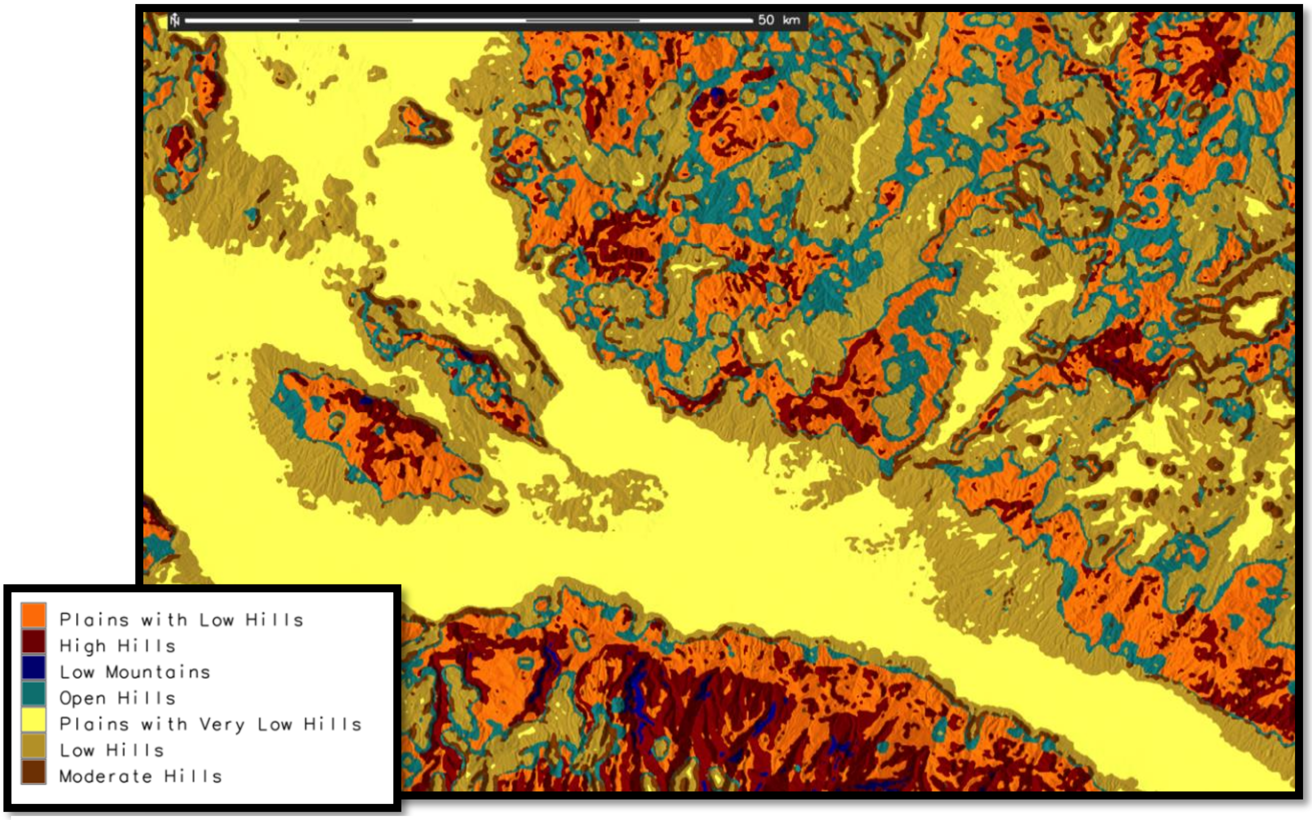

Figure 15 Hammond's Landform classification.

Cellular Automata Modeling of Water Accumulation

DEM-based hydrology models rely on a cellular automata approach to calculate the topographic constraints for the overland flow and collection of water. In cellular automata models, the behavior of each raster cell at each time-step is a function of the state of those raster cells adjacent to it in the previous time-step. The use of time as a factor in cellular automata models, in contrast to the simple neighborhood operations described above, allow for dynamic models that can represent non-linear phenomena.

The hydrological models add water to a DEM grid cell and determine movement to each neighboring cell based on relative changes in elevation, as well as other physiographic factors depending on the particular algorithm. Accumulation is modeled by seeding water in every cell of the DEM, and then allowing it to flow and accumulate naturally based on the structure of the DEM (Figure 16) (Harrower 2010). An accumulation map can then be used to extract potential stream drainages and watersheds (Figure 17).

Alternatively, the topographic constraints on lake configurations with different water supplies can be investigated by seeding the DEM with water at a single point in the center of the lake basin and allowing the water to spread to adjacent cells until a predefined elevation limit is reached (Menotti 1999). The lake bottom actually contains two main sub basins; the center of the eastern sub basin was chosen as the seed point because the majority of modeled stream drainages converged there. The model determines the volume of water in the lake as a function of the elevation parameter, so a series of model runs was made using values above and below the lake's 74 meter-above-sea-level (masl) average height in order to simulate flooding and desiccation, respectively (**Error! Reference source not found.**18). A modern dam restricts the spread of floodwaters to the east; the drought simulation is unaffected by this, but the flood simulations should thus be interpreted as conservative estimates.

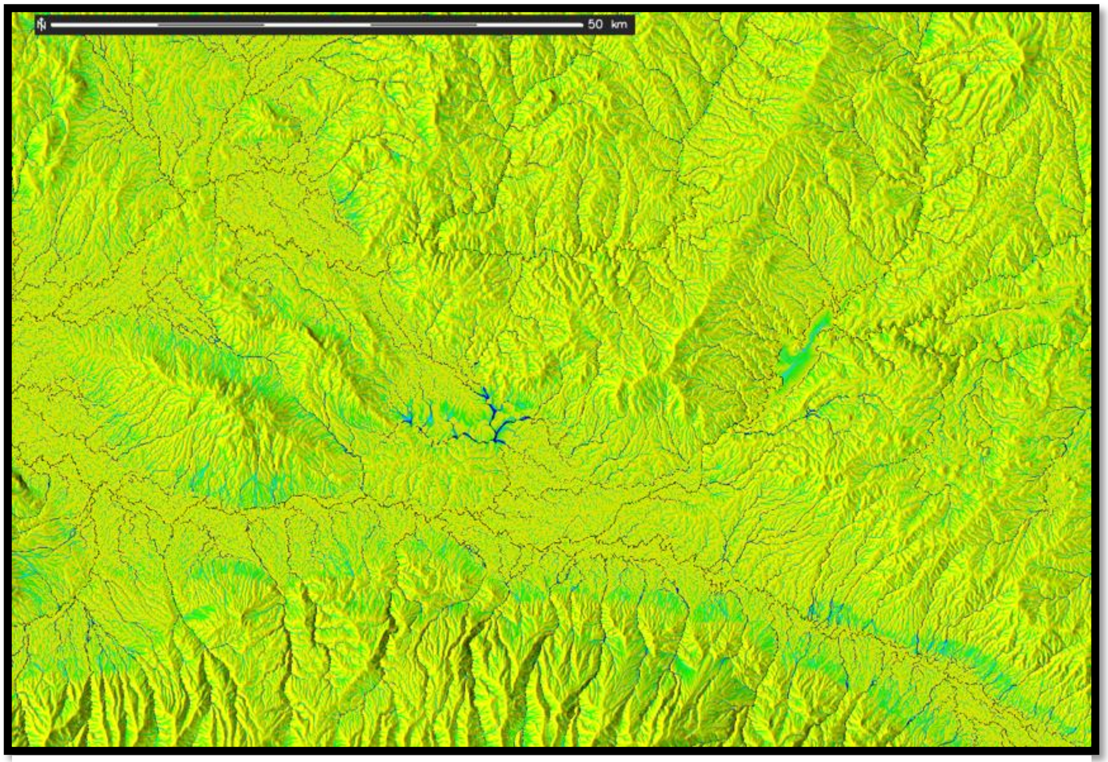

Figure 16 Accumulation raster, blue cells are where water will naturally accumulate on the surface.

