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A multi-proxy reconstruction of anthropogenic land use in southwest Asia at 6 kya: Combining archaeological, ethnographic and environmental datasets

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ABSTRACT

Land use and land cover (LULC) changes have important biophysical and biogeochemical effects on climate via a variety of mechanisms. Several climate modelling studies have demonstrated the impact of LULC scenarios on past climate reconstructions. Testing the impact of anthropogenic land use on mid-Holocene climate thus requires reconstructions of land use that accurately reflect this time frame. To address these concerns, the PAGES LandCover6k working group aims to create data-driven gridded global reconstructions of land use and land cover to provide the climate modelling community with inputs for sensitivity testing of the impact of LULC changes on global climate. As one of the earliest global centres of domestication, agricultural production, and population nucleation, Southwest Asia represents one of the areas of the world expected to display the greatest land use impact and human-induced land cover change at 6 kya, and is therefore critical for the mid-Holocene time frame. Here, we reconstruct land use for Southwest Asia for the 6 kya time frame at a regional scale. We draw on environmental data to reconstruct the range of possible land uses within each particular environment and on archaeological and historical data to reconstruct actualized land use. We then compare this reconstruction to common global LULC models, including the most recent HYDE and KK10 iterations. The reconstruction presented here differs from these previous reconstructions in its methodological approach, spatial extent and resolution. It also differs from both models in population density distribution and land use allocation. While the output of our reconstruction is generally more similar to HYDE 3.2 than KK10, particularly in terms of reconstructed pastoral land use, we model greater agricultural land use than HYDE across the entire region, and less land use overall compared with KK10. The paper provides a method for systematically incorporating archaeological data into models of past land use and demonstrates the value of such an approach for enhancing empirical validity.

1. Introduction

It is widely accepted that anthropogenic activities impacted on climate during the pre-industrial period, but the magnitude of this impact and the timing of its onset remain unresolved (Broecker and Stocker, 2006; Mitchell et al., 2013; Ruddiman, 2003, 2007; Ruddiman et al., 2020; Stocker et al., 2011, 2017). Among these activities, land use and land cover (LULC) changes have important biophysical and biogeochemical effects on climate via a variety of mechanisms (surface albedo, evapotranspiration, impact on the carbon cycle, impact on atmospheric greenhouse gases; Le Quéré et al., 2018; Mahowald et al., 2017; Myhre et al., 2013; Perugini et al., 2017; Pongratz et al., 2010). Climate modelling studies have demonstrated the impact of LULC scenarios on past climate reconstructions (Brovkin et al., 2006; He et al., 2014; Pongratz et al., 2010; Smith et al., 2016; Vavrus et al., 2008), but have shown that they are highly contingent on the LULC forcing specified in the simulation (Gaillard et al., 2010; Kaplan et al., 2011, 2017). Testing the impact of anthropogenic land use on mid-Holocene climate

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thus requires reconstructions of land use that accurately reflect this time frame.

To address these concerns, the PAGES LandCover6k working group aims to create data-driven gridded global reconstructions of land use and land cover to provide the climate modelling community with inputs for sensitivity testing of the impact of LULC changes on global climate (Gaillard et al., 2018; Harrison et al., 2018). The protocols for these reconstructions have been established with reference to the Paleoclimate Modelling Intercomparison Project's (PMIP's) requirements (Harrison et al., 2020), and LandCover6k land use reconstructions use a well-defined global land use classification system, reconstructed on an 8 × 8 km grid system (Morrison et al., 2018, 2021). LandCover6k is divided into regional groups; here we present the results of the land use reconstruction produced for the region of Southwest Asia.

As one of the earliest global centres of domestication, agricultural production, and population nucleation, Southwest Asia is a particularly critical area for the mid-Holocene (6 kya) time frame. Southwest Asia has a long history of urbanism, industry, and intensive agricultural and pastoral land use (by the 6 kya time window, the region had experienced c. 6000 years of agriculture, and c. 3000 years of pastoralism; Matthews, 2003: 74–88; Moore et al., 2000), and therefore represents one of the areas of the world likely to display significant land use impact and human-induced land cover change at 6 kya. Here, we reconstruct land use for Southwest Asia for the 6 kya time frame, drawing on environmental data to model the range of possible land uses within a particular environment and on archaeological and historical data to reconstruct actualized land use, and compare it to commonly used global reconstructions of mid-Holocene land use. The reconstruction presented here differs from previous LULC models in its methodological approach, spatial extent, and resolution, as detailed further below, and employs standard LandCover6k land use classification and variables.

2. Background

2.1. Previous land use reconstructions

Previous global models of past LULC include HYDE 3.2 (Klein Goldewijk, 2001; Klein Goldewijk et al., 2011, 2017a, 2017b), which is frequently used as the basis for land use datasets in climate modelling (Hurtt et al., 2020), and KK10 (Kaplan et al., 2009, 2011, 2017; Kaplan and Krumhardt, 2011). Both of these models rely on particular assumptions regarding population densities, rates of population growth, and estimates of per capita land use. However, the different approaches used by HYDE 3.2 and KK10 result in substantially different absolute estimates of per capita land use over time, and ultimately produce vastly different outcomes in terms of models of anthropogenic land cover change (Kaplan et al., 2011, 2017). Neither approach has produced good agreement in the spatial distribution of land use when compared with REVEALS-based reconstructions of land cover from pollen data (Gaillard et al., 2010; Kaplan et al., 2017). The paucity of relevant pollen records also hampers REVEALS-based reconstructions across much of Southwest Asia. There remains, therefore, a need for better-constrained reconstructions of land use based on archaeological data.

More recently, the ArchaeoGlobe project has published long-term reconstructions of global land use over the last 10,000 years, based on expert opinion (Stephens et al., 2019). These estimates were made at the level of major global administrative regions: sometimes at the country level, sometimes grouping countries or dividing countries into sub-regions. Because modern political boundaries are largely arbitrary in relation to ancient political or cultural zones, as well as in relation to environmental conditions and land use zones, this approach likely elides a great deal of intra-regional variation. Assessments were also made at only four levels of intensity for each land use type (none; minimal [<1%]; common [1–20%]; widespread [>20%]).

Several regional-scale reconstructions of land cover in constrained areas of Southwest Asia have been proposed for various discrete time slices based on archaeological data (Collins et al., 2018; de Gruchy et al., 2016; Moore et al., 2000; Soto-Berelov et al., 2015). These use a variety of different approaches, including species distribution modelling and modelling of plant functional types, as well as satellite imagery, particularly Landsat and Digital Elevation Models (DEMs). Most of these approaches, however, have been focused on land cover, rather than on land use (but see Geyer et al., 2019; Laabs and Knitter, 2021 for exceptions).

A previous LandCover6k paper (Morrison et al., 2021) presented a reconstruction of land use at 6 kya for Iraq, eastern Syria, Jordan and the Arabian peninsula, using the LandCover6k classification system. This initial reconstruction was conservative in its approach, confining land use attributions to areas in which directly dated archaeological evidence could be attributed to the time window in question with a high degree of confidence, and relying on land use reconstructions from previously published syntheses. The reconstruction presented here reconstructs potential land use zones based on a series of primary environmental datasets, and then draws upon a wider range of archaeological settlement and bioarchaeological data to define actual land use practices. It also draws from ethnographic sources and extrapolates some details from better-understood time periods to develop a more comprehensive model of land use. The resulting reconstruction is more spatially extensive than the initial one, incorporating Anatolia, Cyprus, the south Caucasus, the Levant and Iran, and is of higher resolution (90 m vs. 8 km). This resolution is of greater utility for archaeologists, and can be upsampled for climate modelers. The approach and methodology presented here can be employed for other time periods and regions as a means of reconstructing ancient land use and anthropogenic impacts on climate.

2.2. Regional setting

The region considered here for LULC reconstruction covers the modern countries of: Turkey, Syria, Lebanon, Jordan, Israel, Palestine, Cyprus, Iraq, Kuwait, Saudi Arabia, Oman, Yemen, United Arab Emirates, Bahrain, Qatar, Iran, Georgia, Armenia and Azerbaijan.

The period under consideration for this reconstruction of land use is a roughly 250-year window either side of 6 kya (ca. 4250-3750 BCE). While the LandCover6k project aims to create land use datasets for a range of timeframes, this paper focuses on the 6 kya timeframe as a period of high priority for mid-Holocene climate modelling (Kageyama et al., 2018), and establishes the methodology for the region of Southwest Asia that will be extended to other time frames in future.

In terms of chronological terminology, the 6 kya period corresponds to the Ubaid-Uruk transitional period in greater Mesopotamia, the LC1-3 period according to the Santa Fe chronology for northern Syria, the Late Chalcolithic period in much of the Levant, Anatolia and the Caucasus, the transition from the Ceramic Neolithic to the Early Chalcolithic in Cyprus, and the late Neolithic in Arabia (see Akkermans and Schwartz, 2003; Kiguradze and Sagona, 2003; Knapp, 2013; Lyonnet, 2007; Magee, 2014; Özbal, 2011; Palumbi, 2011; Rowan and Golden, 2009; Schoop, 2011 for discussions of various regional chronological terminologies). In most areas of Southwest Asia, this period was characterized by small-scale agropastoral villages and towns, with concomitant evidence for communities that focused more intensively on pastoralism. However, in greater Mesopotamia, this was also a period of incipient urbanism, which witnessed the development of specialized craft production, long-distance trade and monumental architecture (Ur, 2010, 2013; McMahon, 2020). Conversely, in Arabia, major environmental shifts meant that this was a period of significant reconfiguration of lifeways and subsistence strategies that ultimately led to the introduction of irrigated and terraced agriculture (Magee, 2014).

3. Materials and methods

3.1. Theoretical approach

The approach to human land use employed here draws upon three ecological formulations. These are: the fundamental versus the actualized niche (and the role of niche construction behaviors); land use hierarchy; and the consideration of land use zones from the perspective of land versus people.

The general principle of the approach is to model the kinds of land use that are optimal within a given environment, as a starting point for further calculations of the areas in which particular land uses were actually conducted at various points in the past. This is conceptually similar to the idea in ecology of the fundamental niche, as compared to the realized niche (Hutchinson, 1957; Kearney, 2006). If the niche is considered as the multi-dimensional set of environmental conditions occupied by a particular organism, then the fundamental niche is that which can theoretically be occupied under circumstances where there are no other external constraints (e.g., competition, population pressure), while the realized niche is the actual niche occupied by the organism in the real world when constraining conditions are taken into account (Hutchinson, 1957; Kearney, 2006). Similarly, here we consider the fundamental land use zone as the suite of environmental conditions in which a particular human land use could potentially be employed given the set of chronologically-specific technologies available in the period in question that might have modified natural environmental affordances (see further below). We consider the realized land use zone as the area in which this land use was actually practiced at a given point in the past within particular social, political, and economic milieux. We reconstruct fundamental land use zones as a function of critical environmental factors that determine the suitability of particular locations for specific land use types using available pre-industrial technologies such as irrigation, particular landraces of cultigens and breeds of animal domesticates, and modes of transport. Realized land use zones are then reconstructed with reference to these fundamental land use zones using archaeological data, specifically settlement locations, paleoenvironmental, and bioarchaeological data.

In ecology, the realized niche is generally considered to be smaller than the fundamental niche (Soberón and Arroyo-Peña, 2017), but can also theoretically extend beyond the fundamental niche through niche construction behaviours, a factor which is particularly relevant when considering human activities within the landscape (D'Alpoim Guedes, 2016; Laland and O'Brien, 2010). Niche construction can be defined as "the process whereby organisms, through their own metabolism, their activities and their choices, modify their own and/or each other's niches" (Odling-Smee et al., 2003: 419), and in relation to human societies has been most explored in relationship to subsistence behaviours in the past (Laland and O'Brien, 2010; Smith, 2011; Vigne, 2011). The fundamental land use zones reconstructed here are implicitly dependent on a number of niche construction behaviours, insofar as the development of agriculture and the domestication of animals are fundamentally the result of human niche construction (Smith, 2011; Vigne, 2011). The resulting fundamental land use zones are therefore chronologically specific and are meaningful only with respect to the prior development of particular subsistence technologies (agriculture, arboriculture, etc.). For example, the potential agricultural and pastoral zones are only meaningful in the period after particular technologies of agriculture and pastoralism had been developed.

