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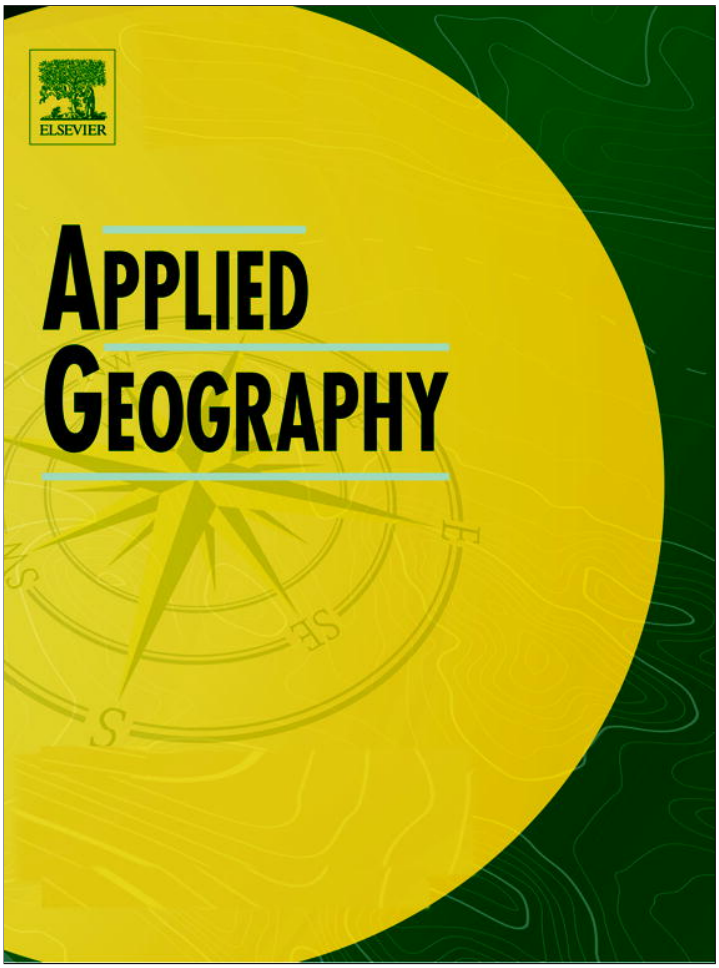

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Maxent modeling of ancient and modern agricultural terraces in the Troodos foothills, Cyprus

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A B S T R A C T

Terracing is a basic component of agricultural land use systems across multiple landscapes and time periods. This study develops a predictive model using the environmental variables that differentiate ancient and modern terrace locations in the foothills of the Troodos Mountains, Cyprus. Model development utilized the maximum entropy principle as applied by Maxent software to estimate probability distributions for both terrace types across geographical space based upon presence-only observations and environmental variables. The Maxent models are effective in predicting potential terrace distributions and reveal systematic differences between ancient and modern terrace arrays in the study area. Surface geology played a key role in predicting ancient terrace locations, but contributed much less substantially in modeling modern terraces, whose locations were influenced strongly by topography. Maxent modeling is shown to be effective in assessing environmental constraints and terrace locations, providing a method that can be used by physical geographers and archaeologists for modeling human–environment interactions in agrarian societies.

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Introduction

Agricultural terraces form basic elements of land use and food production technology over the millennia since the advent of agriculture, particularly in arid and semi-arid regions of the world (Barker, Gilbertson, & Mattingly, 2007; Spencer & Hale, 1961; Wilkinson, 2003). Geographers and archaeologists share acute interests in terracing as a formidable means of human landscape modification and agricultural intensification, with particular attention to the environmental characteristics that influence terrace construction and configuration (Rackham & Moody, 1996; Sandor & Eash, 1991; Treacy & Denevan, 1994). Physical geographers play an important role in developing an understanding of agricultural land use (e.g. Mannion, 1999) and terracing by producing models that define the spatial distribution of land systems associated with terraces and archaeological phenomena (e.g. Vaughn & Crawford, 2009). While terrace walls themselves are notably difficult to date in isolation (Price & Nixon, 2005; Rackham & Moody, 1996), terrace agriculture is a long-standing characteristic feature of modern and pre-modern Mediterranean landscapes (Bevan & Conolly, 2011). In archaeological investigations, the environmental modeling of terraces can play a critical role in inferring land use history, and larger economic and demographic characteristics of agrarian societies.

On the island of Cyprus, terracing is an important facet of land use both today and in antiquity. The locations of terraces are associated with buried archeological sites across Cyprus and offer a promising way of studying ancient land use and potentially isolating important archaeological sites. Modern terraces are also spread widely across this landscape, sometimes masking the presence of ancient terraces. Generally, structural differences, environmental context and active use of the terrace soil can be used to differentiate modern and ancient terraces, but this approach requires intensive survey of the landscape. The research presented here merges principles of biogeography and landscape archeology to produce a predictive framework to distinguish distributions of ancient and modern terraces across geographic space. Toward that end, this study models the locations and environmental parameters of agricultural terraces in the Troodos foothills of Cyprus using maximum entropy methods. By identifying the environmental context for ancient and modern terraces, future survey design and sampling of Cypriot and other landscapes may be optimized to

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guide intensive follow up studies of terraces and associated archaeological features, thereby permitting inference of broader land use patterns.

Background and methods

Agricultural terracing around the Mediterranean

Agricultural systems in regions such as the Mediterranean basin and Middle East commonly utilize hillside terrace walls to conserve pockets of arable soil, restrain erosion and retain limited rainfall runoff (Rackham & Moody, 1996; Treacy & Denevan, 1994). These technological features enable long-term agriculture in locales notable for their denuded natural vegetation, erosion-prone sediments and sporadic rainfall (Sandor & Eash, 1991). Thus, agricultural terraces provide enduring and readily visible indicators of long-term agricultural systems amid the distinctly anthropogenic landscapes of the Mediterranean basin.

Terraced field systems have been hallmarks of intensified agricultural production since the domestication of orchard crops (most importantly, olive and grape) and the development of Bronze Age mercantile economies in southwestern Asia roughly 5000 years ago (Barker et al., 2007; Levy & Alon, 1987; Wilkinson, 2003, pp. 135–136). The island of Cyprus features the same environmental characteristics that necessitate agricultural terracing on the nearby mainland. Bronze Age urbanization and accompanying agricultural intensification, although appearing somewhat later than in neighboring regions, engendered widespread terracing in the island's interior (e.g., Fall et al., 2012; Given & Knapp, 2003, p. 30). This study is inspired by the lengthy history and abundant evidence of agrarian settlement and land use in the arable foothills of the Troodos Mountains, which provide the backdrop for modeling ancient and modern agricultural terracing in the heart of Cyprus.