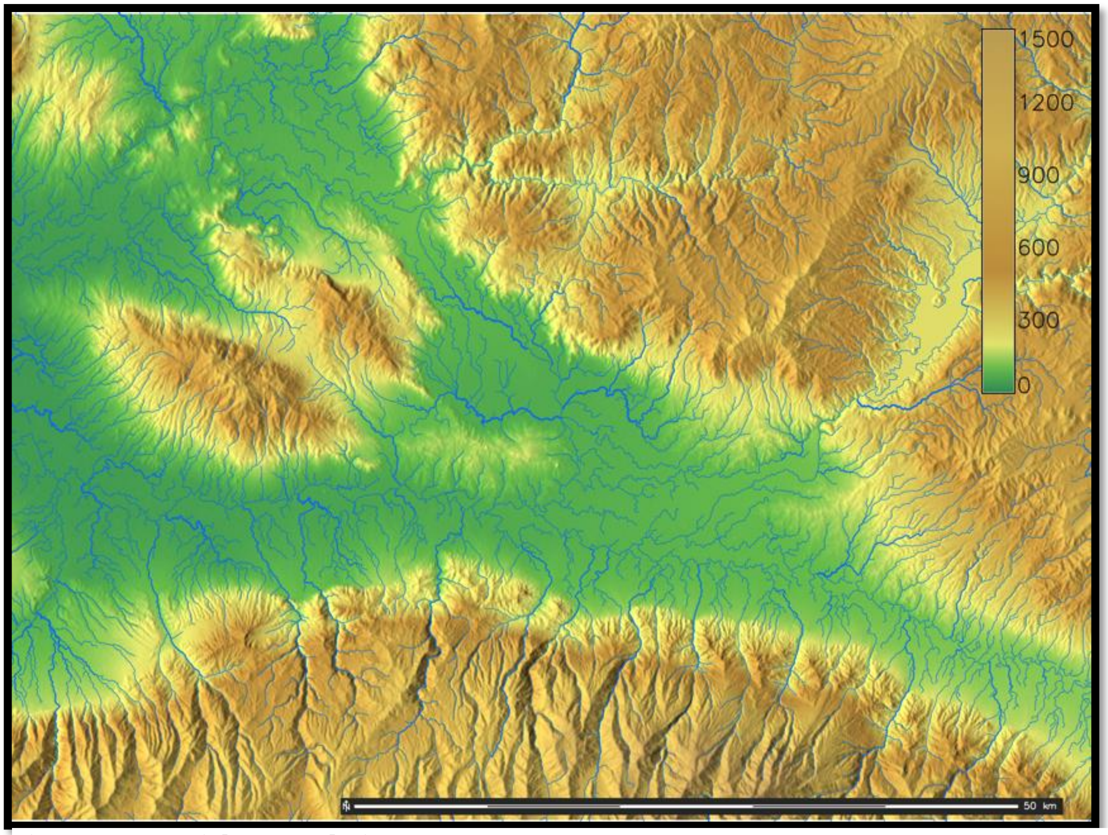

Figure 17 Potential stream drainages.

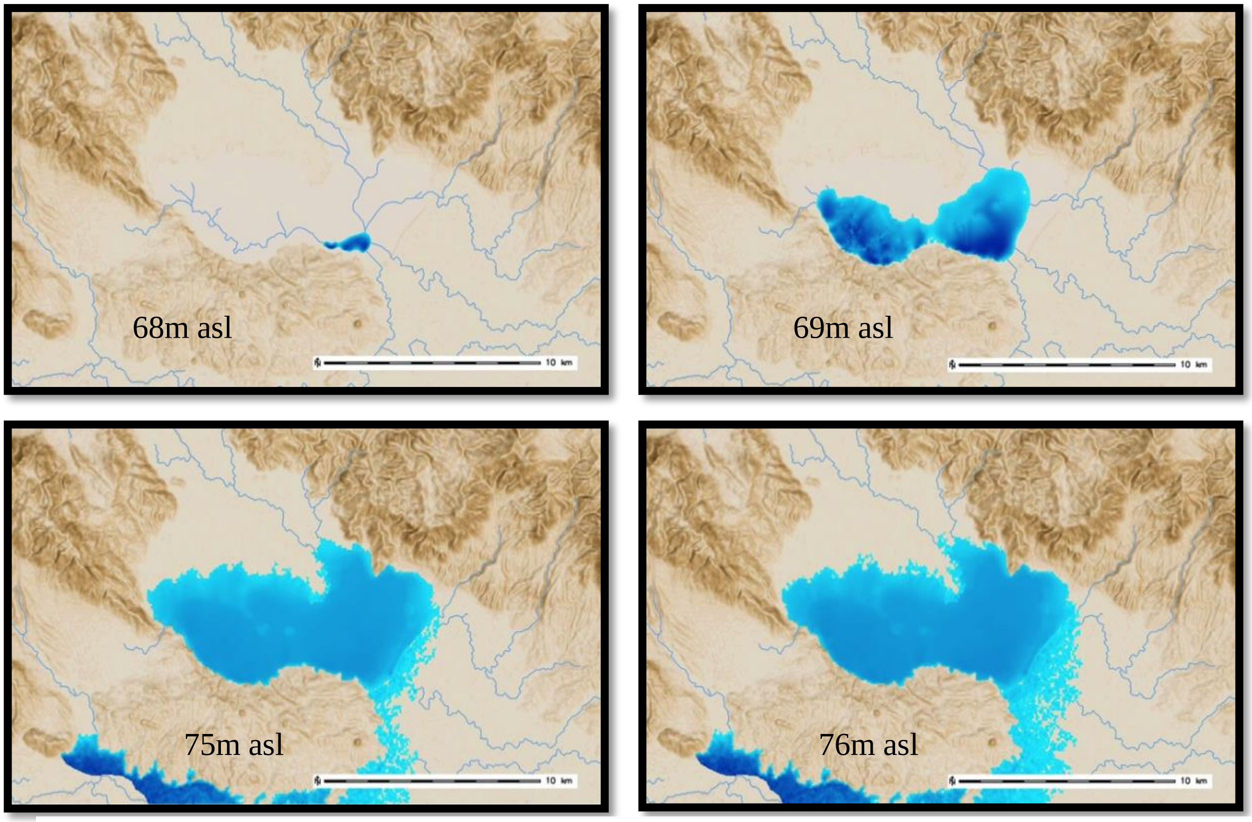

Figure 18 Stream drainage model and flood simulation.

Erosion Modeling

Patterns of erosion and deposition in the Marmara Lake Basin are investigated using a version of the hill-slope erosion/deposition model (HED, also known as unit stream power erosion/deposition or USPED) that has been implemented in GIS for use in Mediterranean environments (Barton, Ullah, and Mitasova 2010). The HED algorithm uses a cellular automata approach, just as the hydrological models described above. The value of each raster cell in the HED model represents the depth of sediment at a specific point in time, the initial conditions of which are calculated by relating potential soil depth to the profile and plan convexity of the landform (Heimsath et al. 1997). When a certain volume of sediment is removed from the cell, it is deposited in the downslope cells, a process which is repeated over every grid cell across multiple time steps.