Beyond this implicit incorporation of niche construction behaviours into the fundamental land use model, we also explicitly take into account land use technologies—also themselves human niche construction behaviours— that expand the range of potential land uses within a given environment. The primary niche construction behaviours that are considered explicitly in the model are the employment of canal irrigation techniques and land terraces as means of extending the zones in which agricultural production would have been possible (Wilkinson, 2003; Wilkinson et al., 2015).

The final reconstruction of fundamental land use zones therefore indicates the maximal area in which a particular land use would be possible given a particular set of past environmental conditions, technologies, and niche construction behaviours appropriate to the 6kya timeframe. The actual observed extent of a particular land use category at a given time will occupy a more limited subset of these expanded fundamental land use zones.

Many areas of Southwest Asia are simultaneously suitable for an array of possible land use types. However, the range of Southwest Asian land use categories can be considered along a continuum with regard to the restrictedness of the environmental conditions under which they could have been practiced. For example, the environmental conditions under which agriculture could have been practiced were constrained by factors such as seasonal precipitation, temperature variability, and topography. Hunting-gathering behaviours and, by 6 kya, animal grazing, by comparison, were less restricted in terms of the specific environmental conditions in which they could have been employed. This flexibility in animal grazing at 6 kya is the case primarily due to thousands of years of selective breeding by humans, which favoured environmental adaptability and/or the development specialized breeds adapted to particular environments (Arbuckle and Hammer, 2019). We proceed with the assumption that ancient Southwest Asian communities employing varied land use strategies would have preferentially practiced land use types with more restrictive requirements in the zones most suitable for them. We reconstruct fundamental land use zones on the basis of the most restrictive land use type that could have taken place in that environment, and assume that these more restrictive land use types took place preferentially in these environments. Therefore, fundamental land use zones are understood here as a cascading hierarchy, organized and reconstructed sequentially from those with the most restrictive requirements to those with least restrictive (agriculture→arboriculture→pastoralism→hunting-gathering-fishing-foraging). We recognize that this hierarchy is somewhat reductive, and that communities may have chosen in particular times and places to prioritize non-"optimal" land uses (e.g. pastoralism) in preference over land uses such as agriculture (Arbuckle and Hammer, 2019). However, we make this simplifying assumption for the sake of modelling over large geographical areas. Land use categories with less restrictive environmental requirements are thus also deemed possible in the unexploited areas of land use zones with more restrictive requirements. For example, agricultural land use can occur in a more limited range of environments and its distribution is therefore restricted, but pastoralism can also occur in areas where agriculture is possible when these areas are not currently being exploited for this purpose. Similarly, hunting-gathering-fishing-foraging can also be conducted in zones suitable for agriculture, pastoralism, or other purposes.

Also critical to the approach employed here is the consideration of land use from the perspective of land as opposed to that of people (Morrison et al., 2021). Archaeologists typically collect data with the aim of understanding the social dynamics within and among the political or cultural groups engaging in particular practices (land use and others) at specific points in space and time. Here we reconstruct land use solely in terms of its geographical distribution, with no commentary on the identities of the individuals or groups practicing those land uses.

3.2. Fundamental land use zones

We reconstruct fundamental land use zones using a form of mechanistic modelling (D'Alpoim Guedes, 2016; Kearney and Porter, 2009), incorporating five environmental variables: sea level, elevation, topographic slope, soil depth, and modelled rainfall. We first create a "possible land use" map using these five variables and then modify it on the basis of archaeological evidence for specific niche construction behaviors—the distribution of the agricultural technologies of irrigation and terracing—to generate a map of fundamental land use zones.

As discussed above, the distribution of fundamental land use zones is chronologically specific. We have reconstructed and modelled for the 6 kya period two of the environmental variables, sea level and precipitation. Compared to the other variables used here, elevation changes relatively slowly or minimally over millennia in many environments, except the lower reaches of river floodplains, so we use static modern representations of topography. The final two environmental variables, slope and soil depth, can vary significantly over time in complex ways. However, we also use static modern representations of these variables given the infeasibility of modeling past variation at regional scale (see further discussion below). Our incorporation of the two anthropogenic variables—irrigation and terracing—is chronologically sensitive in that we model their distribution on the basis of archaeological evidence for the environments in which communities at 6 kya were able to employ these technologies.

All calculations in Sections 3.2 and 3.3 were performed using R Version 4.1.0 (R Core Team, 2021) in the Informatics Laboratory at Durham University. All associated code is provided as Supplementary Data.

3.2.1. Sea level (coastlines)

We began by reconstructing the land available during the period under consideration. Sea level change has significantly shifted Southwest Asian coastlines since 6kya, primarily in southern Iraq (Mesopotamia). Since the Last Glacial Maximum, changing sea levels, ongoing aggradation, and tectonic activity have resulted in changes to the extent of the Persian Gulf. In the mid-Holocene, the Gulf reached further north than at present, achieving its maximum extent ca. 4550 BCE (Aqrawi, 2001; Brückner, 2003; Jotheri et al., 2018; Pournelle, 2003, 2013; Sanlaville, 2003). We constructed areas likely to have been under water at 6 kya as areas of “no human land use” (Morrison et al., 2021). Similarly, low-lying areas of the estuary of the Shatt al-Arab in southern Iraq are associated with extensive marsh regions (Morrison et al., 2021; Pournelle, 2003, 2007; Pournelle and Algaze, 2014; Salim, 1962). We classified these classified according to the land use category Hunter-Gatherer-Fisher-Forager, which covers the sorts of low-level food production and diversified local resource use postulated for this region on the basis of ethnographic analogy (Pournelle, 2003; Salim, 1962; Thesiger, 1964).

3.2.2. Elevation

Elevation is a factor in determining the length of the growing season for local vegetation, particularly as it correlates with temperature variation (Arslantaş and Yeşilırmak, 2020; Mesgaran et al., 2017). In Southwest Asia, higher elevations are generally associated with cooler annual average temperatures, longer winters with lower minimum temperatures, and shorter summers. These areas generally do not support traditional cereal crop species (e.g. wheat and barley), which require minimum temperatures of ca. 5 °C for pollination, and of ca. 13–15 °C for full biomass production (Raes et al., 2018). The dataset used for the classification of elevation is a 1 arc-second SRTM digital elevation model. We considered absolute elevations separately for lowland areas (Mesopotamia, the Levant; Fig. 1a), highland areas (Anatolia, Iran, the Caucasus; Fig. 1b), and the Arabian peninsula (Fig. 1c) to account for local adaptation of agricultural production to high altitudes, but in all cases, we consider areas above 3000m unsuitable for agricultural production (Wilkinson, 2003: 197-8). Elevation bands are constructed to correspond as closely as possible to divisions between major phytogeographic zones (Akhani et al., 2013; Atalay, 1986; Ghazanfar and McDaniel, 2016; Nahal, 1962; Palmer, 2013; Whyte, 1950). Low-lying areas on the Omani and Yemeni coastal plains (<200 m) elevation have produced evidence for the exploitation of marine resources, marked by extensive shell middens (Charpentier, 2008; Magee, 2014; Uerpmann, 2003), and we therefore classify them according to the land use category Hunter-Gather-Fisher Forager.

3.2.3. Slope

Cultivation in sloping terrains increases the danger of soil erosion, causing declining soil fertility (Fischer et al., 2002). Following others, we consider areas with slopes <10% suitable for production of cereal crops and areas with slopes of 10–30% more suitable for arboricultural production (Fischer et al., 2002; Sys et al., 1993). We also consider areas with >30% slope suitable for grazing, up to a maximum slope of 60% (FAO, 1991). These slope values are modified in areas where terraced agriculture was practiced at 6 kya (see further discussion in Section 3.2.6 below).

Slope data is derived from the SRTM digital elevation model. While there were likely significant long-term landscape changes to slope and especially soil depth (see below), there are no large-scale reconstructions of palaeolandscape for Southwest Asia. Regional-scale modelling of geomorphological processes is currently too computationally demanding to perform at large geographic scales (for micro-regional modelling, see Barton et al., 2010a, 2010b, 2015). Even if such modelling could be performed for larger geographical regions than is currently possible, error propagation of uncertainties in key variables would create large uncertainties in the outputs. As a result, we use modern topography and slope here, with the recognition that these datasets may not accurately capture all past conditions, especially at small scales.

3.2.4. Soil depth

Soil depth is also a significant factor in potential land use because shallow soils limit plant growth and present constraints for agricultural productivity (Fischer et al., 2002; Sys et al., 1993). Categorization of agricultural zones is based on the minimum effective rooting depth requirements of primary cereal crop species known to have been grown in ancient times, such as wheat and barley (Sys et al., 1993; Raes et al., 2018). The dataset used here is from SoilGrids, a combination of field-checked and remotely-sensed soil data (depth to bedrock; Hengl et al., 2014). As above, since modelling of potential long-term changes in soil depths is currently infeasible, we use modern values for soil depth with the recognition that past soil conditions may not be accurately reflected. Future work may provide better indications of ways in which millennia of agriculture and other land use may have impacted soil conditions that would allow us to improve our current approach (see, for example, Gron et al., 2021).

3.2.5. Rainfall

Soil moisture is one of the primary limiting factors for agricultural productivity in Southwest Asia and is commonly inferred through mean annual precipitation. The interaction between soil depth (discussed above), soil moisture and rainfall is complex (Wilkinson, 2000b). Modelling this interaction at the scale we are working at is currently impossible, but again, future work could develop models which nuance the approach we have developed here with more sophisticated operationalization of rainfall and soil interaction. Here we compromise and use precipitation as a linear proxy for soil moisture. Following others, we consider areas receiving more than 300 mm of precipitation annually to represent optimal agricultural zones and areas receiving between 200 and 300 mm of precipitation as marginal zones for agricultural production (Kalayci, 2013; Wachholtz, 1996; Wilkinson, 1994, 2000b; Wilkinson et al., 2014; Wirth, 1971). We consider areas receiving less than 200 mm of precipitation per year unsuitable for rainfed agriculture, but those with 100–200 mm of annual precipitation suitable for grazing animals.

Unlike the other variables used in our land use model, which except for sea level/coastlines are considered temporally fixed, for most areas of the study region we use an estimate of regional rainfall based on interpolations of modern rain gauge data shifted using work from Soreq Cave (Hewett et al., 2022), where variations in isotope values in speleothems have been converted to quantified changes in rainfall (mm/year) (Bar-Matthews et al., 1997, 1999; Bar-Matthews and Ayalon,