Study area and research aims

The island of Cyprus is characterized by intermittent seasonal rainfall and hilly topography, both of which are conducive to terraced hillside cultivation (e.g., Rackham & Moody, 1996: 140–142; Wilkinson, 2003: 186–202). Although woodlands persisted later on Cyprus than on contemporaneous ancient Near Eastern landscapes (Klinge & Fall, 2010), agricultural intensification beginning at least as early as the Bronze Age (ca. 2500–1000 BC) placed a premium on terrace wall retention of local rainfall and shallow soils. The region of Cyprus considered for analysis centers on the agricultural landscape surrounding the ancient communities of Bronze Age Politiko-*Troullia* and Iron Age Tamassos, covering approximately 23.5 km^2 nestled in the foothills of the Troodos Mountains, about 20 km southwest of Nicosia (NW corner: 35.04212°N, 33.21656°E; SE corner: 34.99879°N, 33.26918°E; Fig. 1). The study area ranges from 332 m to 519 m in elevation, and straddles a border shared by the Nicosia, Pakna and Upper Pillow Lava geological formations. Here archaeological and historical evidence documents a legacy of settlement and agriculture spanning roughly 8000 years from the Neolithic to the present (Buchholz & Untiedt, 1996; Falconer, Fall, Horowitz, & Hunt, 2005; Fall et al., 2008; Given & Knapp, 2003). Detailed spatial data on terrace configurations, environmental contexts and estimated ages (Fall et al., 2012) provide the empirical basis for this study.

The terrace walls in our study area share many fundamental characteristics, but also vary systematically. Among common attributes, all walls incorporate dry, unmortared, single-row stone construction. Only three walls, all on the slopes adjacent to Politiko-*Troullia*, appear to have been reinforced with secondary stone alignments. A field survey of nearly 200 terrace walls in the study area documented agricultural terraces varying from unwalled terraced fields created by modern bulldozing to premodern walls

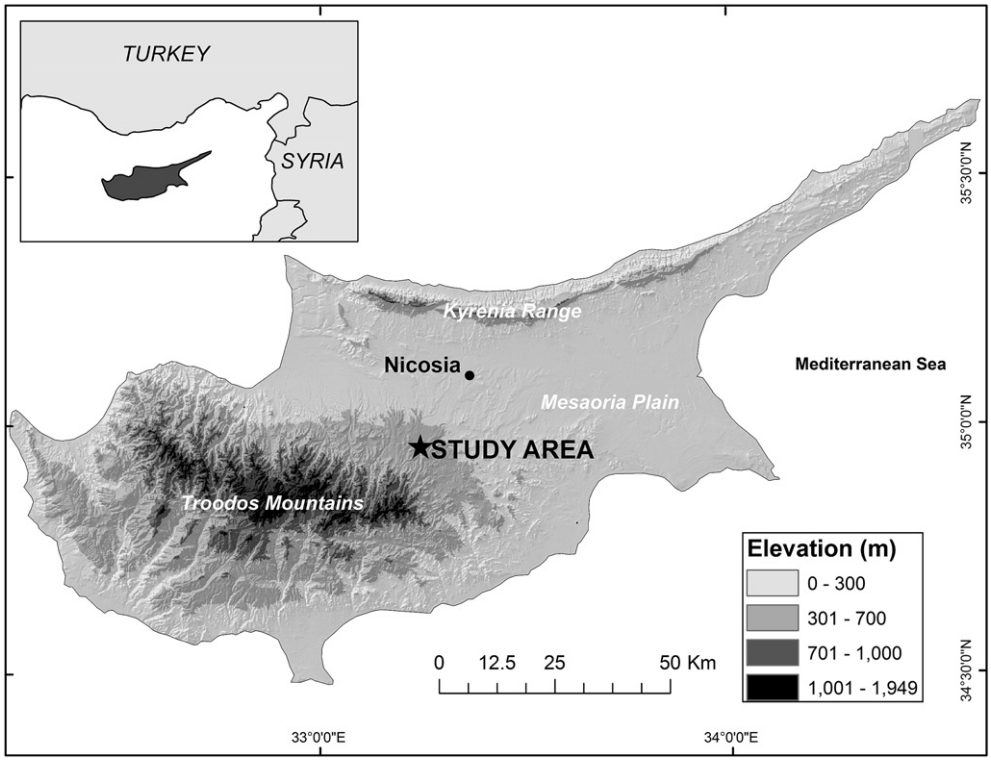

Fig. 1. Map showing the location of the study area in the Troodos foothills on the island of Cyprus in the eastern Mediterranean.

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sometimes chinked with limestone cobbles, Medieval roof tile fragments or Bronze Age pottery sherds (see discussion in Fall et al., 2012). Using a similar approach based on stratified potsherds and the proximity of ancient settlements, Rackham and Moody (1996) infer Bronze Age (Middle Minoan) construction of terrace walls on Crete.

The terrace walls around Politiko-*Troullia*, Cyprus range from eroded alignments several meters long to lengthy continuous stretches more than 50 m in length. Collectively, terrace walls provide the key technological features for soil and water conservation on the long-term agrarian landscape around ancient Politiko-*Troullia* and Tamassos. In this setting, we apply maximum entropy methods, utilizing the Maxent software package,[1] to infer a) the systematic distinctions between the predictive models for ancient and modern terrace locations, and b) the environmental parameters most influential in modeling ancient and modern terrace locations. This approach may be used to guide future archaeological surveys based on geographical parameters for the location of ancient terraces, and offer new insight into the environmental distributions of both ancient and modern terraces.

Maximum entropy modeling

The machine learning community has made great strides in developing algorithms that generate predictive models with high generalizability. For example, Menze and Ur (2012) use a machine learning algorithm (random forests) to predict the presence of ancient settlements across northern Mesopotamia. Their study utilizes environmental attributes such as anthrosols and hydrology to model the locations of archaeological sites that otherwise would be difficult to survey on the ground. Our approach also incorporates a machine learning algorithm, in this case based on the principle of maximum entropy (e.g., Berger, Pietra, & Pietra, 1996; Dudík, Phillips, & Schapire, 2007).

The principle of maximum entropy figures prominently in a number of diverse fields ranging from ecology (Harte, 2011) to urban modeling (Batty, 2010; Wilson, 2010). The principle states that the estimate of the subject probability distribution should be based on known constraints as expressed by an expected value, but the distribution also should be as close to uniform as possible to avoid being biased. This application of maximum entropy has its origins in information theory (Shannon, 1948) and is incorporated commonly in a Bayesian framework (Jaynes, 1957, 2003), where inference using probability distributions requires a prior distribution to represent our current state of knowledge, preferably without being biased. Our approach, as applied by the machine learning community, uses this general principle to predict spatial distributions of a chosen phenomenon (e.g., biotic species, agricultural terraces) by relating presence data to environmental predictors (our known constraints). Distribution modeling commonly utilizes presence/absence or abundance data, but some spatial sampling methods (e.g., archaeological surveys of agricultural features, such as terraces) tend to generate presence-only data, for which the application of maximum entropy methods has proven particularly advantageous (e.g., Elith et al., 2006). The use of maximum entropy approaches across many disciplines may be attributed to the broad applicability of maximum entropy as a concept:

> The mere fact that the same mathematical expression occurs both in statistical mechanics and information theory does not in itself establish any *connection between these fields*. This can be done only by finding new viewpoints from which thermodynamic entropy and information-theory entropy appear as the same *concept* (Jaynes, 1957: 621; emphasis in the original).