The quantity of sediment transported from one grid to another is a function of the amount of water potentially flowing over it, calculated from the slope and accumulation maps developed earlier, as well as a series of environmental parameters that determine how the water interacts with the sediment in the cell (Barton, Ullah, and Bergin 2010). These parameters, derived from the Revised Universal Soil Loss Equation (RUSLE), are rainfall intensity (R), soil erodibility (K), and land cover (C) (Neteler and Mitasova 2008; Barton, Ullah, and Mitasova 2010; Bevan and Conolly 2011). The goal of this model is to examine the topographic controls on erosion and deposition, so the RUSLE parameters were input as constant values representative of empirically derived average conditions in the eastern Mediterranean (Arıkan 2012).

With these DEM-derived topographic variables and RUSLE parameters in place, the model was run for 100 cycles, and net erosion and deposition was added to the original DEM and input again for the next cycle to simulate the movement of sediments across the landscape over a 100-year period (Figure 19). Although the time scale of the erosion model is too small to investigate the role of sedimentation in the formation of the lake (*sensu* Hakyemez, Erkal, and Göktas 1999; Maddy et al. 2008), it does provide insights into the role of erosion at scales most relevant to humans. Yakar (2000: 317) presents a simplified model of erosion in the Gediz Valley, arguing that deforestation-induced erosion in the uplands would harm lowland settlements by replacing arable land with sterile sediments. The model results reveal a more nuanced picture in which this process might have impacted settlements.

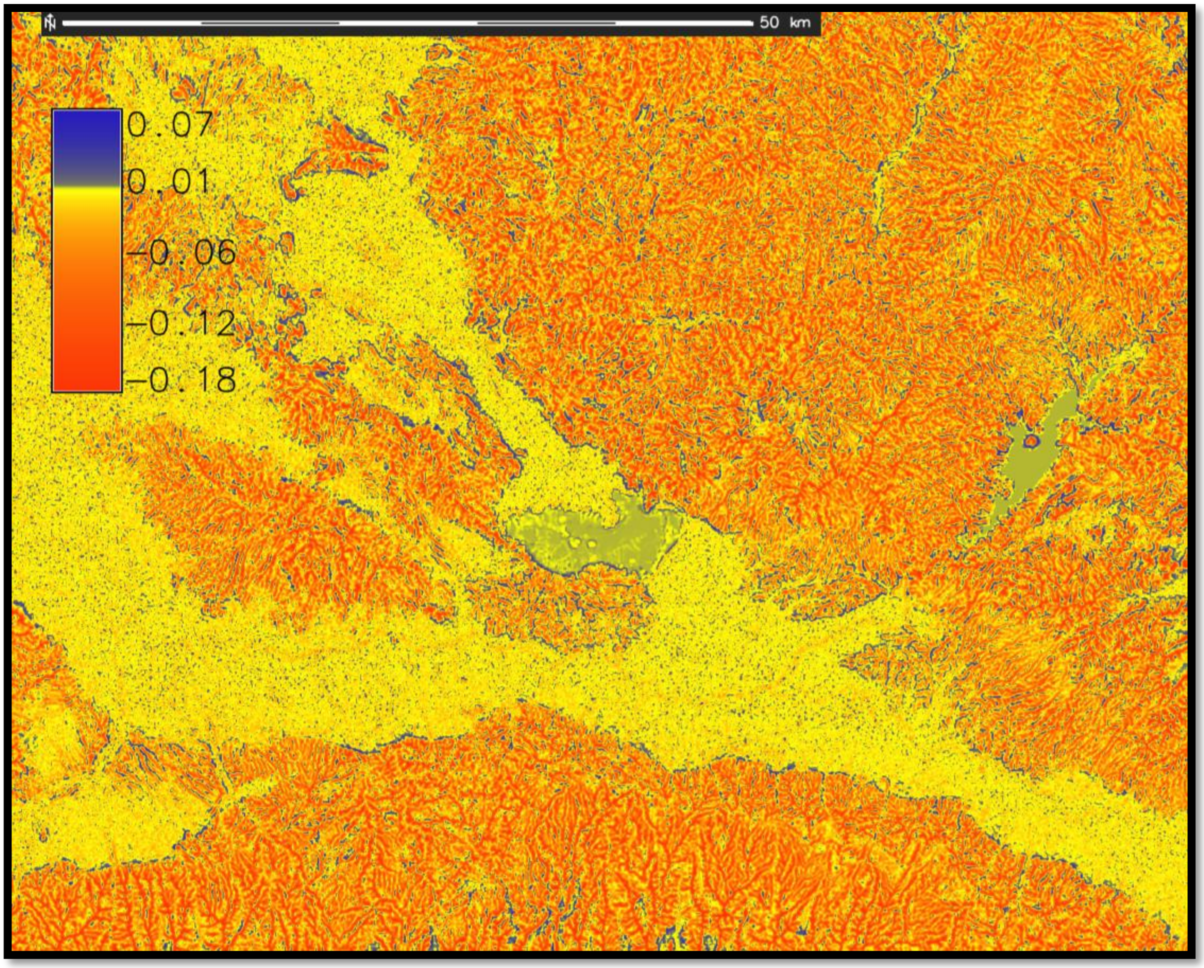

Figure 19 Net sediment flux after 100 years of erosion and deposition. Units are in vertical meters.

Geomorphology Modeling Results

Lowlands

The lowland alluvial valley is classified as “very low hills and plains,” with almost no slopes greater than 1°. The lack of pronounced topography here causes water to flow relatively evenly over the surface, only slightly accumulating where the DEM resolves existing canals and rivers. It was this flat topography on which Lake Marmara originally formed, and as a result the shallow profile of the lake basin results in large changes in the horizontal distribution of the lakeshore in response to comparatively minor disruptions to the hydrological balance. The flood simulations show that the lake level is most variable with low water volumes, when relatively small changes in the hydrological balance have a marked impact on its size and shape. Higher than average water levels do not significantly change the spatial distribution of the lake because it is constrained by local topography. When sizeable flooding does occur, the water flows to the south and east of the lake rather than to the north. It would follow, then, that herding in this zone south and east of the lake is most practical during more arid periods when lake levels are low, not only because wetter conditions restrict the movements of herds, but also because flocks can graze on freshly inundated fields planted in lacustrine mud.

Alluvial Fans and Foothills

Bin Tepe and the northern alluvial fans are largely "low hills," with some "very low hills" where the larger stream channels reach the valley floor. Slopes are generally steeper than in the lowlands, but still within the range from 3-10° and are acceptable for agriculture. This topography is pronounced enough, however, to restrict the spread of floodwaters from the lake, ensuring that even those settlements, fields, and flocks on the very fringes of this zone are secure from inundation.

The erosion model suggests that a comparatively large amount of sediment tends to accumulate in the foothill zone and the immediate fringe along the lowlands. But contrary to the model proposed by Yakar (2003), the hillocky topography restricts the extent of deposition to established channels. By extending the higher elevation zone further across the floodplain, deposited sediments would, over centuries, create more land protected from seasonal floods. The modeled accumulation rate is less than 10cm per year, but this figure does not account for the potentially greater erosion potential of the limestone bedrock.

Mountains and Upland Valleys

The Boz Dağ range itself ranges from plains and low hills to mountains with a series of north-south trending regions of very low hills and plains corresponding to *yaylas* or upland pastures. This landform structure is repeated along the immediate rim of the northern edge of the Gediz Graben, but gives way to "low hills" dissected by NE-running low mountains, corresponding with the fluvial basin system described earlier in this chapter. From a geomorphic perspective, these mountain valleys are very similar to the alluvial fans and foothills in the lowlands, and in the absence of climate differences should be able to support similar patterns of subsistence strategies. Erosion potential across the entire upland zone, however, is much greater than in the lowlands.