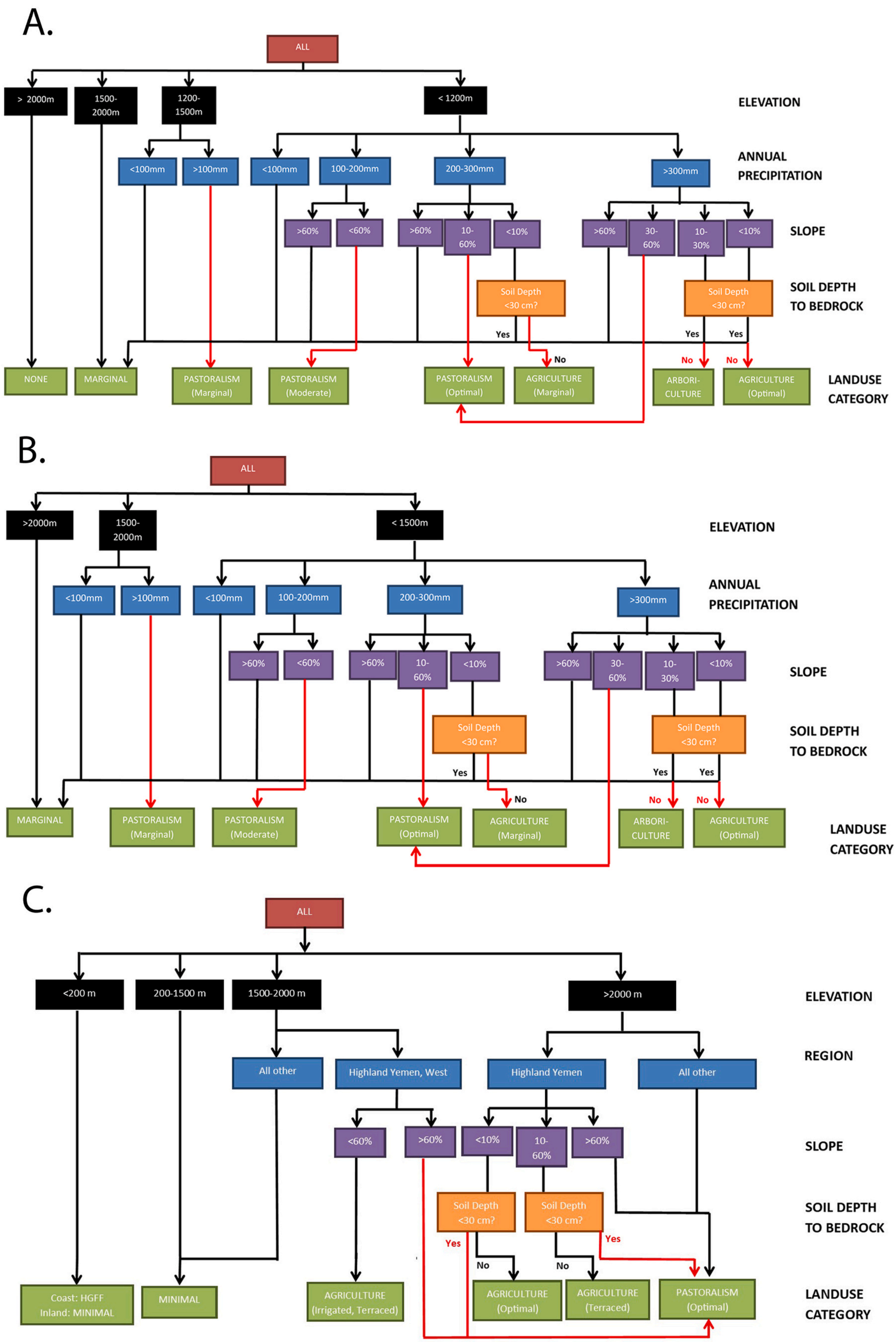

Fig. 1. Flowcharts illustrating variables and classifications used for assigning fundamental land use categories (a: lowland areas; b: highland areas; c: Arabian Peninsula).

2011; Orland et al., 2014), for the time slice closest to 4000 cal BCE.

Our modelled rainfall maps do not extend far enough south to cover Arabia, where rainfall has been affected in complex ways by both the winter westerlies and the Indian Ocean monsoon system, and therefore climate patterns governing rainfall are only loosely connected to those at Soreq Cave. In Arabia, the period around 6 kya represents the transition at the end of the climatically optimal Holocene Humid Period with the southward migration of the Intertropical Convergence Zone, resulting in a significant shift in regional precipitation patterns in Arabia (Lézine et al., 2017). The exact timing, magnitude, and geographical configuration of this shift remains uncertain (Lézine et al., 2017). For these reasons, we exclude annual precipitation as an explicit variable in reconstructing fundamental land use zones for the Arabian Peninsula (Fig. 1c). Despite the uncertainty about precipitation patterns in this period, the use of elevation as a variable implicitly incorporates rainfall to a certain degree, especially in highland southwest Arabia, which received significant rainfall from the Indian Ocean monsoon system that directly correlates with elevation (Babu et al., 2011; Enzel et al., 2015). However, the precise relationship between precipitation and topographic features in Arabia during the mid-Holocene remains unclear.

3.2.6. Irrigated and terraced areas

We then take into account the potential for human modification of natural affordances through niche construction behaviours, particularly those related to water and slope/soil management infrastructure.

We restrict our reconstruction of zones of irrigation to areas in which large-scale irrigation infrastructure (i.e. canal irrigation) was in place; at 6 kya, such irrigation was probably only practiced on the southern Mesopotamian plains (modern southern Iraq and southwestern Iran). Within the time frame ca. 6 kya, there are several areas in Southwest Asia where water management infrastructure possibly relating to floodwater or runoff farming and rainwater harvesting techniques have been identified, including Yemen and the Black Desert in Jordan (Edens and Wilkinson, 1998; Ekstrom and Edens, 2003; Harrower, 2008; McCorriston and Martin, 2010; Müller-Neuhof, 2014; Wilkinson, 2003). However, the exact dating of these examples is often uncertain or, as in the case of Jawa in Jordan, they likely date somewhat later in the 4th millennium BCE (Meister et al., 2017; Müller-Neuhof and Abu-Azizeh, 2016). Furthermore, these techniques extended cultivation over a comparatively limited area. We categorize areas employing smaller-scale floodwater or run-off farming as employing rain-fed agricultural techniques for the purposes of the reconstruction of potential land use.

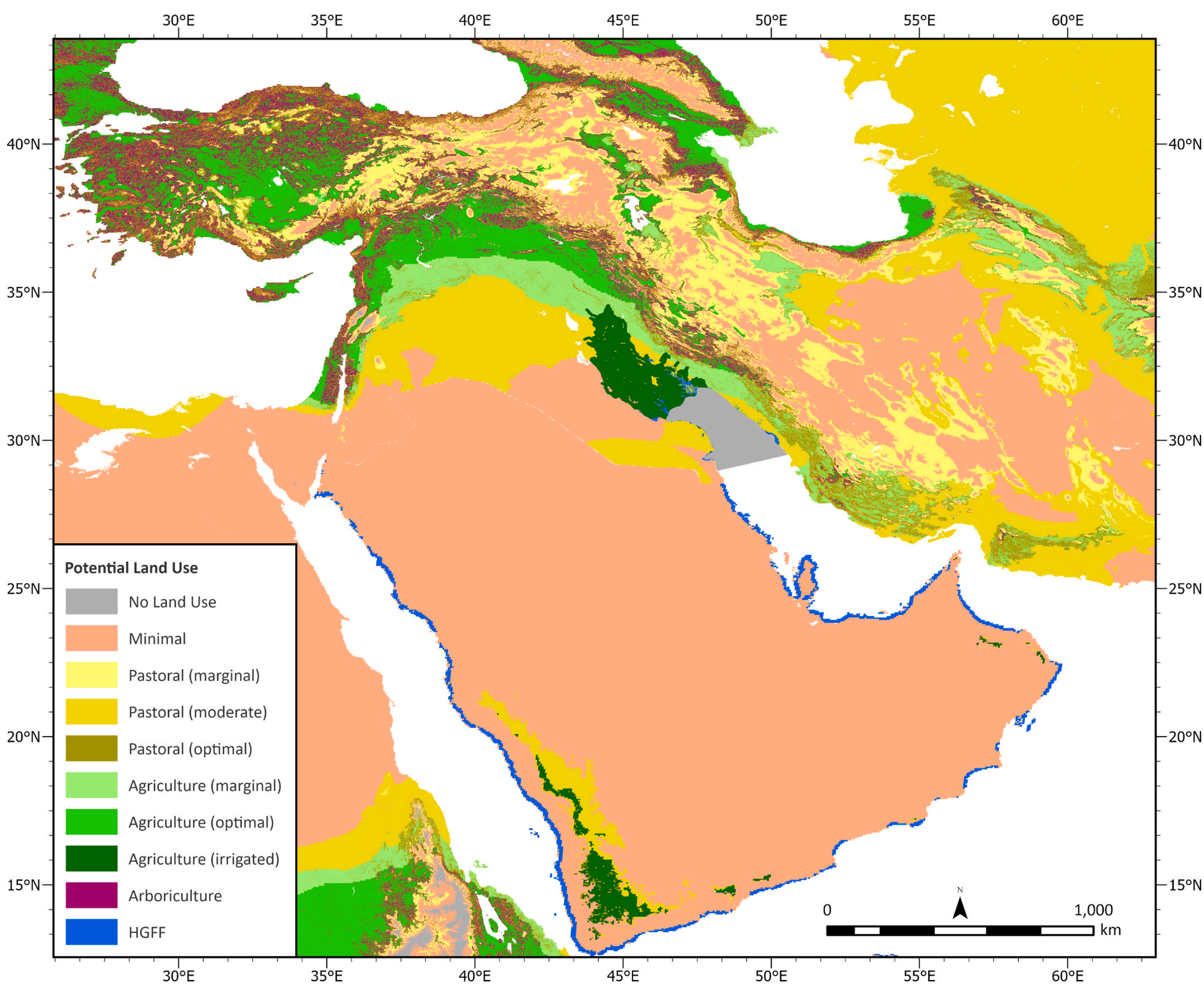

Fig. 2. Map of reconstructed fundamental land use zones at 6kya.

Much of the southern Iraqi alluvium receives less than 200 mm of precipitation annually, precluding rain-fed agriculture, but irrigation canals were used extensively from at least the Chalcolithic period to carry out intensive agriculture over large areas (Adams and Nissen, 1972: Fig. 2; Wilkinson, 2003: 87; Wilkinson et al., 2015). We estimated irrigated areas for the 6 kya reconstruction by creating a 5 km buffer around the reconstructed path of water channels at c. 6 kya in the southern Iraqi alluvium (Morrison et al., 2021; Wilkinson, 2003; Wilkinson et al., 2015; the dataset of known channels was compiled from Algaze, 2001; Gasche, 2004, 2005, 2007; Hritz, 2010; Jotheri, 2016; Pournelle, 2003). This 5 km buffer is based on a combination of textual data and geomorphological studies, which suggest that early canals were confined to river levees extending at most 2–3 km on each side of the watercourse (Wilkinson et al., 2015). For the estimation of the fundamental land use zone for irrigated agriculture, we use a maximal interpretation of this potential buffer size.

Another form of agricultural infrastructure relevant for this period is the use of terracing to permit agriculture in areas with steep slopes and high levels of soil erosion. Broadly speaking, evidence for terraced agriculture around 6 kya is confined to highland Yemen and some parts of lowland eastern Yemen where two different types of water and landscape modification, terracing and runoff irrigation, respectively, were used to make cultivation possible on slopes and in dry wadis. While dating evidence for terraced agriculture is notoriously problematic, and thus the extent of terracing in this time frame is difficult to assess, clear evidence for agricultural terracing exists in the highlands of Yemen by the early 4th millennium BCE (Wilkinson, 2003: 190; Ekstrom and Edens, 2003). Following Morrison et al. (2021), we have reconstructed terraced agricultural areas in highland Yemen on the basis of ethnographic and archaeological data.

3.2.7. *Creation of fundamental land use distribution*

We classified the environmental variables described above (Sections 3.2.2-3.2.5) on a pixel-by-pixel basis according to the flow charts illustrated in Fig. 1, which are translated into a series of decision rules resulting in the land use classifications outlined in Table 1. We combined these land use classifications with the reconstructed extent of ancient coastlines (Section 3.2.1), and maps of the extent of the human niche construction behaviours (irrigation and terrace-related zones) specific to 6 kya, as discussed above (Section 3.2.6), to produce the final map of fundamental land use zones presented in Fig. 2.

3.3. *Reconstructing actualized land use*

We combined the fundamental land use zones described above with archaeological settlement data to reconstruct actualized land use patterns at 6 kya. Southwest Asia is uniquely positioned for the reconstruction of land use based on settlement data, as the region has a long tradition of archaeological survey, resulting in the generation of large settlement datasets. The volume of data is not so large and dispersed that synthesis is precluded (as in much of Europe), but not so small as to compromise data quality and coverage (as for most other regions, especially in parts of the world where archaeological information is not systematically collected by local nation states; excepting China, see Hosner et al., 2016). The wider Mediterranean area also has a long history of survey, but in many regions comparability between survey datasets is a notable problem due to variability in sampling strategies and differences in site characteristics and definition (Alcock and Cherry, 2004; Wilkinson, 2000a). In Southwest Asia, archaeologists have generally carried out full coverage survey for relatively large regions, with broadly similar sampling approaches. This means that although some archaeological sites may be missed, the systematic bias is against small sites from periods long after the 6 kya window (Lawrence et al., 2017; Wilkinson, 2000a).

Table 1
Fundamental land use categories and their definitions.