In our application, maximum entropy is utilized because it "minimizes the relative entropy between two probability densities (one estimated from the presence data and one from the landscape)" (Elith et al., 2011: 43). We adopt the approach applied in ecology whereby the maximum entropy principle is employed within the Maxent platform to model the distribution of flora and fauna from environmental data in species distribution models (SDMs). SDMs often link the presence of a species with environmental data at its observed locations (i.e., environmental covariates) to generate predictive models of potential species occurrence and spatial patterning within a study area (e.g., Deblauwe, Barbier, Couteron, Lejeune, & Bogaert, 2008; Elith et al., 2006; Kumar & Stohlgren, 2009). This approach allows us to infer terrace location probabilities by linking data on the presence of agricultural terraces with environmental data from their landscapes.

The appeal of the Maxent platform (hereafter Maxent) lies in its ability to create complex models from presence-only data with low sample sizes while adhering to the principle of maximum entropy (Dudík et al., 2007; Phillips, Anderson, & Schapire, 2006; Phillips & Dudık, 2008, Phillips, Dudík, & Schapire, 2004). To distinguish the distribution of environmental covariates at terrace locations from the probability distribution of environmental covariates across the landscape, our presence-only observations are augmented with pseudo-absence data drawn from the landscape through random sampling of additional points in the study area. Maxent forms prior probability distributions from background data (rather than from true absence data) and terrace presence data across many covariates. Thus, our goal is to elicit the strongest possible distinction between the environmental contexts of our terraces and those of the randomly sampled background environment. Maxent software utilizes a predictive algorithm to maximize the entropy of the observed sample distribution (i.e., terrace locations), maximize the distribution of the background sample, and *minimize the relative entropy* of the ratio between these two distributions (Elith et al., 2011). The modeling outputs include assessments of model performance, tabulated contributions of each covariate to the models, and mapped probabilities of terracing at each pixel in the study area (the logistic output).

Terrace data

Our ground reconnaissance included visits to both ancient and modern terraces across the study area. Ancient terraces, particularly those on the hill slopes adjacent to Politiko-*Troullia*, were distinguished by abundant associated archaeological remains (e.g., Bronze Age potsherds, Medieval roof tiles) and weathered, sometimes-collapsed stone masonry (Fall et al., 2012). Despite the antiquity of settlement and agriculture in central Cyprus, ancient terraces are far from ubiquitous, and modern terraced fields may be distinguished readily. For instance, our survey coverage included roughly 100 ha west, south, east and northeast of Politiko-*Troullia* in which no ancient terraces or pre-modern artifacts were identified. In contrast to their ancient counterparts, modern terraces showed signs of current or recent agrarian use, including more freshly cut, intact stonework, association with plowed fields and modern material culture (e.g., 55 gallon oil drums), and lacked pre-modern archaeological remains. Once these distinctions were established on the ground, pronounced architectural integrity and immediately adjacent cleared field plots made the modern terraces readily discernible both on the ground and through remote sensing.

Archaeological survey in the countryside surrounding Bronze Age Politiko-*Troullia* utilized a hand-held GPS unit to record the latitude,

[1] http://www.cs.princeton.edu/~schapire/maxent/

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longitude and elevation at end points and wall faces of 168 ancient terrace walls in the study area (Fall et al., 2012, Fig. 2). This pedestrian survey further documented the present condition and spatial relationship of each terrace wall. Subsequent data processing with ArcGIS permitted judicious merging of partial or eroded wall segments. These walls, constructed with unmortared, single-row stone masonry, sometimes incorporate ancient potsherds or roof tile fragments, and are founded on bedrock or sediments immediately above bedrock. Modern terrace latitude, longitude and elevation were obtained from QuickBird (2003) imagery by scanning for the indicators of modern terracing (i.e., visually defined fields and field boundaries), resulting in the identification of 28 modern terraced fields.

To minimize the differences in survey strategies – pedestrian survey for ancient terraces vs. imagery analysis for modern terraces – a bias grid was incorporated in our Maxent modeling. The bias grid identifies areas surveyed or most likely to have been surveyed and replaces the Maxent default of a randomly selected background sample, thus minimizing any sample selection bias, as the same bias is present for both terrace observations and background sample points (Appendix A). Because the pedestrian survey covered more limited portions of the study area and is a non-random sample, the bias grid was used for modeling the ancient terraces so that measurements of our environmental covariates accommodate the biases of our pedestrian survey sampling (see Fall et al., 2012 for sampling strategy; bias grid use following Phillips et al., 2009). The bias grid was not applied to the modern terrace models as terrace locations had equal probability of selection across the entire study area based on QuickBird imagery.

Environmental covariates

Several noteworthy studies deduce a suite of key factors that influence terrace construction, relating to geology and physiography, soil management, moisture retention, erosion control and microclimate regulation (e.g., Bevan & Conolly, 2011; Frederick & Krahtopoulou, 2000; Treacy & Denevan, 1994). In light of these inferences, we selected a series of variables to define or measure these properties in our study area (Table 1). These variables can be quantified from GIS datasets or satellite imagery, and each merits a brief description.

Elevation (DEM in Table 1). Elevation is measured across a continuous surface, according to height above sea level, as modeled by NASA ASTER imagery (Advanced Spaceborne Thermal Emission and Reflection Radiometer) in the form of a Digital Elevation Model (DEM).

Spring vegetation (SprSAVI). Spring vegetation was documented by IKONOS satellite imagery taken in April 2010 at 3.2 m resolution. We quantified vegetation by using the Soil-Adjusted Vegetation