Despite the steep slopes in the uplands to the north of the lake basin, these areas are still classified as moderate hills. In contrast to the low mountains of the Boz Dağ, where the high relief would have restricted passage, movement among the northern mountains is still possible. Although high slopes can block movement locally, the overall lower relief and open topography mean that individuals could easily find routes through the mountains. This suggests that pastoral land use would be less restricted here than agricultural land use, in contrast to the mountainous Boz Dağ, where the closed landscape would have severally restricted both agricultural and pastoral land use.

The results of the stream modeling show that the majority of the water flowing into the lake basin originates in northern highlands, primarily from the northeast. They do not empty into modern lake because of the dam on its eastern edge, but prior to its construction they would have fed the marshland connecting the lake with the Gediz River. This supports the hypothesized former location of the lake in the eastern edge of the basin (Hakyemez, Erkal, and Göktas 1999), and calls into question whether flow from a channel of the Gördes River on the northwest was the main source of water feeding the incipient lake.

Summary

By comparing the elevation derivatives and surface process simulations it possible to examine the kind and degree of topographic variability across the landscape of the Gediz Valley, the dynamics of that variability over time, and its potential impact on agropastoral land use. In general, the alluvial fans and foothills seem to display an optimal balance of moderate topography and protection from floodwaters. This suggests that settlement systems in the foothills are more protected from environmental variability than in the lowlands and uplands, and thus might have been more stable across time. To investigate this further it is necessary to integrate these topographic models with the vegetation and climate data more fully, in order to show how these dynamics impact broader environmental systems around Lake Marmara.

Chapter 6: Statistical Modeling of Vegetation, Land Use, and Climate Change

Climate change is one of the few exogenous influences on agropastoral land use in the Marmara Lake Basin; not even the most intensive grazing practices can change large-scale atmospheric patterns. But while climate changes can set the timing and pace of some social dynamics, the size or intensity of these changes do not scale directly with one another and instead exhibit historically contingent, non-linear responses (Wilkinson 1997; Coombes and Barber 2005; Phillips 2006; Roberts et al. 2011). Even when climate is not the direct cause of change, variations in climate can enhance or dampen changes in hydrology, sediment dynamics, and land use (Erol and Randhir 2012).

Vegetation change is a key intermediary between large-scale climate changes and smaller-scale cultural dynamics. Climatic and topographic factors delimit ecological niches for broad vegetation types and, less directly, for certain land-use practices that depend on certain vegetation types. Reduction in grasslands used for pasture due to drought conditions, for instance, will influence the productivity of animal herds and set upper limits on the success of adaptive management strategies (Frachetti 2008). Indeed, in western Anatolia, the maximum size of herds is largely a function of the availability of winter pasture, due to the timing of caprine reproductive cycles (Yakar 2000; Henton, Meier-Augenstein, and Kemp 2010). Knowledge of natural vegetation dynamics is thus indispensible for understanding the nature of ancient and modern land use around Lake Marmara.

Chapter 2 outlined the broad elevation-based land use and vegetation patterns in the lake basin, but further analysis is necessary to quantify the relationship between topo-climatic variables and modern vegetation potential. This chapter seeks to quantify these relationships and determine the sensitivity of the environmental system to changes in key parameters by integrating the models and data from Chapters 4 and 5 into a Maximum Entropy (Maxent) probability model of vegetation and land use types in the lake basin. Though valuable for inferring general trends, the proxy data from the Lake Gölcük cores preclude its integration with the Maxent model for retrodicting past vegetation conditions because of its spatial uncertainty and indirect proxy nature. Spatially explicit paleoclimate reconstructions were computed instead using a Macrophysical Climate Model (MCM) (Bryson and DeWall 2007), the results of which were then validated against the record from Lake Gölcük.

A top-down Macrophysical Climate Model (MCM) is then applied to modern weather station data to reconstruct the variability in past climatic regimes. The climate reconstruction is then compared with the Maxent models to isolate potential socio-environmental dynamics in the prehistory of the lake basin.

Maximum Entropy Modeling (Maxent)

Maxent, a statistical program that computes maximum entropy probability distributions for use in biogeography (Phillips, Anderson, and Schapire 2006; Elith et al. 2011; Galletti et al. 2013) is used to produce spatially explicit models of modern land-use patterns. Maxent takes data for the presence of a single species or vegetation zone and builds a model quantifying its relationship to a series of background environmental variables. The resulting correlations can then be used to simulate, for instance, the impact of climate change on the potential distribution of vegetation types by extrapolating the statistical model to a different series of climate values.

Model Inputs

The land-cover classes from the reclassified CLC2006 map were used as the main inputs in the Maxent model. Remotely sensed data of this kind are ideal for Maxent modeling because they minimize the potential spatial bias inherent in data collected directly from the field (Phillips, Anderson, and Schapire 2006). The background maps were the elevation, slope, aspect, landform class, soil depth, distance from streams and seasonal drainages, and the January/July temperature and precipitation maps described previously. The land-cover and background variable maps were then collectively sampled at 500,000 random points in order to condense the multiple landscape-scale datasets into a single comma-separated value (CSV) file for importation into the Maxent software.

Model Algorithm

A statistical model that maximizes entropy works under the assumption that the probability that a certain phenomenon (in this case a vegetation community) will be found at a discrete point in space is entirely a function of the average values of each background variable (Phillips, Anderson, and Schapire 2006; Galletti et al. 2013). Once the maximum entropy probability distribution is known, Maxent software develops a model that uses the smallest background variable set that will retain a high entropy value. The model is developed across several iterations using varying groups of training and test data in order to reduce overfitting and to verify the internal accuracy of the model (Phillips, Anderson, and Schapire 2006).

Maxent then assesses the absolute accuracy of the modeled correlations by comparing the results of a model against those computed using a random probability distribution. This analysis results in an "area under the curve" (AUC) value between 0 and 1, where values near 1 suggest a strong positive correlation between the model and the observed distribution, and values near 0.5 suggest the model is no better than random (Elith et al. 2011). Following the "environmental determinism as null hypothesis" approach introduced in Chapter 1, a model with AUC values near 0.5 might suggest that cultural factors play a greater role than environmental parameters in determining the distribution of that particular vegetation type across the landscape.

Maxent is also able to validate and analyze the model by "jackknifing" the results (Elith et al. 2011). Jackknifing is a statistical resampling technique that determines how the modeled results are affected either when one variable is changed with the rest held constant or when one variable alone is used to develop the model. This test not only helps isolate potential correlations between two or more environmental variables, but also allows the sensitivity of specific vegetation communities and land use types to those variables to be determined precisely.

Vegetation Model Results

Grass and Maquis

The Maxent model shows that the presence of grass on the landscape is largely a function of slope and winter precipitation, with 50% of the model's predictive power coming from these two variables alone. Grass is correlated with moderate hills and plains, particularly on slopes steeper than 7° and below 500m in elevation. Its prevalence drops off on slopes above 30°, though it is still much more common than below 7° slopes. It also shows a slight preference for north-facing slopes. Grasses seem to benefit from lower winter precipitation and colder annual temperatures. In interpreting these results it is important to remember that the presence data for grass is derived from remotely sensed data. This introduces a potential bias in that grass can grow in places undetectable by satellite sensors, under tree canopies, for instance. This does not impact the generalizability of these findings, however, as long as they are interpreted as reflecting ecological conditions where other vegetation types cannot grow, and where grass is only free from competition and more visible in general.

Maquis vegetation is negatively correlated with elevations below 300m and above 1000m. Slope preferences are similar to grass, although they are less sensitive to slope overall. Within that range, however, there is neither a strong positive or negative correlation with elevation. Instead, maquis in this elevation range is sensitive to summertime precipitation, seeming to prefer lower summer precipitation and winter temperatures.