Zone	Land Use	Elevation (m)	Rainfall (mm)	Slope (%)	Soil Depth (cm)
lowlands	None	>2000			
highlands	Minimal	>2000			
Arabia (other)	Pastoralism (Optimal)	>2000			
Arabia (highland Yemen)	Pastoralism (Optimal)	>2000		>60	
Arabia (highland Yemen)	Agriculture (Terraced)	>2000		10–60	>30
Arabia (highland Yemen)	Pastoralism (Optimal)	>2000		10–60	<30
Arabia (highland Yemen)	Agriculture (Optimal)	>2000		<10	>30
Arabia (highland Yemen)	Pastoralism (Optimal)	>2000		<10	<30
lowlands	Minimal	1500–2000			
Arabia (highland Yemen)	Pastoralism (Optimal)	1500–2000		>60	
Arabia (highland Yemen)	Agriculture (Terr + Irr)	1500–2000		<60	
Arabia (other)	Minimal	1500–2000			
highlands	Pastoralism (Marginal)	1500–2000	>100		
highlands	Minimal	1500–2000	<100		
lowlands	Pastoralism (Marginal)	1200–1500	>100		
lowlands	Minimal	1200–1500	<100		
highlands	Minimal	<1500	>300	>60	
highlands	Pastoralism (Optimal)	<1500	>300	30–60	
highlands	Arboriculture	<1500	>300	10–30	>30
highlands	Minimal	<1500	>300	10–30	<30
highlands	Agriculture (Optimal)	<1500	>300	<10	>30
highlands	Minimal	<1500	>300	<10	<30
highlands	Minimal	<1500	200–300	>60	
highlands	Pastoralism (Optimal)	<1500	200–300	10–60	
highlands	Agriculture (Marginal)	<1500	200–300	<10	>30
highlands	Minimal	<1500	200–300	<10	<30
highlands	Minimal	<1500	100–200	>60	
highlands	Pastoralism (Moderate)	<1500	100–200	<60	
highlands	Minimal	<1500	<100		
lowlands	Minimal	<1200	>300	>60	
lowlands	Pastoralism (Optimal)	<1200	>300	30–60	
lowlands	Arboriculture	<1200	>300	10–30	>30
lowlands	Minimal	<1200	>300	10–30	<30
lowlands	Agriculture (Optimal)	<1200	>300	<10	>30
lowlands	Minimal	<1200	>300	<10	<30
lowlands	Minimal	<1200	200–300	>60	
lowlands	Pastoralism (Optimal)	<1200	200–300	10–60	
lowlands	Agriculture (Marginal)	<1200	200–300	<10	>30
lowlands	Minimal	<1200	200–300	<10	<30
lowlands	Minimal	<1200	100–200	>60	
lowlands	Pastoralism (Moderate)	<1200	100–200	<60	
lowlands	Minimal	<1200	<100		
Arabia (all)	Minimal	200–1500			

(*continued on next page*)

Table 1 (*continued*)

Zone	Land Use	Elevation (m)	Rainfall (mm)	Slope (%)	Soil Depth (cm)
Arabia (coastal)	HGFF	<200			
Arabia (inland)	Minimal	<200			
lowlands	Agriculture (Irrigated)	located within 3 km of a known irrigation channel			

3.3.1. Settlement dataset

The settlement dataset used here combines and harmonizes data from a variety of published sources, including several previously published datasets themselves collated from a variety of sources (Greenberg and Keinan, 2009; Lawrence, 2012; Lawrence et al., 2016, 2017; Palmisano et al., 2021; Savage and Levy, 2014), with additional data from site gazetteers and survey reports.

The surveys combined in this dataset represent a variety of methodological approaches and were conducted with varying intensities and chronological precision. Sites from these datasets were recorded as point data with attributes noting the presence/absence of evidence for occupation in regionally standardized cultural periods defined according to generally accepted absolute chronological dates (Lawrence, 2012). There is also a great deal of variation in the representation and density of available settlement data across different sub-regions within Southwest Asia. While the Levant, south-central Anatolia, and Mesopotamia are relatively well-represented, areas such as northern and western Anatolia, the Caucasus, and Iran have less data available. A certain portion of this variability likely reflects real patterns in settlement density, but some is due to different intensities of research.

When considering Southwest Asia as a whole, variation in research intensity represents a substantial problem for reconstructing likely population density or land use intensity purely on the basis of known settlement sites. As a result, we have used an approach that uses known settlement data in well-surveyed regions to estimate settlement densities in under-explored regions.

We have used data from 74 high-quality systematic archaeological

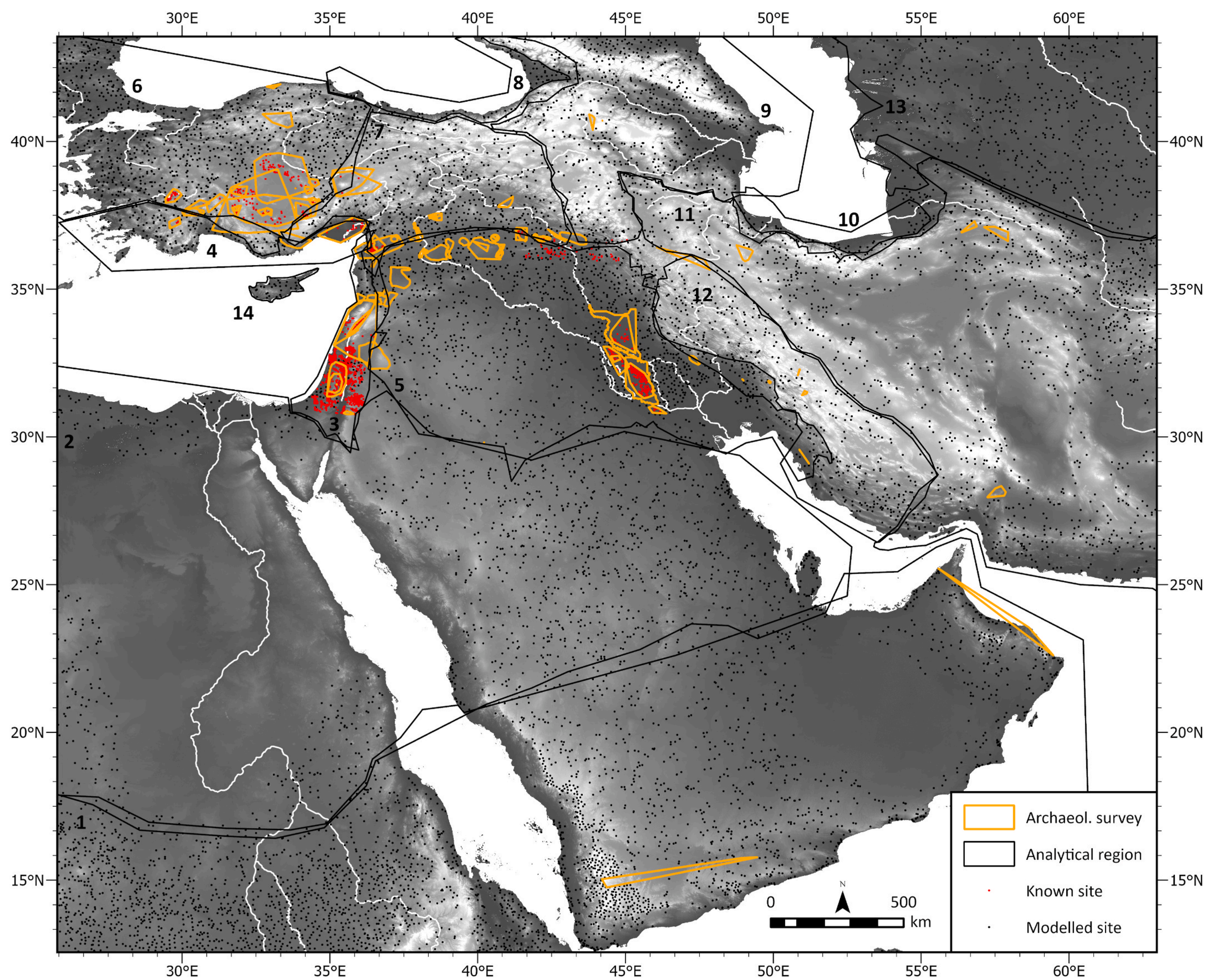

Fig. 3. Map illustrating locations and extents of surveys employed for calculating site densities (yellow border polygons), with archaeologically identified (red) and simulated (black) sites at 6 kya. Full list of surveys is provided in Supplementary Table S1, references in Supplementary Text ST. Black border polygons indicate analytical regions: 1. Sudan and southern Arabian Peninsula, 2. Egypt and central Arabian Peninsula, 3. Levant, 4. Turkish Mediterranean coast, 5. Iraq and Syria, 6. Northern and western Turkey, 7. Central Turkey, 8. Black Sea, 9. Caucasus and eastern Turkey, 10. Caspian, 11. Iran, 12. Zagros, 13. Turkmenistan, 14. Cyprus. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

surveys that most accurately reflect settlement densities within the surveyed areas, selected based on publication quality and comparability due to similarities in aims and methodologies (illustrated in Fig. 3, and listed in Supplementary Table S1 with references in Supplementary Text ST2). Sites dating to the period covering a roughly 250-year window on either side of 6 kya (roughly 4250-3750 BCE) were included. The surveys that have produced this settlement data have varying degrees of precision in their chronology, so our basic approach has been to use the narrowest possible chronological range as defined by the system employed by each individual survey.

3.3.2. Site densities and distributions within land use zones and regions

For each survey, we have compared the number of sites falling within each potential land use zone to the total area attributed to that zone within the survey's boundaries to calculate site densities for each potential land use zone. We then calculated average site densities per square kilometre for each land use zone on a regional basis (Table 2, Fig. 4).

We extrapolated site densities based on these well-surveyed regions to areas in which site distributions are less well understood. This approach may introduce some degree of error because site densities in surveyed areas may not be representative of unsurveyed areas. Despite these limitations, however, this offers a better estimate of the likely scale of population distribution than the alternative approach of assuming that unsurveyed areas were unpopulated.

We converted the various site density rates to site distributions through a multistage process. First, within surveyed areas, we used the locations of known sites dating to the 6 kya time window. For areas that have not been surveyed, we calculated anticipated numbers of sites so that the density values would be consistent with site densities observed in each land use class in surveyed areas. Within land use zones, we further weighted densities of sites according to observed site densities within rainfall bands (<50 mm, 50–100 mm, 100–200 mm, 200–300 mm, 300+ mm annually). We then place sites within unsurveyed areas using a random point generator according to the weighted site density calculations. Our use of land use zones and rainfall bands as the main weighting variables for site placement in unsurveyed areas likely oversimplifies the complex relationship between site location and environmental variables across the region, but was chosen to balance the variables mostly likely to affect spatial patterning with computational complexity. In future, more nuanced modelling of site clustering patterns according to further environmental variables would improve the placement of randomly generated site locations. The resulting settlement distribution is represented in Fig. 3.

3.3.3. Calculations of land use per settlement

We model actualized land use using the reconstructed site distribution. As described above, we proceed sequentially, beginning with land use types with the most restrictive requirements (agriculture) and assuming that these land use types occurred preferentially in areas most suitable for them, and then progressing to land use types with less restrictive conditions (pastoralism, hunting-gathering-fishing-foraging [HGFF]). We assume that sites located in agricultural and arboricultural zones (including both the marginal and optimal agricultural zones) represent sedentary agropastoral communities, while sites located in marginal, moderate or optimal pastoral zones represent specialized pastoralist communities.

There have been several attempts at quantifying land use requirements from archaeological data (Hughes et al., 2018; Kay and Kaplan, 2015). These methods calculate agricultural cultivation areas, for example, using approximations for average agricultural yields and the caloric contents of primary cereal crops, along with estimates of average village sizes and caloric requirements per person. The assessments employed here make use of existing estimates based on similar calculations, but are also combined with evidence for agricultural sustaining areas from landscape archaeology and textual data specific to our region. Previous approaches to producing spatialized representations of these quantified estimates (Bonnier et al., 2019; Geyer et al., 2019; Knitter et al., 2019) generally require more computationally or data intensive modelling than is feasible over the large areal extent considered here, so a simplified approach is utilized. Full justification for the values used in the discussion below are provided in Supplementary Text ST1.