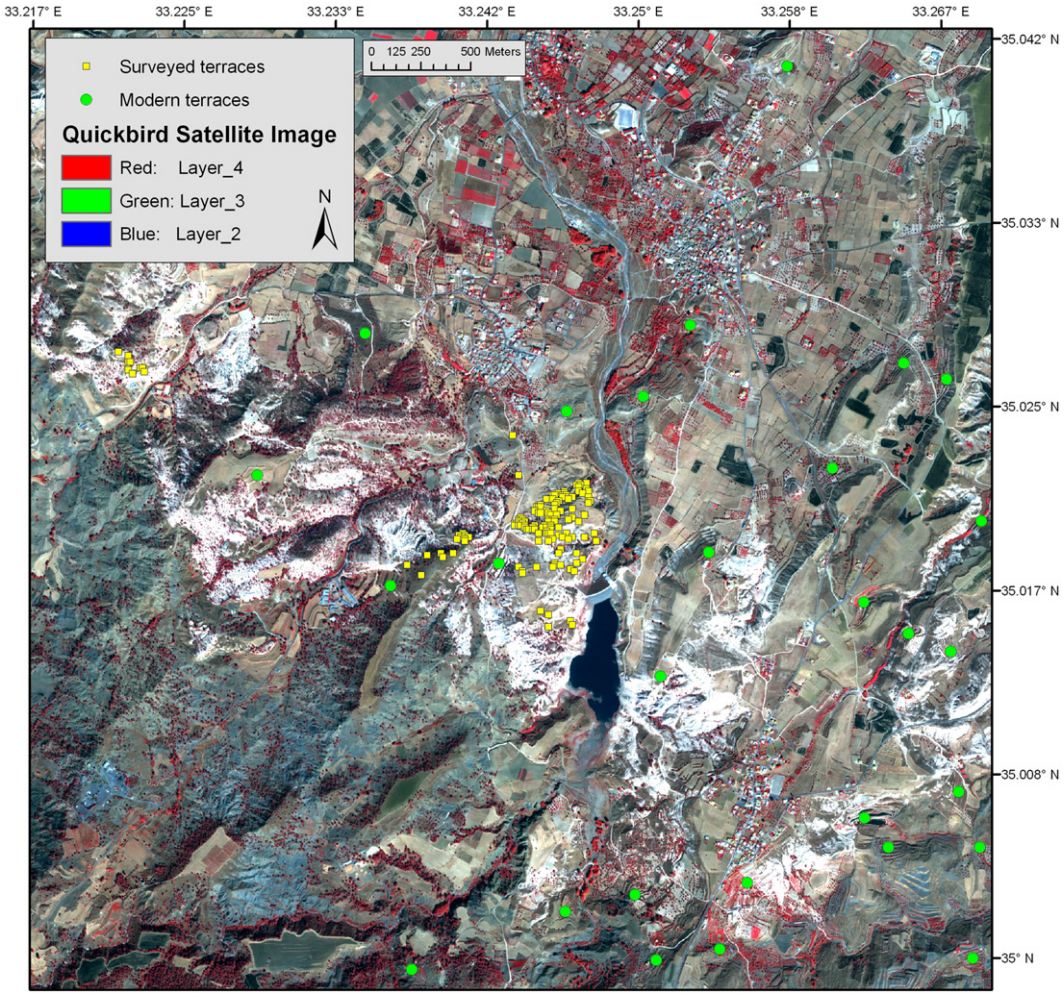

Fig. 2. QuickBird image of the study area in the Troodos foothills of Cyprus, showing locations of ancient terraces documented by archaeological survey and modern terraces inferred from QuickBird imagery. The QuickBird image is a false color composite that accentuates the biophysical features of the landscape shown in the photo, particularly vegetation. The near infrared band of the QuickBird data is set to red, the red band is set to green, and the green band is set to blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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Table 1
Environmental covariates used for maxent modeling of predicted ancient and modern terrace locations in the Troodos foothills, Cyprus.

Variable	Variable description
Calc	Calcareous; distance to nearest pixel classified as calcareous
Plava	Pillow lava; distance to nearest pixel classified as pillow lava
Stream	Stream; distance to nearest pixels with a calculated flow accumulation of 1000+ pixels
DEM	Elevation in meters; derived from ASTER satellite
Slope	Degree difference of a pixel to three surrounding pixels; derived from the DEM
Temp	Surface temperature; derived from Landsat TM band 6 (thermal infrared)
SprSAVI	SAVI (Soil Adjusted Vegetation Index); derived from Ikonos imagery dated April 2010
Albedo	Surface energy balance as a ratio of downwelling irradiance to upwelling
FallSAVI	SAVI (Soil Adjusted Vegetation Index); derived from QuickBird imagery dated October 2003
Rad	Radiation calculated from DEM; estimated radiation received as the sun travels overhead on a per-pixel basis

Index (SAVI; Huete, 1988), a modified version of the Normalized Difference Vegetation Index (NDVI), which reduces the impact of soil reflectance in arid, sparsely vegetated landscapes, like those of Cyprus. Both SAVI and NDVI measure photosynthetic activity and, thus, vegetation growth in the months following the winter rainy season. Indices of spring vegetation provide proxy measures of the erosion control and soil retention properties of terraces, in some cases despite their apparent long-term disuse. Active spring vegetation is likely to include annual taxa (including crop species), as well as perennials (including orchards and other trees).

Fall vegetation (FallSAVI). Autumn vegetation was assessed similarly, using SAVI derived from QuickBird satellite imagery captured in October 2003 at 2.4 m resolution. Measurement of fall vegetation again provides an indication of growing plants, this time during the months following the summer dry season. Thus, QuickBird SAVI is particularly appropriate for assessing moisture retention by terraces, which permits the growth of perennial taxa (e.g., orchards and other trees) that are suited to survive the dry months of the year.

Distance to nearest calcareous sediments (Calc). Exposed calcareous sediments in central Cyprus derive from Cretaceous/Tertiary limestone and chalky deposits. QuickBird imagery permits mapping of calcareous units; measurement of distance to these units was calculated using Euclidean distance in GIS. Since limestone and other carbonate geology carry high erosion coefficients (Amiri, 2010), this distance variable relates to geology, soil management and erosion control.

Distance to nearest major stream (Stream). Stream networks were modeled using an ASTER DEM where a conditional function filtered out all pixels with less than 1000 pixels of flow accumulation, leaving the remaining pixels to approximate stream channels in the study area (Conolly & Lake, 2006: 258–262). This variable, which relates to physiography and water management, is measured using Euclidean distance.

Slope (Slope). Measurements of slope were calculated from the ASTER DEM and expressed in degrees of vertical incline/decline. These measurements capture a critical physiographic variable and relate to the necessity of initial terrace construction to avoid loss of soil and moisture. Due to the mechanization of agriculture over time, it is expected that modern terracing is found across a wider range of slope values, and most particularly in areas of steeper slope angles.

Albedo (Albedo). Landsat imagery (taken August 2010) was converted to reflectance, and albedo values were calculated using weighted reflectance bands, as outlined in Allen, Tasumi, and Trezza (2007). Albedo, which measures reflected surface radiation, is linked to microclimate regulation and constitutes an important variable for assessing ecosystem functioning.

Radiation (Rad). This measurement of solar radiation is calculated from latitude and exposure to the sun, based on an ASTER DEM. Since excessive radiation can desiccate agricultural soils, while insufficient sunlight can impede photosynthesis, this variable affects potential agricultural productivity.

Distance to nearest pillow lava (Plava). Pillow lava units in the Troodos Mountain foothills represent ancient underwater lava extrusions that are erosion resistant and correlated with high-quality copper deposits (Sinclair, 1995). Pillow lavas in the study area were plotted from geologic maps and QuickBird imagery, and distances were measured as Euclidean distance to the nearest raster cells with surface geology designated as pillow lava.

Temperature (Temp). Surface temperature was estimated from an August 2010 Landsat TM image, based on the sixth band (thermal infrared), using Idrisi Taiga. Temperature has been interpreted as an important indicator of microclimate regulation associated with agricultural terrace construction (Treacy & Denevan, 1994).