Grass and maquis thus have similar geomorphic preferences but differ in climatic sensitivity (Table 2). Maquis in the Marmara Lake Basin favors dry summers while grass favors dry winters. Both favor cooler conditions overall, but maquis would be less negatively impacted than grass by an increase in hotter summers in particular. The grass model in Maxent also has a higher AUC value than the maquis model, which means environmental parameters are better predictors of grass than maquis. This suggests that the distribution of maquis is shaped by human activity, likely the grazing of goats, to a greater extent than grass.

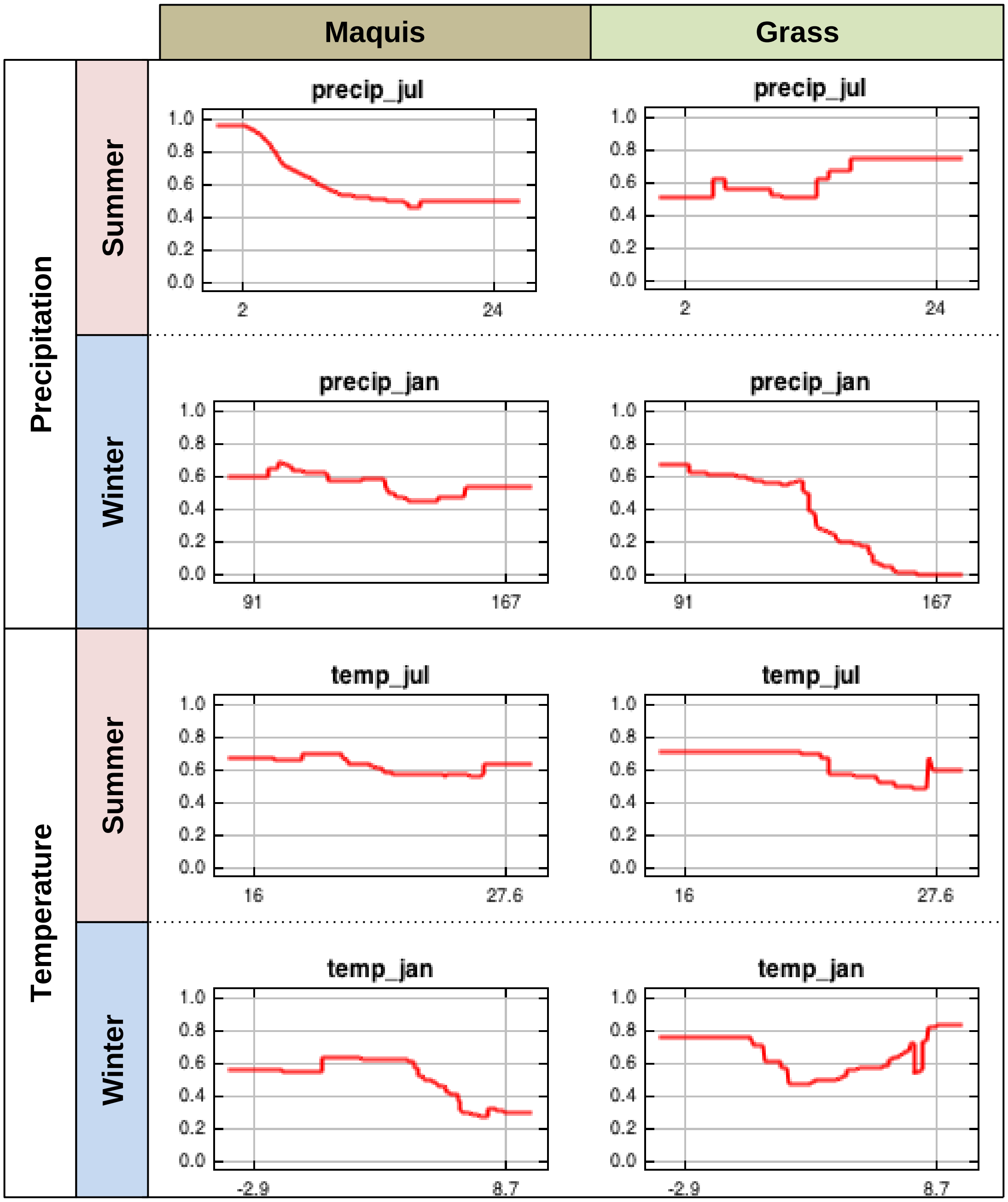

Table 2 Comparison of response to climate variables in the Maxent models for Maquis and Grass. The response curves represent the probability that the vegetation type will be present given different values of the environmental parameter, assuming other parameters remain constant.

Agricultural Land

The model for irrigated agriculture has a high AUC at 0.933, while non-irrigated agriculture has an AUC of 0.724. This may be because irrigation farming fills a more specific ecological niche, in comparison to dry farming. Unlike dryland farming, which is equally prevalent on all slope angles below 15°, irrigated farming exhibits a linearly negative correlation with slope, likely because irrigated farmland requires access to water and flat land for channel networks. Irrigated farming is less likely to occur where there is higher January precipitation, though this might only reflect that wetter areas can be exploited with non-irrigated agriculture instead.

Agricultural land predictably shows a marked negative correlation with slopes greater than 15°. Maxent shows that a good degree of dryland farming is still practiced on some slopes between 15°-20°, however, and expansion of farmland to these steeper slopes might be a feasible means of intensifying production (Figure 20). Cooler summer temperatures also more readily predict the occurrence of

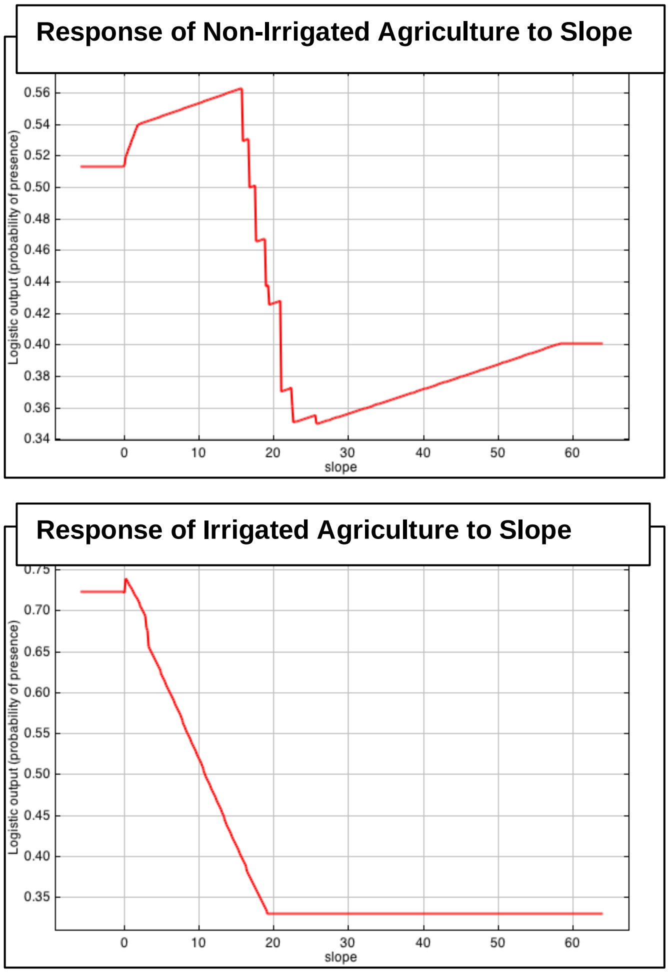

Figure 20 Modeled sensitivity of agricultural land-use types to slope (y-axes are rescaled to better compare the shapes of the response curves).

dryland farming than winter temperatures. The Maxent model for land cover zones that are transitional between agriculture and natural vegetation show far greater similarity to the model for dryland farming than to those for maquis and grass. This suggests that unfarmed plots in these areas result from land-use choices rather than environmental constraints and that farming of this transitional zone might indicate attempts to intensify agricultural production in the lake basin.