In the optimal and marginal agricultural zones, where agriculture is primarily rain-fed, fixed agricultural buffers are reconstructed around sites in order to calculate agricultural land use from settlement densities. In the absence of consistent settlement size data from all surveys in all regions, we assume a static buffer of 5 km around each site, regardless of size. In the irrigated agricultural zone, we assume a similar total cultivated area to that observed for sites in the optimal and marginal agricultural zones, but consisting of a buffer of 5 km on either side of the related water course (Wilkinson et al., 2015).

There was considerable overlap in the marshy regions of southern Mesopotamia between areas where we reconstructed HGFF as a major fundamental land use zone, and the distribution of sites with evidence for irrigated agriculture, necessitating allocation of agricultural land. In these areas, we have chosen to reconstruct irrigated agriculture as the primary land use in this period, with HGFF as a secondary but significant contributor. Within agricultural buffer zones surrounding individual settlements in all regions, we assume that a variety of other types of land use were taking place simultaneously, including some HGFF of resources available in the local area, and other food production activities such as horticulture, which likely occurred close to settlements. We also assume some animal production, including raising of animals that consumed a mixed diet (such as pigs), and animals grazed on agricultural land after harvest or on fallow fields.

We consider separately the issue of additional land required by sedentary communities for the primary purpose of grazing animals, based on reconstructed community-level herd sizes and stocking rates. We assume a total of 20 cows and 500 sheep/goats per agropastoral community and 1000 sheep/goats per specialized pastoralist community, and use stocking rates of 3 ha per sheep/goat for agropastoral

Table 2
Regional site densities per km^2, by region and land use zone.

	ALL REGIONS	Anatolia	Arabia	E Medit W Syria	Iran Caucasus	Jazira Kurdistan	S Mesopotamia
neg1_Missing_Data	**N/A**	N/A	N/A	N/A	N/A	N/A	N/A
0_No_Land_Use	**0.00026**	0.00000	0.00053	0.00000	0.00000	0.00000	0.00000
1_Minimal	**0.00079**	0.00079	0.00146	0.00146	0.00053	0.00000	0.00000
2_Pastoral(Marginal)	**0.00053**	0.00053	0.00000	0.00238	0.00040	0.00000	0.00000
3_Pastoral(Moderate)	**0.00106**	0.00000	0.00040	0.00119	0.00146	0.00000	0.00225
4_Pastoral(Optimal)	**0.00252**	0.00132	0.00000	0.00689	0.00000	0.00477	0.00000
5_Agriculture(Marginal)	**0.00066**	0.00000	0.00000	0.00000	0.00066	0.00000	0.00093
6_Agriculture(Optimal)	**0.00318**	0.00172	0.00000	0.00940	0.00106	0.00834	0.00066
7_Agriculture(Irrigated)	**0.00808**	0.00000	0.00000	0.00000	0.00000	0.00000	0.00808
8_Arboriculture	**0.00305**	0.00172	0.00000	0.00755	0.00106	0.00742	0.00252
9_Hunter-Gatherer-Fisher-Forager	**0.01298**	0.00000	0.00000	0.00000	0.00000	0.00000	0.01298

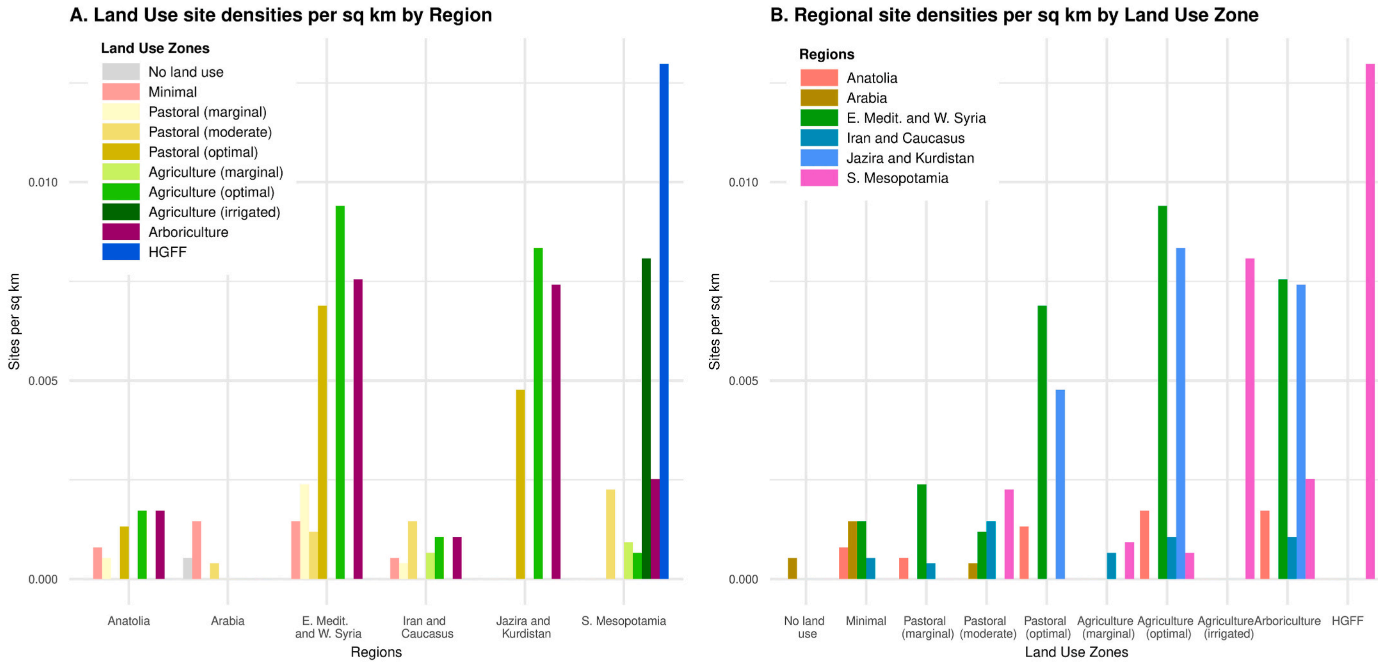

Fig. 4. Regional site densities per km^2, organized by a. region and b. land use zone.

communities in the optimal agricultural land-use zone, and 4.5 ha per sheep/goat for the marginal agricultural land use zone. Further discussion of these values can be found in Supplementary Text ST1.

We allocated land use using circular buffers of fixed areas around each site location (observed and modelled sites, as described in Section 3.3.2), first allocating agricultural land, and then the required area for pastoral land use. This method frequently results in overlapping land use buffers between proximate sites, particularly in the southern Levant and in southern Mesopotamia (Fig. 5). This identifies areas that exhibit discontinuities between reconstructed land use needs and available land, suggesting overexploitation of existing land resources or that site populations required smaller amounts of agricultural and grazing land than we have modelled here. We initially conducted experiments with methods involving land use allocation on a pixel-by-pixel basis around each settlement until the required area for each land-use type was met for each settlement. This method frequently resulted in sites being allocated land (for both agricultural and pastoral land uses) located several hundred kilometres from the site, obviously an unlikely scenario. We therefore ultimately decided to use fixed land use buffers as described above.

3.4. Conversion of land use reconstruction to LC6k system

Our raster of reconstructed actualized land use for 6 kya has a resolution of ca. 90 m, while the grid system used by the LandCover6K project has a resolution of 8 × 8 km (Morrison et al., 2021). Upsampling of the 90 m land use reconstruction accommodates the grid system used by LandCover6k. The land use classifications for each grid cell correspond to the LandCover6k land use classification system as illustrated in Table 3. Based on the raster of reconstructed actualized land use, we calculated the land-use values for each LandCover6k 8 × 8 km grid cell according to the land use category that forms the maximum percentage of the area of each grid cell, as illustrated in Fig. 6.

In addition to these land use classifications, according to the LandCover6k system, several additional descriptive variables are assigned to each grid cell specifying major crops and animals as well as the presence/absence of technologies, land use practices, and settlement characteristics such as fire-based industries, landscape-scale burning, and urbanism or large-scale mining (Morrison et al., 2021). For each 8 × 8 km grid square assigned to a particular land use in Fig. 6, we assigned the crop and animal variables on a regional basis using published palaeobotanical and zooarchaeological evidence, as summarized in Table 4 and discussed in further detail in Supplementary Text ST1. In areas where multiple variable values are likely to have been in use simultaneously (e.g., multiple cultigens, domestic animal species), values are organized so that those values most likely to have been the dominant ones are listed first.

4. Results

The final map of reconstructed fundamental land use zones is presented in Fig. 2. Average site densities per square kilometre for each of these land use zones, calculated on a regional basis, are shown in Table 2 and Fig. 4. The settlement distribution used to reconstruct actualized land use, including both known and modelled sites, is represented in Fig. 3.

Across the whole area under consideration, site densities are generally low in marginal zones, and higher in areas with optimal conditions for particular land uses. Site densities are higher in optimal pastoral and optimal agricultural zones compared to moderate or marginal pastoral and marginal agricultural zones, respectively. Site densities in the irrigated zone are highest among the agricultural zones, a pattern which is broadly expected due to the high agricultural productivity associated with irrigation agriculture. Site densities are highest overall in areas of the southern Iraqi marshes, where we reconstruct broad-spectrum resource use.

Regional differences in both absolute site densities, and in the distribution of site densities between different land use types, are evident (Table 2, Fig. 4). The most notable regional variations in site densities appear in the optimal agriculture and arboriculture zones. Site densities in both these areas are highest in the Eastern Mediterranean/Western Syria and in the Jazira/Kurdistan regions, with intermediate values in Anatolia. Intermediate site density values are also observed in the arboricultural zone in southern Iraq.

The degree of overlap for reconstructed land use buffers between proximate sites is shown in Fig. 5. This figure highlights areas where site-level population size may have been more constrained or where possible competition for resources indicates a need for more

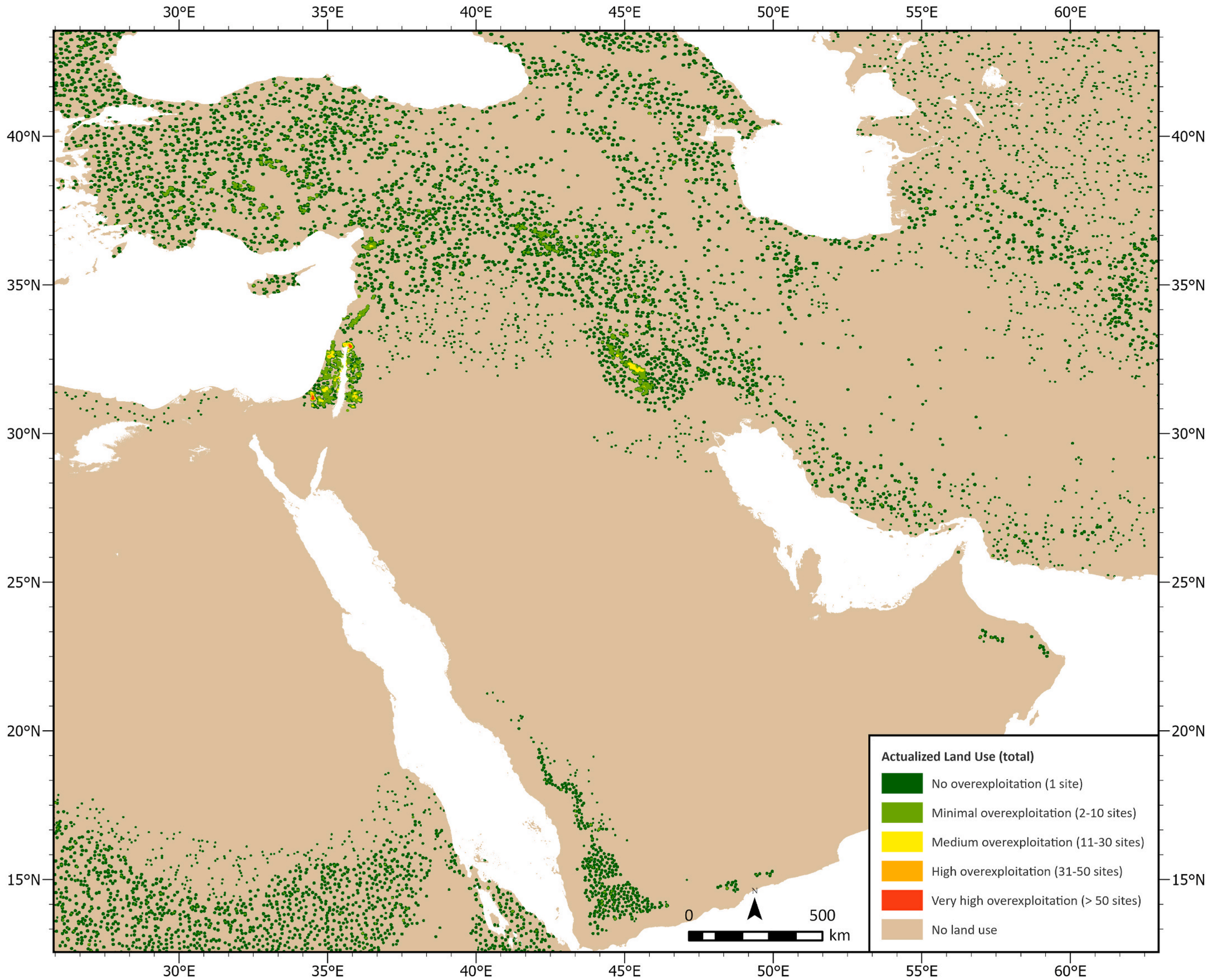

Fig. 5. Map illustrating the distribution of all land use types, highlighting areas where land use buffer regions for individual sites overlap, with colour indicating the number of site land use buffers overlapping. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Correspondence between actualized land use categories and Landcover6k classification system (as defined in Morrison et al., 2021).