Data preparation

Data for these environmental covariates were assembled into grids (or rasters) of values for each variable: a locational grid utilizing data at terrace locations and a predictor grid based on data drawn from background locations across the study area. Prior to analysis in Maxent, all locational and predictor grids were clipped to the same geographic extent and interpolated to a ten-meter pixel resolution. Maxent requires that all rasters have the same pixel size. A ten-meter pixel was used to retain the variability of the vegetation captured using high-resolution imagery. There was initial concern about re-sampling some data (ASTER DEM) to ten-meter pixels, however hydrology covariates showed generally good agreement with known streams as observed in high resolution imagery. As a means to reduce sampling and autocorrelation bias among the terrace sampling points, only one point per ten-meter pixel was used for model building and evaluation (following Webber et al., 2011). A (Pearson) correlation matrix of the covariates suggests most of the environmental variables were not correlated significantly, with a few covariates exceeding a correlation coefficient of 0.4 (Table 2). In similar modeling projects, highly correlated values often are pruned from sets of potential environmental variables or, at a minimum, their results are interpreted with caution. However, Elith et al. (2011) found that even in the presence of correlated variables Maxent performs better than most other modeling methods, thus all described covariates were retained for the final model.

Model building

The default settings for Maxent software have been fine-tuned and validated over a range of species, environmental data, sample sizes and differing sample selection biases, allowing the creation of robust models for many types of presence-only datasets (Phillips & Dudık, 2008). These default settings for the Maxent software were employed for building both the ancient and modern terrace models with the following adaptations:

1. Response curves were created to evaluate each model's performance in relationship to each environmental variable.
2. Jackknifing was used to evaluate the relative importance of each environmental variable. Maxent trained each model, first with each environmental variable omitted, and then with each environmental variable as the sole variable, to determine each variable's relative contribution to model construction.

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Table 2
Correlation coefficients for environmental covariates used in predictive modeling of terrace locations.

	Plava	QB100	Rad	Slope	Stream	Temp	IK100	DEM	Calc	Alb
Plava	1.00	−0.05	0.14	−0.33	0.02	0.14	0.16	−0.69	0.32	0.14
QB100		1.00	−0.04	−0.04	−0.10	−0.11	0.46	−0.01	0.03	−0.11
Rad			1.00	−0.59	0.22	0.39	−0.02	0.10	0.13	0.23
Slope				1.00	0.14	−0.24	−0.21	0.35	−0.26	−0.11
Stream					1.00	0.10	−0.20	0.35	−0.07	0.06
Temp						1.00	0.01	−0.06	0.19	−0.01
IK100							1.00	−0.22	0.19	−0.11
DEM								1.00	−0.18	−0.19
Calc									1.00	−0.30
Alb										1.00

3. Ten replicates for each ancient terrace model and ten replicates for each modern terrace model were run with cross-validation to examine the variability possible in model building.
4. With each run, a different random seed was selected. Thus, with each model replicate, the sample data were divided randomly into different partitions for training and testing, and different random subsets of background samples were selected.
5. All samples were added to the background, allowing for their potential selection as random background points in addition to their availability as points for training or testing. Phillips and Dudık (2008) found that simply adding the data for observed sample locations to the background data raised model performance.

Model performance

Area Under the Curve. The receiver-operating characteristic (ROC) plot's area under the curve (AUC) is a threshold-independent measure of model prediction accuracy. The AUC of the ROC plot is constructed by plotting the false-positive error rate (1-Specificity) on the *x*-axis versus the true positive rate (Sensitivity) along the *y*-axis for every probability value predicted by the model. The AUC is the sum of the area occurring under the ROC curve (Hanley & McNeil, 1982). By convention, AUC values between 0.5 and 0.7 are indicative of low model performance, values of 0.7–0.9 indicate moderate model performance and values above 0.9 indicate high model performance (Franklin, 2009: 222–224; Manel, Williams, & Ormerod, 2001; Swets, 1988). The applicability of the AUC for the assessment of presence-only modeling techniques, such as Maxent, has been questioned (e.g. Heumann, Walsh, & McDaniel, 2011; Lobo, Jiménez-Valverde, & Real, 2008), since the AUC is normally calculated to establish a model's ability to differentiate between presence and absence observations. However, Heumann et al. (2011) note that the AUC is still a useful measure when evaluating the model between individual runs and the testing and training datasets. We apply the AUC in a similar fashion, to determine model performance during model building. In addition, the AUC is useful in comparing modeling results based upon different sample sizes and predictors (Franklin, 2009: 222–224). We thus interpret the AUC statistic as an indicator of how well the model discriminates between presence observations and random prediction. In this case, the AUC ranges from 0.5 to 1.0, with values above 0.5 interpreted broadly as indicating model performance better than random prediction. Both the ROC plot and the AUC are calculated automatically by Maxent, using observation and background data.

Model gain. The algorithm within Maxent is designed to generate the optimum distribution that satisfies all constraints. Each unique model begins with a uniform distribution, which guarantees the maximum possible entropy for that model, and over a set number of iterations the algorithm increases the probability of correctly predicting the locations of the phenomena modeled. The increase in probability is displayed as the model gain, which is calculated as the log of the number of grid cells minus the average of the negative log probabilities of the sample locations (log-loss). The gain increases with each iteration of the model until it falls below the convergence threshold or until the model performs the maximum number of iterations allowed. Smaller log-loss values indicate a higher likelihood of suitable conditions necessary for presence (Phillips & Dudık, 2008).

Performance gain. Kvamme's gain statistic (Kvamme, 1988) provides an alternate assessment of how well a model predicts terrace locations, based on a measure of how well the model predicts terrace locations compared with prediction rates based on random chance. This gain statistic is used extensively in archaeological site location modeling (e.g., Conolly & Lake, 2006: 184–186):

$$\text{gain} = 1 - \left[\frac{(\text{predicted area}/\text{total area})}{(\#\text{correctly predicted terraces}/\text{total number of terraces})}\right]$$

The Kvamme gain statistic produces values between −1 and +1. A value of zero or near zero means the model performs no better than random chance. Values approaching +1 indicate that the model performs better than random chance. Negative values mean the model is working contrary to its intended purpose. Generally any value above zero indicates that the model offers greater predictive power than random chance. We measured this gain statistic for the ancient and modern terraces separately as a means of validating the models independent of the Maxent software.

The Maxent software produces a map that displays the probability of terrace occurrence as a value from 0 to 1 for each pixel (logistic output). From this logistic output, two model thresholds were evaluated using the Kvamme gain statistic. The first is the threshold that had maximum training sensitivity plus specificity based on the ROC curve, which is a measure of how well a pixel that is likely to have a terrace can be discriminated from a pixel that is not likely to have a terrace, thus reducing both type I (false positive) and type II (false negative) errors. The second evaluation was made for a threshold of 0.50 for both modern and ancient terraces. The

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0.50 threshold was used because this is an intuitive cutoff point for high and low probability of occurrence. Evaluating the thresholds with the Kvamme gain statistic allows a comparison of the relative predictive power for each model.