Macrophysical Climate Modeling (MCM)

The MCM adopts a “top down” approach using multiple linear regressions to correlate local climatic variables to global circulation patterns, in contrast to the “bottom up” approach employed by General Circulation Models (GCMs) rooted in atmospheric physics (Bryson and DeWall 2007). While admittedly a more synthetic approach to climate modeling, the MCM requires much less computing power and produces models with markedly higher spatial and temporal resolution. MCM outputs nevertheless correlate well with those from GCMs in subtropical latitudes, and the former actually tend to represent climate at higher elevations more accurately than the latter when both are checked against paleoclimate proxy records (Ruter et al. 2004).

Model Inputs

The 30-year climate normal from Salihli, Manisa, Akhisar, and Ödemiş were used as inputs into the MCM. An initial regression-based calibration of the model is required for each weather station, in order to quantify the relationship between local climate and the modern atmospheric circulation. The temperature data can be related to the global latitudinal gradient as-is, but the precipitation regression must first be calibrated by changing the size and latitude of the relevant circulation systems to match the observed precipitation values better. This process of local calibration against point-based inputs allows the model to factor in site-specific accessory variables implicitly, including topography.

Model Algorithm

The MCM uses the principals of synoptic climatology to represent regional climate as a function of the relative positions of the major atmospheric circulation systems. Precipitation in Europe and Central Asia is modeled as a function of the latitudes of the Jet Stream at 0° longitude, the Subtropical High Axis at 0° longitude, and the Cyrenaican High over North Africa (Bryson and DeWall 2007: 159). Temperature is represented by a simple latitudinal gradient. The MCM estimates how these atmospheric variables have changed over the past 40,000 years in response to variations in orbital forcing and volcanism and has been calibrated against multiple paleoclimate proxy records. This allows the local temperature and precipitation values to be extrapolated back to 40,000 years BP at 100-year time steps (Bryson and DeWall 2007).

Paleoclimate Reconstruction Results

The R-squared value of the calibrated precipitation regression, which represents how well the model fits the observed data, showed a high degree of correlation with the Salihli climate data at 0.9987236 (with $R^2 = 1$ representing a perfect fit). In all but one month, the modeled values were within 5mm of the observed values, while those for January and July were much more accurate. Because only the summer and winter values are necessary for understanding annual variability, the higher variance in intermediate months does not impact the model’s generalizability. The temperature regression from the Salihli normals matched the input data with an R-squared value of 0.9842821 and had varied in accuracy between months less than did the precipitation regression.

The reconstructions of past temperature and precipitation around Salihli based on MCM regressions are presented below (Figure 21). Two trends become immediately apparent in the reconstructed precipitation data from the Early Holocene to the present. The first is a long-term decrease in winter precipitation; the second is marked inter-millennial variation in summertime precipitation exhibiting decreasing intensity and increasing periodicity within the last 5,000 years. Modern climate patterns begin after 3,000BP. The patterning in the Holocene climate reconstruction is consistent with the Lake Gölcük sedimentary record, as well as with results of a MCM developed previously for all of Anatolia (Sullivan 1989; Bryson and Bryson 1999).

Though the temperature and precipitation values produced by the MCM regressions may not reflect past climate absolutely, they do represent their variability accurately on both the seasonal and the millennial scale. Conditions in the Middle Holocene (ca. 8200–4200BP) are generally stable after the end of the Younger Dryas cold period around 10,000BP. Precipitation stabilizes first after the Younger Dryas, then temperature approximately 1000 years later. Winter temperatures steadily increase until 5500BP. 5500BP also marks the onset of a period of markedly fluctuating summer precipitation that continues for the next 1,500 years. The beginning of the Late Holocene at 4200BP comes with a drop in summer temperature. Conditions remain generally arid yet stable for the next thousand years despite a slow increase in summer precipitation and decrease in winter precipitation.

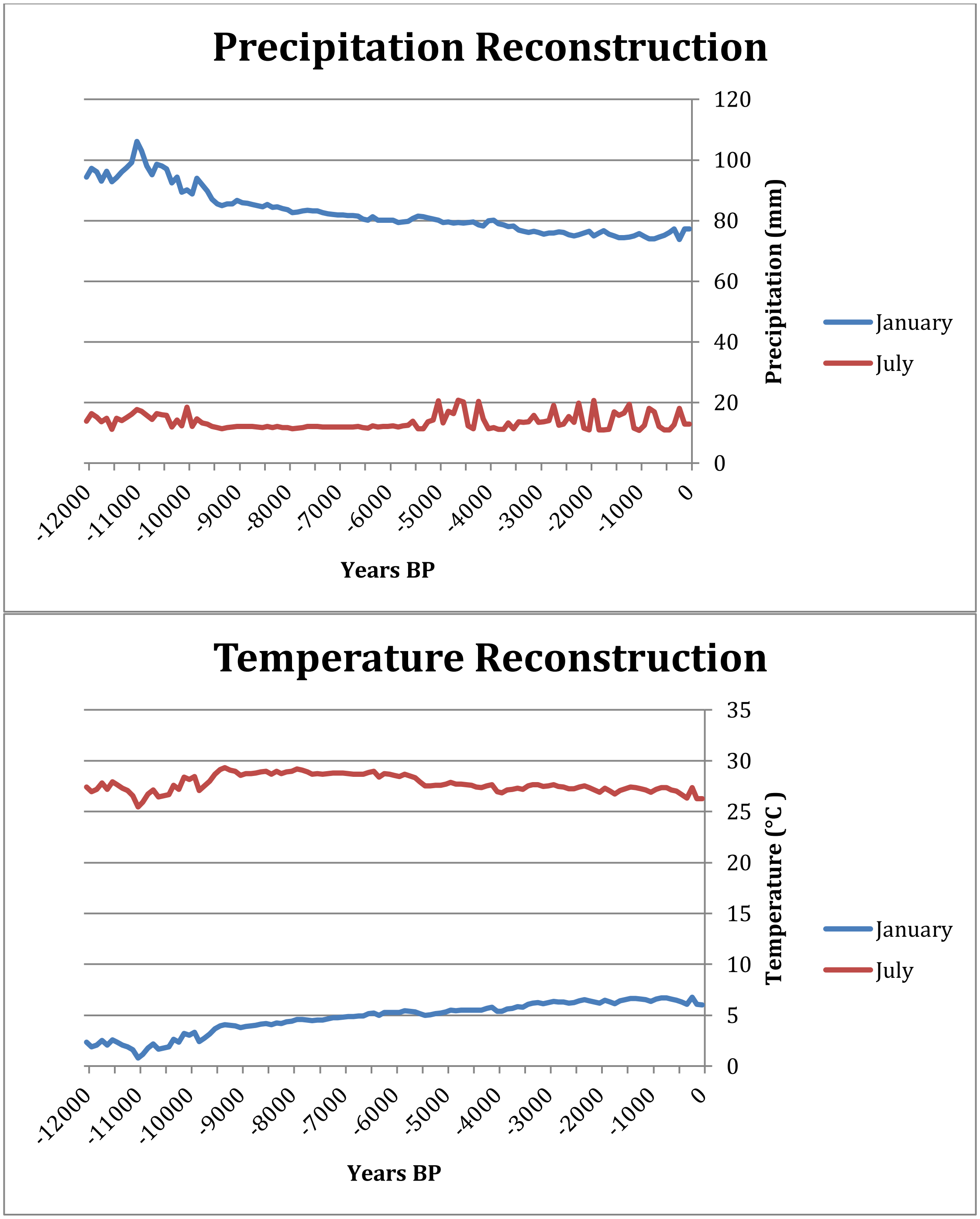

Figure 21 MCM climate reconstructions for January and July.