Land Use Shorthand	LU1	LU2	LU3
None	No human land use	–	–
Minimal	Extensive/ minimal land use	–	–
HGFF	Hunting-gathering-fishing-foraging	Broad-based and aquatic resources	–
Agriculture	Agriculture	Herbaceous/ground crops	–
Irrigation	Agriculture	Herbaceous/ground crops	–
Arboriculture	Agriculture	Agroforestry/ arboriculture	Arboriculture (tree crops)
Pastoralism	Pastoralism	Anchored (in agricultural zones); Mobile-regular (in pastoralist zones)	–

investigation. Notably, this issue arises predominantly in areas involving site locations derived from archaeological survey data and occurs very infrequently in areas with randomly generated site locations, indicating that it is a real observed phenomenon and not an artifact of our site distribution process in unstudied areas. Rather, it indicates that there are additional factors influencing site location that contribute to site clustering that are not reflected in our random site generation process. It also suggests that site clustering would result in similar land use model results elsewhere, if actual survey data were produced for currently unsurveyed regions. The availability of chronologically specific site size estimates for surveyed sites would mitigate this issue, but accurate datasets on site size through time require intensive survey and excavation and will likely never be available for all identified archaeological sites.

The final reconstructed land-use values for each LandCover6k 8 × 8 km grid cell are illustrated in Fig. 6.

4.1. Comparison with previous global land use datasets

To determine how different modelling decisions impact large-scale land use reconstructions, we compare our reconstruction with

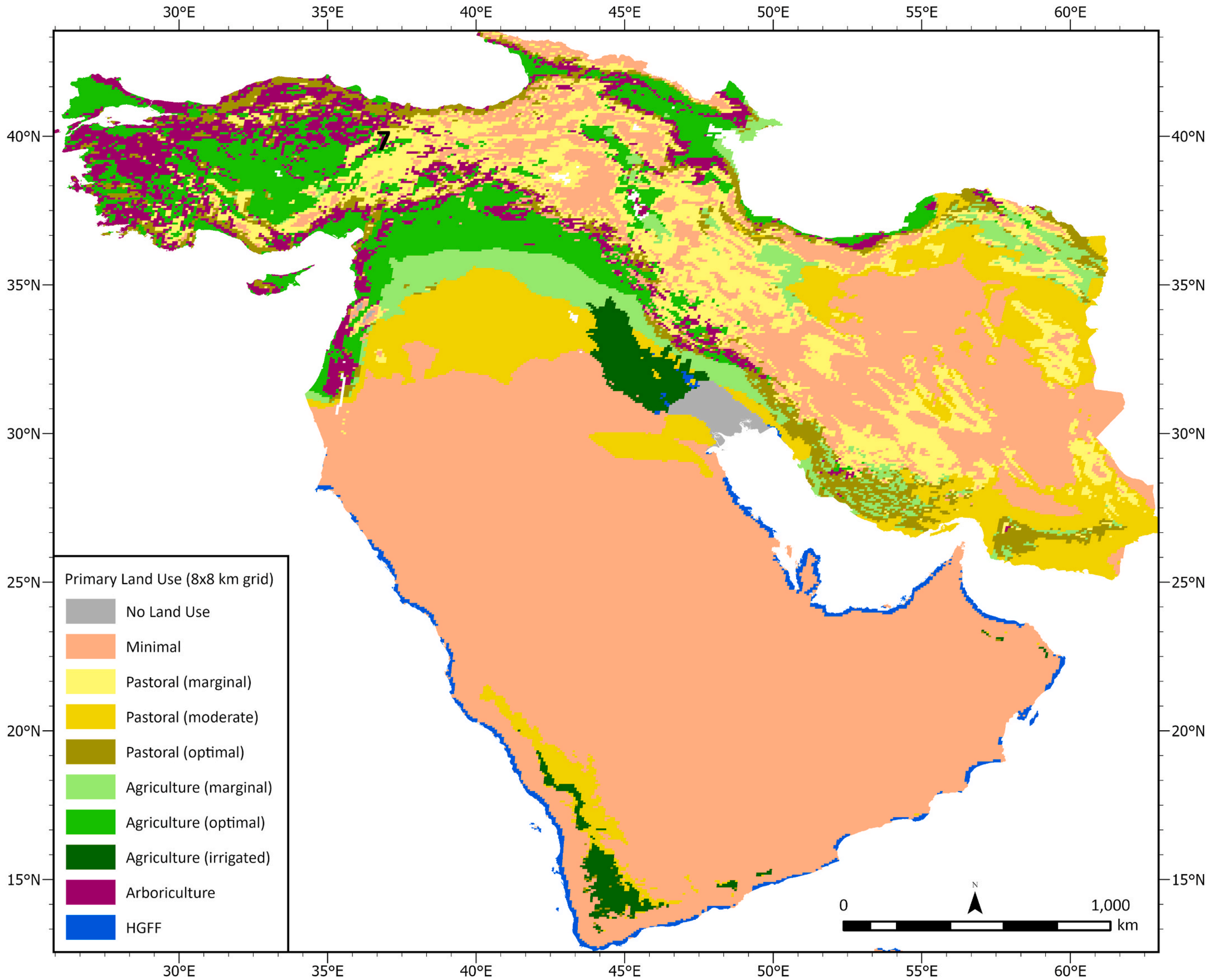

Fig. 6. Reconstruction of primary land use per 8 × 8 km Landcover6k grid cell at 6 kya.

commonly used global land use models, HYDE 3.2 (Klein Goldewijk, 2001; Klein Goldewijk et al., 2011, 2017a, 2017b) and KK10 (Kaplan et al., 2009, 2011, 2017; Kaplan and Krumhardt, 2011). In each case, to avoid *post hoc* manipulation of previously published model data, we represent our reconstruction in the same scale as these models were originally conceived and presented (i.e. percentage land use vs. square kilometres) and conduct our comparison on this basis. Comparison with HYDE 3.2 can be achieved at a more nuanced level because it uses similar land use categories to those employed here (i.e. agriculture and grazing, Fig. 7b–c, 8c-f). KK10 (Fig. 7a and 8a-b) provides only the percentage of each grid cell that is under *any* type of land use, without breaking this percentage down by land use type.

Our reconstruction differs from KK10 and HYDE 3.2 in two significant methodological ways:

- the distribution of population, which interpolates archaeologically observed settlement densities to environmentally similar areas with no available settlement data. The HYDE model estimates spatial distribution of population based on modern and recent historical sources and assumes gradual population growth over time that is relatively evenly distributed across space within modern administrative regions (Klein Goldewijk et al., 2010, 2017a). The KK10 model allocates population density between national and supra national units according to historical estimates (c. 1000 BCE- 1850 CE) of relative population density (Kaplan et al., 2009, 2011).
- the land use allocation, which follows a buffer-based approach. This means that areas under agricultural and/or pastoral land use are allocated around the modelled sites, and not allocated at all in the other areas. In contrast to the more continuous pattern produced by the modelling techniques used to create KK10 and HYDE 3.2, in part through their reliance on modern administrative divisions, our method results in a 'salt-and-pepper" effect caused by high local spatial heterogeneity between neighboring used and unused lands (Fig. 7).

We evaluated the differences between our model and the KK10 and HYDE 3.2 models (Fig. 8) by statistically testing the differences in pixel values through a region-based approach. We defined fourteen regions based on the spatial subdivision used to model rainfall data, which was in turn based on topographic and climatological homogeneity (Hewett et al., 2022; regions are shown in Fig. 3). We calculated (1) the under/overestimation of land use per region and (2) the clustering/dispersion of the differences.

In order to assess the under/overestimation between our model and

Table 4
Values assigned for Landcover6k variables (as defined in Morrison et al., 2021), by region (full discussion in Supplementary Text ST1).

		Southern Mesopotamia	Northern Mesopotamia	Levant	Anatolia	Caucasus	Iran	Arabia	Cyprus
HGFF	CULTIGENS	Date?	N/A	N/A	N/A	N/A	N/A	–	N/A
	ANIMALS	Cattle						Cattle, sheep/goat	
	WATER/LANDSCAPE MODIFICATION	–						–	
	TILLAGE	–						–	
	PYROTECHNOLOGY							–	
	SETTLEMENT MODE	Dispersed						Dispersed	
Agriculture/ Arboriculture	CULTIGENS	Barley, wheat, pulses, date	Barley, wheat, pulses	Barley, wheat, pulses, olive, grape?	Barley, wheat, pulses	Barley, wheat, pulses	Barley, wheat, pulses	Barley, wheat, chickpea, date	Barley, wheat, pulses
	ANIMALS	Cattle, sheep/goat, pigs	Sheep/goat, cattle, pigs	Sheep/goat, cattle, pigs	Sheep/goat, cattle, pigs	Sheep/goat, cattle, pigs	Sheep/goat, cattle, pigs	Cattle, sheep/goat	Sheep/goat, cattle, pigs
	WATER/LANDSCAPE MODIFICATION	Canals/channels, flood	Rainfed, manuring?	Rainfed	Rainfed	Rainfed	Rainfed	Rainfed, terracing	Rainfed
	TILLAGE	Plow/ard	Plow/ard	–	–	–	–	–	–
	PYROTECHNOLOGY	Ceramic	Ceramic, Metal (copper/ bronze/tin)	Ceramic, Metal (copper/ bronze/tin)	Ceramic, Metal (copper/ bronze/tin)	Ceramic, Metal (copper/ bronze/tin)	Ceramic, Metal (copper/ bronze/tin)	–	Ceramic, Metal (copper/ bronze/tin)?
	SETTLEMENT MODE	Aggregated, urban centres	Aggregated	Aggregated	Aggregated	Aggregated	Aggregated	Aggregated	Aggregated
Pastoralism	CULTIGENS	–	–	–	–	–	–	–	–
	ANIMALS	Sheep/goat	Sheep/goat	Sheep/goat	Sheep/goat	Sheep/goat	Sheep/goat	Cattle, Sheep/goat	Sheep/goat
	WATER/LANDSCAPE MODIFICATION	–	–	–	–	–	–	–	–
	TILLAGE	–	–	–	–	–	–	–	–
	PYROTECHNOLOGY	Ceramic, Metal (copper/ bronze/tin)?	Ceramic, Metal (copper/ bronze/tin)	Ceramic, Metal (copper/ bronze/tin)	Ceramic, Metal (copper/ bronze/tin)	Ceramic, Metal (copper/ bronze/tin)	Ceramic, Metal (copper/ bronze/tin)	Ceramic, Metal (copper/ bronze/tin)?	Ceramic, Metal (copper/ bronze/tin)?
	SETTLEMENT MODE	Dispersed	Dispersed	Dispersed	Dispersed	Dispersed	Dispersed	Dispersed	Dispersed