Results

Maxent modeling reveals profound differences between the predicted distributions of ancient and modern terraces. The primary output of our study was a continuous probability map showing the likely areas to contain an ancient terrace (Fig. 3) or a modern one (Fig. 4). The AUC for the ancient terrace locations indicates very good discrimination from random, falling in the upper range of possible AUC values at 0.975 (Table 3). The AUC for modern terrace locations is lower, at a value of 0.87, but still indicates the model is able to discriminate clearly between random points and the environment associated with modern terrace locations. Using the thresholds set by an analysis of the ROC curve (maximum training sensitivity plus specificity), the continuous probability map could be filtered to show the likely area of ancient and modern terraces. Based on these thresholds, ancient terraces are predicted to occur in an environment that consists of a cumulative area of 1.29 km^2 in the 23.5 km^2 study area (Fig. 3), while modern terraces are predicted over 8.61 km^2 (Fig. 4). These predictions were set using a logistic threshold of 0.265 for ancient terraces and 0.383 for modern terraces. Using an alternative threshold of 0.50, ancient terraces are predicted to occur in an area of 0.3703 km^2 (Fig. 3), while modern terraces are predicted to occur in an area of 5.28 km^2 (Fig. 4).

Kvamme's gain statistic evaluates the predictive power for both ancient and modern models as much better than random chance. When the thresholds are set for maximum training sensitivity plus specificity, the modern terrace model produces a gain of 0.620 and correct prediction for 27 of 28 modern terraces (96%), while the ancient terrace model generates a much higher gain of 0.941 and correct prediction for 135 of 145 terraces (93%). When using a threshold of 0.50, the ancient terrace gain was 0.982 while correctly predicting 127 of 145 sites (88%) and the modern terrace prediction gain was 0.749 while correctly predicting 25 of 28 sites (89%). Both models were exceptional in terms of the percentage of terrace locations predicted correctly. The prediction of ancient terrace locations benefited greatly from much lower entropy over a smaller area of prediction at the above thresholds. Modern terraces are characterized by greater entropy relative to our selected environmental covariates and they range over a much wider portion of the study area.

Environmental covariates differ considerably in their contributions to Maxent modeling of ancient and modern terraces in both rank and magnitude (Table 4). Percent contributions are tracked by Maxent during the model building process to gauge the gain in model performance with and without each covariate, essentially providing a measure of the relative importance of each covariate. Among contributions to our ancient terrace modeling, the distances to calcareous units (*Calc*) and pillow lava (*Plava*) provide similarly high contributions, followed by smaller influence from the distance to stream channels (*Stream*) and the comparatively minor influences of the remaining seven covariates. In contrast, three different covariates emerge as the highest ranked contributors in modeling modern terrace locations: slope (*Slope*), temperature (*Temp*) and elevation (*DEM*). The covariate of topographic slope single-handedly provides the major contribution to modern terrace modeling, while the remaining covariates contribute at levels about an order of magnitude lower. In the course of modeling both ancient and modern terrace locations, three covariates provided negligible contributions: Albedo (*Albedo*), Fall Vegetation (*FallSAVI*) and Radiation (*Rad*).

Maxent models of both ancient and modern terraces performed well in terms of predictive power and reducing the amount of predicted area. The lower entropy values for ancient terrace modeling indicate generally less uniformity relative to our selected covariates and greater capability of the ancient terrace model for predicting possible locations.