Summary

The combined results of the MCM and Maxent analyses provide insight into both the timing of past environmental changes and the potential manifestation of those changes within the local environmental of Lake Marmara. The amelioration in climate that began around 9000BP, characterized by sudden decreases in winter precipitation and increases in annual temperature, would favored the expansion of grasslands available for pasture in the foothill zone. The rapidly fluctuating summertime precipitation that characterized the period between 5500BP and 4000BP would have lead to similar variability in the prevalence of maquis stands surrounding the lake at moderate elevations. Higher precipitation during this period would have also made dryland farming more productive in general, while increased flooding in the lowlands and overall instability in the precipitation regime might have been met by the expansion of agricultural activity in foothills, especially on steeper slopes previously left uncultivated.

Chapter 7: Calibration and Validation, Integration and Expansion

“All models are wrong . . .”

In Chapter 1, the simplicity of the models in this study was presented as one of their strengths, allowing each model’s operation to remain transparent and its outputs easily understood. But while simple models remain attractive from an analytical standpoint, they must be tempered with caution concerning potential errors introduced by the selective abstractions made in their development. The omission of certain key variables and parameters from a model has the potential to fundamentally change its behavior in unpredictable ways. A candid assessment of potentially untenable assumptions is important not only for verifying the accuracy of these models, but also for isolating important processes and relationships for future empirical or theoretical exploration.

Dynamic Land Surfaces

The DEM and associated derivatives calculated in Chapter 4 only represent the structure of the modern landscape, but it is improbable that the form of the modern landscape is identical to that from each period of interest. Although it is possible that inherent properties of the soil and bedrock would have prevented significant changes in landscape form, this proposition should be shown empirically rather than simply assumed or argued from circumstantial evidence. The principal of equifinality – whereby distinct processes can lead to the same result – prevents one from simply reversing the erosion model to reconstruct the landscape. For example, the shallow slopes of an area identified by erosion modeling to undergo only moderate erosion today might have been present in antiquity, but are equally likely to reflect a relatively recent stable outcome of millennia of erosion. The development of a reconstructed DEM of the Marmara Lake Basin, from a period in the Late Pleistocene/Early Holocene prior to any significant human presence on the landscape, would help investigate the stability of the landscape.

The construction of such a DEM would require in-field geomorphological survey. Remnants of ancient land surfaces found in the field must first be mapped accurately, and then the heights of associated strata interpolated in a GIS to reconstruct the paleosurfaces from which they were derived. By dating the sediments in these layers, the chronological sequence of different stable surfaces can be determined. The models presented in the chapters above could then be rerun using the new DEM. The modern DEM would then serve as a calibration tool to test how precisely the reconstructions of socially and naturally driven processes of landscape change can recreate the modern topography (Barton et al. 2012).

Sensitivity to Empirical Parameters

The process-based models presented in Chapter 5 involve multiple parameters that should ultimately be derived from empirical measurements made in the field. Secondhand data or regional averages were used in this study where direct field measurements were lacking. The average soil erodibility (K) factor for the eastern Mediterranean was used in the erosion model, for instance, rather than the interpolated results of grain-size analyses from multiple sampling points in the Marmara Lake Basin. In-field calibration of the process-based models is a prerequisite for any future quantitative integration. A lack of empirical groundtruthing makes the potential for unpredictable error propagation in an integrated model unacceptably high.

Sensitivity analysis of existing models can help streamline future model calibration. The sensitivity of a model to any one parameter is largely a property of the model itself, and can thus be quantified regardless of the kind or quality of the data available for input. For the erosion model, a sensitivity analysis may show the model outcome to be highly dependent on initial K values, thus emphasizing the importance of on-site soil surveys; alternatively, it could show that in the unique topography of the study area the impact of soil erodibility is masked by land cover, and that limited time and money available for fieldwork would be better spent quantifying another parameter. Thus, in addition to having an interpretive value unto itself, the simplified modeling approach employed here can also guide, and is arguably a necessary first step to, future fieldwork.

Cultural Steppe

The Maxent model suggested that variability in potential pastures that support grasses or maquis is a primary interface between broad climate changes and everyday land use. But the use of broad vegetation types rather than discrete species or species communities for the model inputs masks a great deal of potential ecosystem interactions. Some varieties of Mediterranean scrub vegetation are actually part of a “cultural steppe” – a partially stable equilibrium response to long term grazing pressures (Butzer 1982: 124–126). For instance, certain species of grass and scrub have thorns and hardened casings indicative of “antipastoral” or “antipyric” adaptations to pressure from herbivores and fire, respectively (Riehl 2006).

It will be important to determine to what degree each zone in the lake basin covered by scrub vegetation reflects primarily cultural impacts rather than natural vegetation growth. An ongoing component of CLAS research involves botanical survey and the creation of a reference collection of plant species in the modern lake basin. The results of that research are intended to supplement archaeobotanical studies from future excavations, but can also be used as inputs into more refined Maxent models. More specific models of modern species distributions can also assist in extrapolating point-based archaeobotanical datasets onto the landscape scale for use in paleoenvironmental reconstructions.

Lacustrine Microclimate

Interpretations of the MCM climate reconstructions presented in Chapter 6 were rooted in the assumption that climate changes were entirely exogenous to landscape-scale environmental changes. In reality, evaporation from the surface of Lake Marmara can create a distinct microclimate where precipitation and temperature changes might be less intense, or lag behind those in surrounding regions (Menotti 1999; Dimitriou and Zacharias 2010). Because the MCM used real-world time series data from the Salihli weather station, the model implicitly accounts for the lacustrine microclimate. That is, Salihli is close enough to Lake Marmara that data from its weather station reflects some of the lake’s moderating effects, as do the climate retrodictions based on them.

The potentially untenable assumption is that the relationship to the lacustrine microclimate to wider climatic regimes has remained constant over time. Because lake levels can change drastically in response to climate variations, and the amount of water in the basin influences the microclimate in turn, there is a nonlinear relationship between regional climate changes and their localized manifestations in the lake basin. Closer examination of modern time-series data of climate and lake level fluctuations will provide a clearer understanding of the feedbacks between Lake Marmara, the microclimate of the lake basin, and the regional climate of western Turkey that will be necessary to fully contextualize the MCM reconstructions in the future.

“. . . but some are useful”

Although each model developed in this study serves as a kind of hypothesis in and of itself, it is nevertheless fruitful to discuss some robust patterns supported by each set of models that relate to the development of agropastoralism in the Marmara Lake Basin. The phrase “all models are wrong, but some are useful” is a common mantra in the modeling community. To the extent that a simple model represents a more objective, formalized version of the a researcher’s mental models and hypotheses, understanding how a model might fail to capture reality allows one to challenge one’s own previous assumptions in an equally objective and formalized manner. In light of the assumptions discussed above, none of these models should be considered as an exact reconstruction or explicit evidence for past dynamics *per se*, but like any hypothesis they serve as a guide for further data collection and a tool for quickly processing new information as it becomes apparent. The utility of a model goes beyond organizing and interpreting existing data, however, these hypotheses will be indispensible for focusing and expanding the suite of environmental models in the future.

Model-Based Hypotheses

Comparisons to Neolithic sites in Anatolia, particularly the evidence from Çatalhöyük discussed in Chapter 3, suggest that Neolithic settlements around Lake Marmara were located either on the shores of the lake itself or in the nearby wetlands. The relative stability of Early Holocene climates attested by the MCM explains how such settlements could survive and potentially prosper: the risk of catastrophic floods and droughts was simply less than in later periods. Stable lake levels might also have reduced the intensity of regional climate change, as manifested in the lake basin. But the hypothesized location of Neolithic settlements here is difficult to falsify, because if true they are buried below several meters of alluvium. Pollen sequences from the lake are an alternative source of potential evidence, as they might record the clearing of forests and expansion of steppe land associated with the land use practices of those deeply-buried sites.