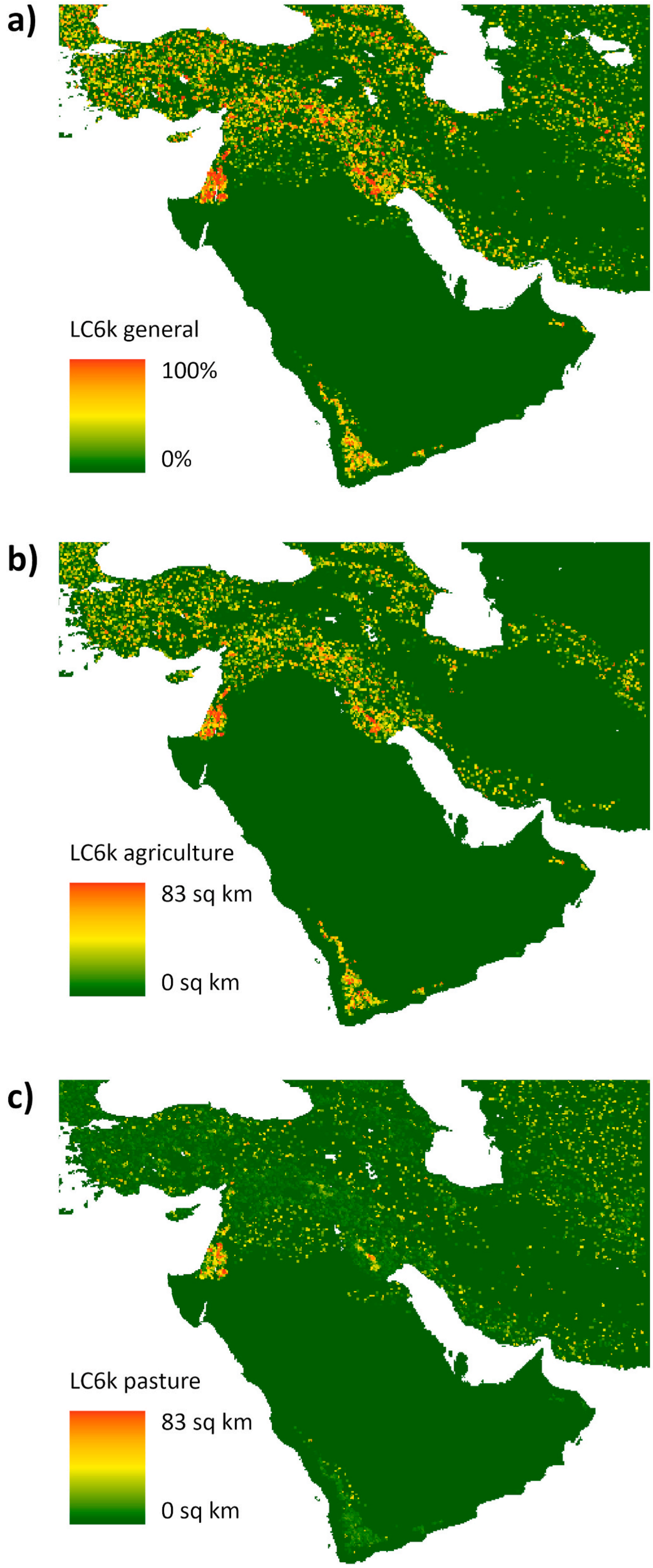

Fig. 7. Intensity of land use at 6 kya for this reconstruction showing a. all land use categories as a percent of area under land use (sum of areas of all agricultural, pastoral and arboricultural land use categories divided by total grid cell area); b. total area in square kilometres allocated to agricultural land use; and c. total area in square kilometres allocated to pastoral land use.

the compared models (1), we utilized the one-sample Wilcoxon signed rank test with a 95 percent confidence interval to determine whether the median of the differences in the pixel values is equal to zero (i.e., no difference between our model and the compared model). We also estimated the effect size (*r*) by dividing the *z* statistic by the square root of the sample size. We assessed 0.1–0.3 values as a *small effect*, 0.3–0.5 as a *moderate effect*, and $\geq$ 0.5 as a *large effect* based on criteria from Cohen (1988), albeit these values are arbitrary and should not be considered rigidly. Positive and negative values indicate whether our model (first variable) has respectively a greater or lesser total than the compared model (second variable). We employed Moran's test for spatial autocorrelation to determine the rate of clustering or dispersal of pixel value differences (2). Fig. 9 (values are reported in Supplementary Table S2) shows the obtained values as a cartesian plot with each quadrat describing the potential combinations of (1) and (2). Regions where statistical significance ($p = 0.05$) has not been achieved are marked in grey.

Our reconstruction tends to agree relatively well with the KK10 model (Fig. 10a) in the Mediterranean (R4) and Central Turkey (R7), the Caspian Region (R10) and the Caucasus (R9), while it slightly underestimates (*small effect*) land use in the Levant (R3) and Turkmenistan (R13) compared to KK10. The differences are particularly significant (*moderate effect*) in Syria and Iraq (R5), the Zagros (R12) and Iran (R11). In particular, KK10 displays very high levels of land use in the region of northern Iraq, a pattern that does not agree with the archaeological evidence and the reconstruction here (see Fig. 10a, inset 1). The distribution of land use in KK10 is likely affected by the model's method of allocating population density between national or supra-national units according to historical estimates of relative population density. One result of this approach is the appearance of major discontinuities along national borders in the KK10 dataset, perhaps most visible along the Iraq-Iran border.

Differences between KK10 and our approach are also visible in the northern part of the Arabian Peninsula (R2). While we modelled the entire region as minimal land use, KK10 allocates land use in the Hafar Al-Batin area due to recent population density data; these densities are made possible by modern groundwater pumping technology, which supports higher populations than would have been possible in the past. When compared to KK10, our model seldom overestimates (*moderate effect*) land use, and this mostly applies to Cyprus (R14) and the Black Sea area (R8). Due to the high density of archaeological sites, patterns of clustering differences in pixel values are found in the Southern Levantine region (R3, Fig. 10a inset 2), as well as in the Caucasus (R9), particularly the Kura-Araxes River lowlands and the plains of Southern Dagestan and Chechnya, where our model placed several randomly distributed sites in archaeologically unknown areas. The pattern is equally clustered in Iraq (R5) where archaeological sites are numerous in the Fertile Crescent and the rest of the region corresponds to minimal land use.

Major differences characterised our model and the HYDE 3.2 reconstruction of agricultural land use (Fig. 10b), particularly around cities that are major modern centres since HYDE projects these high population numbers back into the past, gradually replacing modern population distributions at greater time depths with weighting maps based on proxy variables similar to those used in our reconstruction of fundamental land use zones (e.g., soil suitability, slope; Klein Goldewijk et al., 2017a). The residual effect of this is most clearly visible along the Syrian and Lebanese coasts, in the Damascus basin in Syria (R3), and in the areas around Tehran and Rasht in Iran (R11, Fig. 10b inset 1). However, the modern distribution of population does not match the ancient distribution of population as reflected in the available archaeological data for 6 kya. A further difference between the allocation of agricultural land in HYDE 3.2 and that in our reconstruction pertains to the distribution of rainfed vs. irrigated agriculture (Supplementary Fig. 1). HYDE reconstructs much of the agriculture in southern Iraq (R5) as rainfed (except in the vicinities of modern Baghdad and

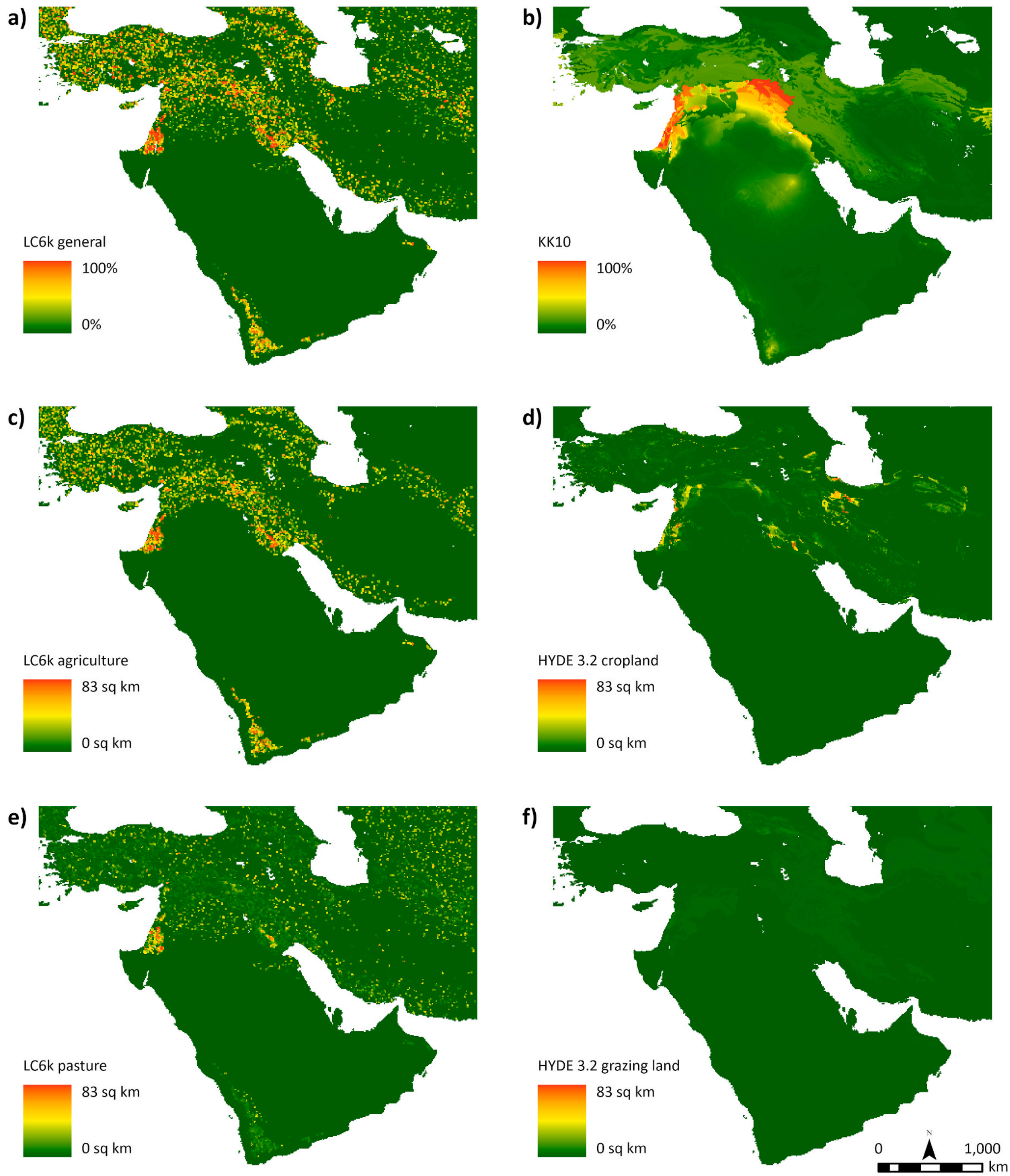

Fig. 8. Distribution of land use at 6 kya for a. this reconstruction, showing all agricultural, pastoral and arboricultural land use categories combined as a percentage of total area; b. KK10, showing all land use types as a percentage of total area; c. this reconstruction, showing all agricultural land use in square kilometres per grid cell; d. HYDE 3.2, showing all cropland in square kilometres per grid cell; e. this reconstruction, showing all pastoral land use categories in square kilometres per grid cell; f. HYDE 3.2, showing all grazing land in square kilometres per grid cell.

Karbala-Hilla-Najaf), whereas we reconstruct that agriculture as irrigated. Archaeological and climatic evidence strongly indicates that agriculture in this region was irrigated rather than rainfed. Our reconstruction shows somewhat greater (*large effect*) agricultural land use in the Caucasus (R9) when compared with the HYDE 3.2, and is more similar to the KK10, with agricultural land use prevalent in the Kura-Araxes Lowlands and the Samur-Davachi plains, where HYDE 3.2 models intensive grazing. Similarly, greater (*large effect*) agricultural land use is modelled in the Arabian Peninsula, Egypt, and Sudan (R1 and R2). This is particularly visible in the areas of terraced agriculture in highland Yemen (Fig. 10b inset 2), the alluvial plainlands of Sudan and the Danakil Depression. Major differences also characterize Anatolia (R6) but this mainly results from different absolute values of pixels, due to our buffer-based method, rather than in a different spatial pattern.