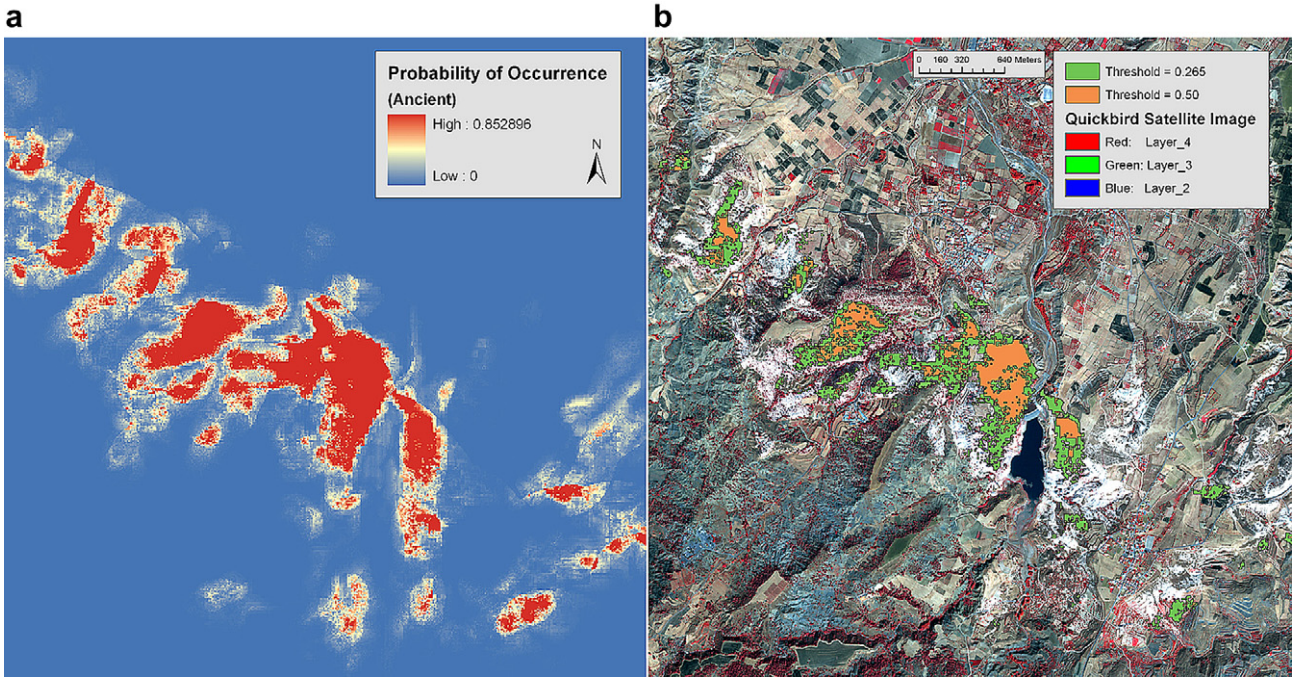

Fig. 3. A map of the logistic output showing the probability of occurrence for ancient terraces (left) across the entire study area. On the right is a QuickBird image of the study area showing thresholds of 0.265 and 0.50. The cumulative predicted area of occurrence for the 0.265 threshold is approximately 1.29 km^2 (shown in green). The cumulative predicted area of occurrence for the 0.50 threshold is approximately 0.3703 km^2 (shown in orange). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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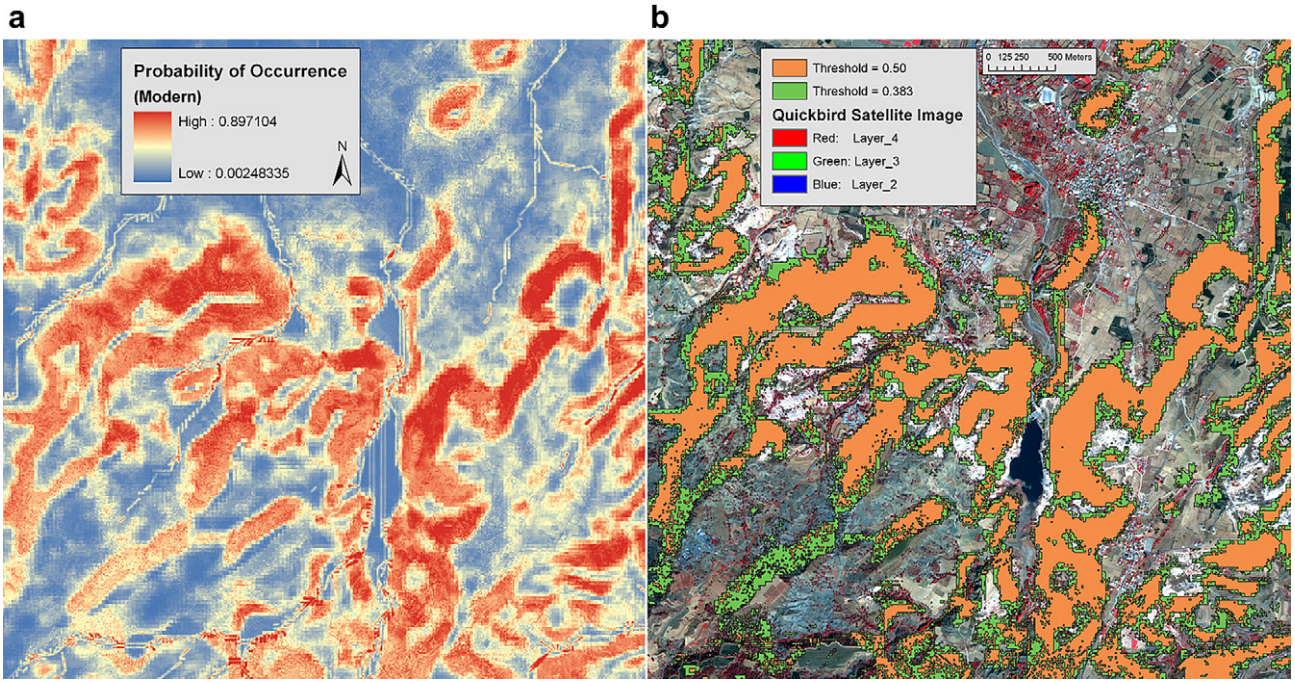

Fig. 4. A map of the logistic output showing the probability of occurrence for modern terraces (left) across the entire study area. On the right is a QuickBird image of the study area showing thresholds of 0.383 and 0.50. The cumulative predicted area of occurrence for the 0.265 threshold is approximately 8.61 km^2 (shown in green). The cumulative predicted area of occurrence for the 0.50 threshold is approximately 5.28 km^2 (shown in orange). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Discussion

Maxent modeling of terraces

Maxent modeling of ancient terraces shows exceptional predictive power, as measured by the Kvamme gain statistic, not only by predicting the occurrence of terraces accurately, but also by winnowing the areas predicted for ancient terracing considerably. These results hold immediate potential for tailoring the sampling strategies implemented by archaeological and environmental surveys on Cyprus and elsewhere. Systematic differences between our Maxent models of ancient and modern terracing provide key insights for broadened application of these methods and results. Identification of environmental covariates that are noteworthy for their substantial modeling contributions, or lack thereof, suggest a framework for further predictive terrace modeling on Cyprus based on revised sets of variables. The Maxent modeling approach operates best when the desired level of prediction requires an understanding of the differences between known locations of terraces and areas that are randomly selected from the study area. In other words, Maxent models what is known (the presence of a terrace) versus what is unknown (points outside of known terrace locations), thus creating a predictive model of archaeological potential (Vaughn & Crawford, 2009).

Table 3
Summary statistics for performance of maxent modeling of predicted ancient and modern terrace locations in the Troodos foothills, Cyprus.

	Ancient	Modern
Test AUC	0.975	0.870
Training AUC	0.980	0.836
Kvamme gain (threshold = 0.50)	0.982	0.749
Kvamme gain (threshold = max train sens. + spec.)	0.941	0.620
Area predicted (threshold = 0.50)	0.3703 km^2	5.28 km^2
Area predicted (threshold = max train sens. + spec.)	1.29 km^2	8.61 km^2

Ancient and modern terrace models for central Cyprus

Our findings illustrate a large number of differences between ancient and modern terracing. Most ancient terraces throughout the Mediterranean basin were built either relatively close to, or on, calcareous units. For example, ancient terraces on Crete occur on a variety of substrates, but are found most commonly on hard limestone (Rackham & Moody, 1996). On the other hand, modern terraces are more dispersed and their locations are largely unrelated to geological substrate. In our Maxent modeling, Elevation (*DEM*) and Slope (*Slope*) play minor roles in determining ancient terrace locations, while the covariates related to vegetation and microclimates contributed minimally. The strong association between ancient terrace locations and geology, as indicated by the contributions of covariates *Calc* and *Plava*, agrees with other studies (e.g., Bevan & Conolly, 2011; Luedeling & Buerkert, 2008) that reveal strong connections between geology and terracing in nearby regions. Luedeling and Buerkert (2008) also found a strong

Table 4
Relative contributions of environmental covariates to maxent modeling of predicted ancient and modern terrace locations in the Troodos foothills, Cyprus. Boldfaced values identify the three variables that make the largest contributions to each model.

Variable	Ancient terraces	Modern terraces
Calc	**33.4**	2.2
Plava	**30.9**	1.9
Stream	**14.4**	5.5
DEM	6.6	**8.4**
Slope	6.2	**67.3**
Temp	3.0	**9.1**
SprSAVI	1.6	5.1
Albedo	1.1	0
FallSAVI	1.5	0.6
Rad	1.4	0

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association between mountainous agriculture and hydrology, which we are able to corroborate in our model of ancient terraces, but not with modern terraces. Their explanation is that close proximity to arable sediments is particularly crucial for the establishment of mountain agriculture. Accordingly, terrace agriculture is dependent on the availability of these sediments for the construction of the tread (or bed), and on hydrology for rainwater capture and adequate drainage. On Cyprus, the three covariates most strongly associated with ancient terrace locations (*Calc, Plava* and *Stream*) confirm the observations above, but as Bevan and Conolly (2011) observe, cultural contexts are important too. The inter-related importance of ancient copper mining in the pillow lavas, and water-dependent metallurgy and agriculture practiced by nearby settlements (e.g., Politiko-*Troullia* (Fall et al., 2008) and Tamassos (Buchholz & Untiedt, 1996)), along with the necessary physiographic and geologic features described above, suggest that the Troodos foothills were an important nexus for the cultural and natural elements of terrace agriculture in the past and a long, continuing tradition of terracing on Cyprus.

Our modern terrace modeling also produced higher entropy values than those for our ancient terrace modeling, which suggests more uniformity among the covariates used to model modern terrace locations. Indeed, the nine covariates other than *Slope* each provide comparably low contributions (<10%) to our modeling of modern terrace locations. Among these variables, only temperature (*Temp*) and spring SAVI (*SprSAVI*) provide appreciably greater contributions to modeling modern terraces than to modeling ancient terraces. These two variables may suggest greater rainfall moisture retention and microclimate control among modern terraces. These results reflect less modern agricultural dependence on stream water, and broadened land use strategies that include terracing for pine reforestation, as well as maximized agricultural productivity, thus leading to terraced fields across wide geologic and physiographic distributions.