The climatic variability that the MCM suggests began in the Middle Holocene would have led to much more pronounced changes in lake levels. The unpredictability of lake level fluctuations and their potentially destructive impacts likely made the lakeside settlements of the Neolithic unsustainable in the Chalcolithic and Early Bronze Ages. This would explain why the archaeologically attested settlement patterns from these periods center on the margins of the lowland hills, above which even drastic fluctuations in water levels could not reach.

The variability in the quality of lowland fields would also have favored risk-buffering agropastoral strategies involving expansion of dryland farming onto Bin Tepe and pastureland into the moderate upland hills in a process of small-scale transhumance. Outbreaks of malaria caused by the poorly drained wetlands might also have favored some degree of seasonal mobility. Because the Maxent modeling showed that maquis vegetation communities are particularly sensitive to the kind of variability in summertime precipitation that characterizes this period, it is possible that the resulting growth of maquis communities led to an increase in the dependence on goats, which browse maquis, in comparison to sheep, which graze on grass. Less clear is how the herders who grazed their flocks on Bin Tepe and other low hilly land would have responded to the expansion of dryland farming into these zones.

Though able to adapt in the short term, agropastoral economies would have been vulnerable to sudden restructuring in response to the varied climatic regimes of the Middle Holocene (Wilkinson 1997). The settlement shift attested archaeologically at the end of the Early Bronze Age may reflect this vulnerability in distributed agropastoral systems. The comparative archaeological evidence for the Middle and Late Bronze Ages from Chapter 3 suggests that increased social complexity during these periods was reflected in more top-down economic control, increasing differentiation between agricultural and pastoral production, and increased reliance on regional trade networks. Growing requirements for surplus livestock for trade and sacrifice on an institutional scale may have begun to overshadow purely environmental factors in the structuring of agropastoral land use. The construction of hilltop citadels during this period is consistent with that hypothesis, as they would have maximized access to upland pasture zones while opening up lower elevations to intensive cultivation. The climate during this period was relatively stable in the short term, but the longer-term cycle of change on the millennial scale would have resulted in these land use practices being unsustainable in the long term. Geomorphologic evidence for accelerated soil erosion in the uplands at the end of the Late Bronze Age might be one signal of such maladaptive land use practices.

Modeling Complexity in Agropastoral Systems

While linear narratives like the hypotheses presented above may be more satisfying and easily understood explanations, they fail to capture the full complexity of reality. The human mind simply cannot conceptualize the full scope of interactions between units in even a moderately complex system, making it nearly impossible for one to understand intuitively how a complex system operates (Sterman 2002). One example is the debate in archaeology over the “collapse” of civilizations, where different researchers propose different linear narratives (e.g. forest clearance > erosion > collapse; climate change > erosion > collapse) that although accurate in their own domain, fail to capture the entirety of the problem. Because the hypotheses presented above are such a narrative, qualitative integration of the model outputs, they are subject to the same restrictions. Even if they are not technically false, they cannot capture the full complexity of agropastoral land use in the Marmara Lake Basin.

The long term patterning of agropastoral land use arises from the complex interaction of environmental and ecological variables and the culturally constrained strategies of herd managers (Danti 2000; Janssen, Anderies, and Walker 2004; McAllister et al. 2006). These variables include climatic controls on the extent and productivity of pasture, the impact of predators and competition with similarly adapted animals, and the timing and rate of births and deaths in a population. Though herders can respond directly to these challenges, for instance by adjusting the timing of foddering to delay the annual birth cycle in drought years, social norms, such as a taboo against using certain parcels of land for pasture, can also structure these management decisions.

These interactions are not unidirectional, however, because what began as a functionally arbitrary restriction against using one of two similar pasturelands might over centuries result in tangible differences in the relative quality of each parcel of pastureland that, in turn, can influence environmental and ecological processes in ways that ultimately reify or change cultural norms (*c.f.* Hammer 2012). These nonlinear feedbacks are characteristic features of coupled social and natural systems (Liu et al. 2007).

Complex, nonlinear evolutionary dynamics have been shown to drive both changes in the physical landscape (Turcotte 1997; Dearing and Zolitschka 1999; Phillips 2006; Wiel and Coulthard 2010) as well as the human societies that operate on it (Boyd and Richerson 1985; Shennan 2002; Tehrani and Collard 2002; Matthews et al. 2011). The interaction between human societies and the natural environment can, in turn, be understood as a complex adaptive system, because the behavior of the whole system emerges from the coevolution of its multiple constituent parts (Janssen 1998; Liu et al. 2007).

To capture the complexity of these systems and move beyond linear narratives, some form of direct, quantitative integration is needed. This would require connecting the inputs and outputs of the models and allowing new dynamics to emerge as a natural, but not easily intuited, result of their interaction.

Dynamic Hydrological Models of Lake Level Fluctuations

A dynamic hydrological model of Lake Marmara would be one potential method of integrating the models developed in this study. A lake-level model requires data about flux in and flux out of the basin. The absolute flux of water into the lake could be derived from the MCM reconstructions as a function of precipitation both over the lake itself and across the lake's catchment. Precipitation would accumulate where modeled in Chapter 5, but would do so more realistically than the model in Chapter 5 because it would be determined by the actual availability of water rather than arbitrary depth cutoffs. The potential depth of water accumulation in those areas could be determined by recording the depth contours of stream drainages along GPS transect perpendicular to direction of flow. Maxent-derived land cover maps as well data on the impact of different soil types on potential infiltration could also influence the movement of water into Lake Marmara. Flux out of the lake would be a function of withdrawals of water through stream drainages and canals as well as evaporation values computed from the MCM reconstruction.

Agent Based Simulations of Agropastoral Land Use

Regardless of the complexity and attention to detail, environmental models will only vaguely approximate real-world environmental systems if they do not directly address the human presence on the landscape. Agent-based simulations are the primary methodological tool for modeling multicomponent systems that involve human decision making (Janssen 1998; Barton et al. 2012). In an agent-based model, multiple discrete agents (individuals, houses, villages) programmed with particular goals and behaviors are allowed to freely interact with each other and their environment to attain those goals. Long-term cultural and natural processes are thus allowed to emerge naturally from the behavior of individual social units.

An agent-based model of agropastoral land use around Lake Marmara could be designed to simulate contrasting human responses to the environments of the Early, Middle, and Late Holocene. Programming agents to remain within the areas of the landscape hypothesized to have been the focus of land use in each period would allow for testing of the hypotheses described above. For example, a model of Neolithic land use would examine what population-level patterns emerge when simplified representations of herders and farmers are seeded on the landscape in the hills and lowlands, respectively, and allowed to react freely to dynamic lake levels and climatically driven vegetation changes. These simulated agropastoral landscapes can then be compared to ongoing archaeological and paleoenvironmental research in the lake basin. The goal, in essence, will be to "grow" those complex social and environmental dynamics attested archaeology from a series of simpler starting conditions.

For archaeologists investigating long-term human-environment interactions on a landscape scale, these kinds of integrated social and natural simulations can provide much more robust explanations of change than can either strict environmental determinism or synthetic historical narratives, both of which depend on equally linear conceptions of causality. The strength of such an integrated modeling approach would be in its ability to simulate the dynamic responses of past societies to a complex network of environmental interactions, allowing hypotheses concerning the interaction of multiple environmental cycles to be more fully and rigorously explored.

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