Implications for modern terracing

A variety of insights exemplify the value of an approach grounded in applied geography to the modeling of agricultural terracing. For instance, models of distribution potential can assist forest monitoring activities and watershed management. The Maxent model generates a potential distribution of terraces, which shows that the high probability areas for modern terraces are widespread across the study region, a result that carries several implications. Forests around the Mediterranean are susceptible to degradation from changing land use and climate (le Polain de Waroux & Lambin, 2012; Serra, Pons, & Sauri, 2008). Future land use projections show that agricultural expansion increases the risk of biogeochemical alterations within watersheds, thereby affecting water resources (Tong, Sun, Ranatunga, He, & Yang, 2012). Terraces enable a unique type of agricultural land use because they are particularly suited to hilly and sloped terrain, making them well suited to landscapes in which flat cultivated fields are not available (Barrow & Hicham, 2000; Geri, Amici, & Rocchini, 2010). Since continued agricultural expansion is likely, and terraces are common in Cyprus, terrace technology and land use are likely to expand further into the foothills. As agriculture land use increases, not just in Cyprus but also in other parts of the Mediterranean, forest resources may be at risk and increased agricultural land holdings could potentially inject phosphorus and nitrogen into watersheds where fertilizers are used to support cultivation. However, terraces also have proven beneficial in reforestation and soil retention on Cyprus and elsewhere (Fox et al., 2012; Gardner & Gerrard, 2003), highlighting the variable impacts of terracing on agrarian landscapes past and present.

Implications for ancient agrarian society on Cyprus

A growing body of evidence portrays prehistoric Cypriot society and landscapes as strikingly different from those of the mainland Middle East. Urbanism developed on this island ca. 1500 B.C., largely in coastal cities (Knapp, 2008: 74–82; Steel, 2004: 125–139), a millennium or two later than on the surrounding mainland. A modest number of settlement excavations (most notably Alambra-*Mouttes* (Coleman, Barlow, Mogelonsky, & Schaar, 1996); Marki-*Alonia* (Frankel & Webb, 2006); Sotira-*Kaminoudhia* (Swiny, Rapp, & Herscher, 2003)) illuminate earlier Prehistoric Bronze Age agrarian communities in detail, while a few systematic surveys sample regional settlement patterns and agricultural features (e.g., Given & Knapp, 2003; Given, Kassianidou, Knapp, & Noller, 2008). Interpretation of recently excavated paleo environmental data from Politiko-*Troullia* and its hinterland (Fall et al., 2012; Klinge & Fall, 2010) now portrays this community in a relatively sparsely populated landscape of persistent woodlands and readily available copper. Following the subsequent abandonment of the *Troullia* locality during the rise of coastal urbanism, the town of Tamassos arose as an Iron Age and Classical political and religious center (Buchholz & Untiedt, 1996). Subsequent medieval settlement dispersed to peasant villages and more distant manorial estates (Given, 2000). Thus, the archaeological record for central Cyprus provides a palimpsest of evidence for an apparently intermittent and variable pattern of long-term land use (Fall et al., 2012).

In this relatively arid landscape of seasonal rainfall and erosion-prone sediments, terracing played, and continues to play, a fundamentally important role enabling successful agricultural subsistence. In order to comprehend the agrarian legacy of this region it is, accordingly, imperative to comprehend the environmental variables that have molded and constrained agricultural terracing. This endeavor, as exemplified here through the application of maximum entropy methods as applied within the Maxent platform, permits predictive modeling of terracing and agricultural landscapes, and expeditious incorporation of these landscapes into reconstructions of ancient society on Cyprus. The models discussed here provide a systematic basis for hypothesizing land use patterns that expand on site- or survey-specific interpretations. For example, previous syntheses of Bronze Age Cyprus suggest simply a general expectation that many pre-urban Bronze Age settlements were situated in proximity to perennial water sources along the interface of the central Mesoria plain and the Troodos foothills (Knapp, 2008: 70–72). Our Maxent modeling, however, provides an empirically rigorous means of hypothesizing detailed patterns of terrace construction and long-term land use that can, for instance, link the landscapes around excavated settlements (e.g., Marki-*Alonia*, Alambra-*Mouttes*, Politiko-*Troullia*) with those of smaller villages (e.g., Aredhiou-*Vouppes* (Given & Knapp, 2003: 179)), Analiondas-*Palioklichia* (Webb & Frankel, 1994) or specialized copper production sites (e.g., Politiko-*Phorades* (Knapp, 2003)) farther afield. In particular, this study reveals a detailed predictive pattern of ancient terracing and land use in the copper-bearing pillow lava foothills in the vicinity of Politiko-*Troullia* and Tamassos. This result holds the potential, with expanded investigation, to provide a general model for ancient land use more broadly across the Troodos foothills, which embody a particularly formative landscape for ancient Cypriot agrarian society.

Conclusions

Maxent modeling proved an effective means of predicting potential areas for ancient and modern agricultural terraces in a 23.5 km^2 study area in the foothills of the Troodos Mountains,

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Cyprus. Maxent modeling also revealed clear distinctions between the environmental variables related to ancient and modern terraces. The distribution of ancient terraces relates to geologic substrate and, to a lesser extent, proximity to stream channels, while hill slope provides the major predictor for modern terrace locations. Our results provide a means for environmental and archaeological scientists studying agrarian societies to adapt their sampling strategies and broaden their inferences of land use for optimal reconstruction of long-term patterns of settlement and agriculture.

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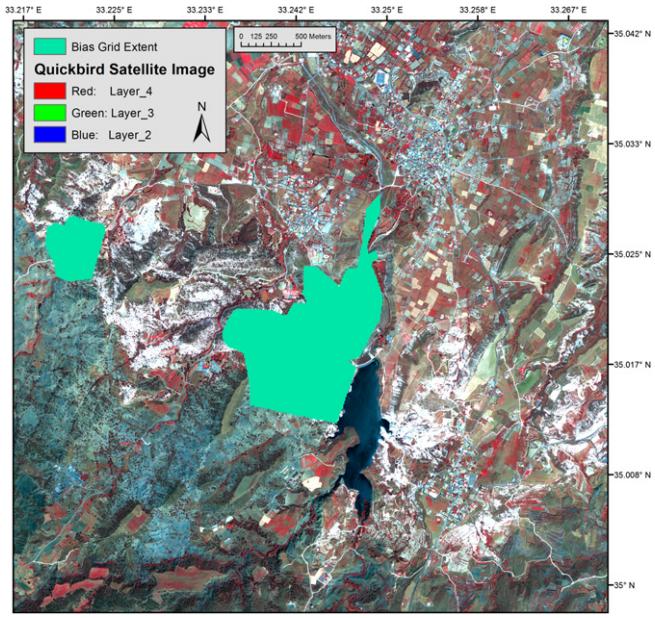
Appendix A



Map showing areas masked by bias grid to assess potential differences in terrace identification based on pedestrian survey and image analysis.

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