Another significant feature of our reconstruction compared to that of HYDE 3.2 is the greater emphasis in our reconstruction on pastoral land use (Fig. 10c), which we reconstruct as more widely distributed across large areas of the region compared to HYDE 3.2's relatively sparse allocation of pastoral land at 6 kya. The most notable difference can be seen in Iran (R11, Fig. 10c inset 1), where our model reconstructs a greater rate of pastoral land use in the Kopet-Dag Mountains, in the Ghezel Ozan area and surrounding Lake Urmia, when compared with

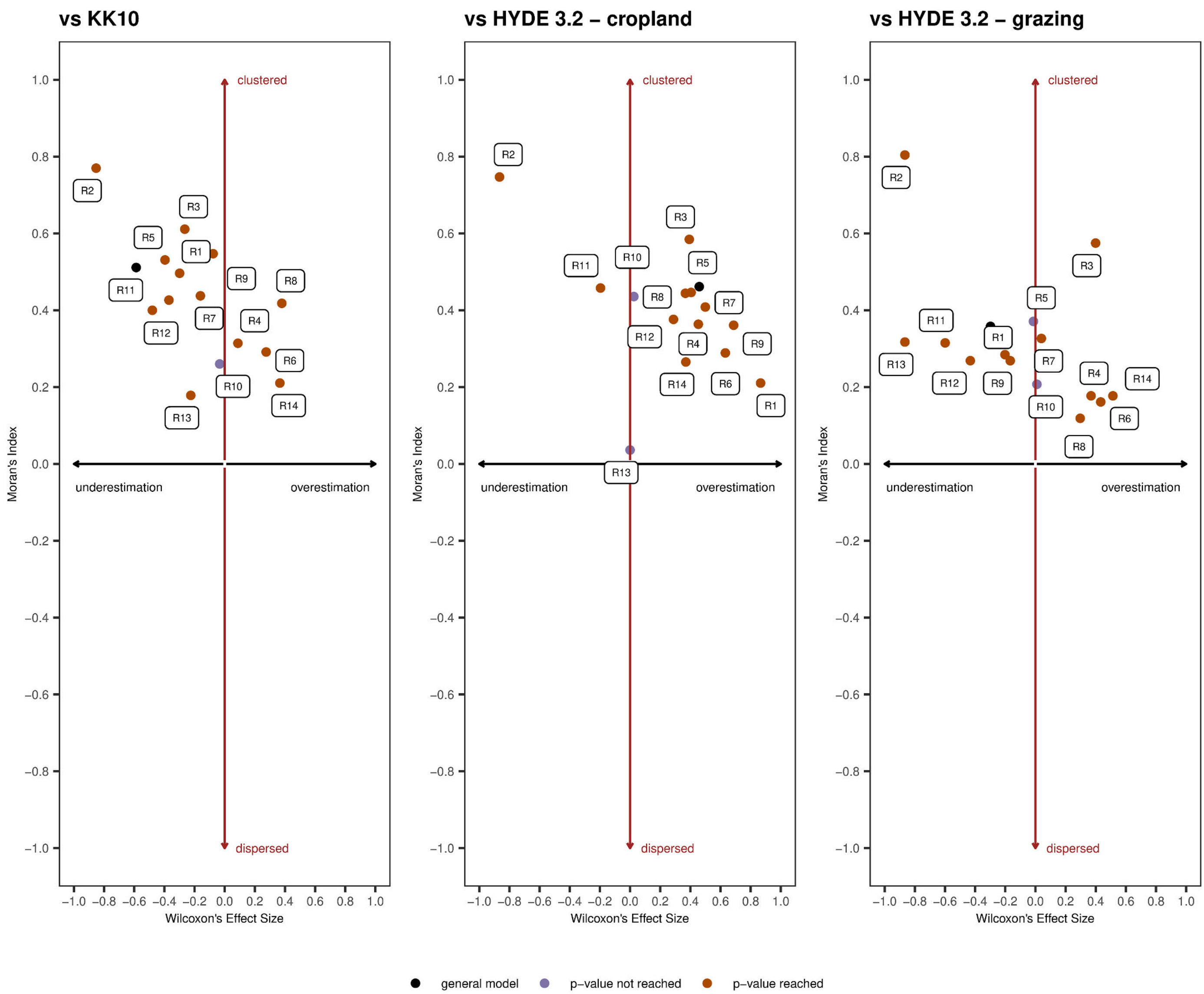

Fig. 9. Cartesian plots showing regional comparisons between this reconstruction and KK10 (left), HYDE 3.2 cropland (centre) and HYDE 3.2 grazing land (right). For each plot, the x-axis indicates the Wilcoxon effect size for each regional comparison, and the y-axis represents the Moran's index of spatial autocorrelation, indicating the degree of clustering versus dispersal of pixel value differences for each region.

HYDE 3.2. Similarly, we reconstructed intensive pastoral activities in the Zagros area (R12), although pastoral land use is not allocated in our model beyond 2000 m above sea level, unlike HYDE 3.2. Regarding Syria and Iraq (R5), unlike HYDE 3.2 our model does not cluster pastoral activity along the axis formed by the Jabal Abu Rujmayn and Jebel Bishri, and distributes land use more evenly (Fig. 10c inset 2) across Mesopotamia and the pre-desertic areas of the Middle Euphrates region.

5. Discussion and conclusion

In this contribution, we have reconstructed land use for Southwest Asia at 6 kya by drawing upon a variety of environmental data (topography, soil depth, precipitation, etc.) to suggest a range of possible land use types that could have been employed in particular environments, given the technological constraints particular to this timeframe. We have then used archaeological data, particularly settlement data, to reconstruct actual land use patterns for this period. Our results, when compared with the most commonly used global land use reconstructions (HYDE 3.2 and KK10), are generally more similar to HYDE 3.2, although showing greater agricultural land use and somewhat different spatial patterning. Our reconstruction shows less overall land use compared to KK10. These results support the idea that archaeological data can be successfully used to constrain land use reconstructions to create empirically derived datasets for use in global climate modelling scenarios.

The large-scale reconstruction of land use at 6 kya resulting from the approach outlined here can be improved through the incorporation of additional settlement data as they become available, permitting more accurate estimation of regional variability in site density, and less reliance on settlement density extrapolation. Further experimentation with more nuanced methods of modelling site placement in relation to additional environmental variables would also improve the weighted random generation of site locations based on observed datasets. The potential for greater data availability in the short term varies. In some areas, no additional settlement data is currently available and newly acquired data is likely to be limited in the short term but in others, such as Iraqi Kurdistan and the Arabian Peninsula, settlement datasets are rapidly growing through ongoing archaeological survey work. For other areas, for example Iran, additional data exists but has not yet been systematically collated and synthesized. This reconstruction could also

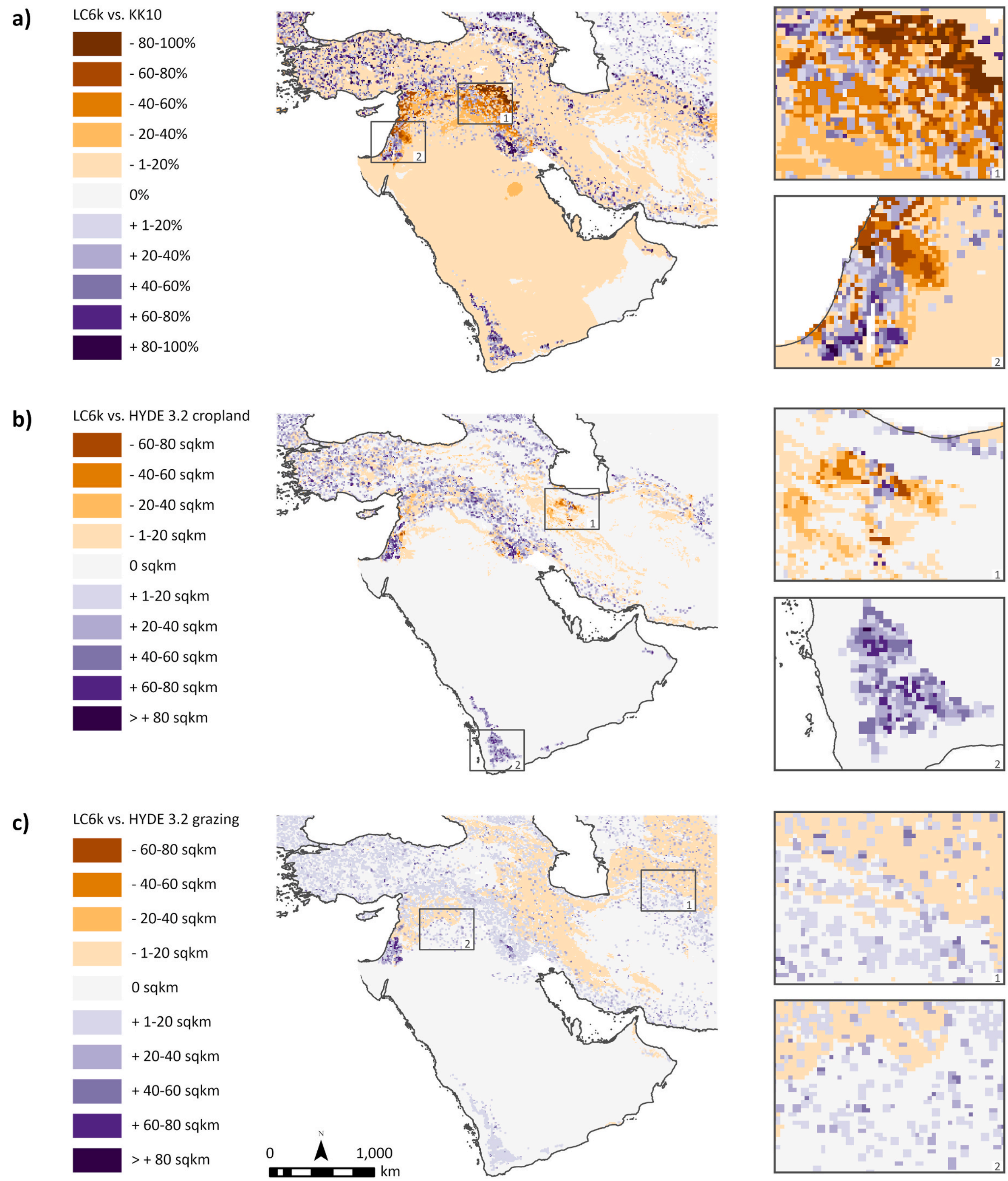

Fig. 10. Map illustrating spatial distribution of percent differences in land use between a. all land use in this reconstruction and KK10 (insets for 1. northern Iraq and northeastern Syria; 2. the southern Levant), b. agricultural land use in this reconstruction vs. HYDE 3.2 cropland (insets for 1. northwestern Iran; 2. southern Yemen); and c. pastoral land use in this reconstruction vs. HYDE 3.2 grazing land (insets for 1. northeastern Iran; 2. central Syria). Areas where this reconstruction indicates less land use than KK10/HYDE3.2 shown in shades of brown; areas indicating more land use shown in shades of purple. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

be improved by the creation of more widespread palaeo-topographic reconstructions, and by the availability of larger datasets estimating past precipitation in the region originating from a wider variety of climatic zones.

The methodology outlined here can also be employed to reconstruct land use patterns for other time frames, contextualizing the results of this study through more nuanced consideration of changes in land use over time. Further investigation is also required to more systematically compare regional patterns of land use to available bioarchaeological datasets, and to link these patterns to social phenomena such as urbanism (Lawrence et al., 2023). Such an investigation has been undertaken for zooarchaeological data (Gaastra et al., 2021, 2024), but additional study of the relationship between land use and available palaeobotanical data remains essential. There also remains a need for more nuanced modelling of land use potential, and comparison between larger and smaller regional or micro-regional scales (Bonnier et al., 2019; Geyer et al., 2019; Laabs and Knitter, 2021; Knitter et al., 2019).

The approach employed here has significant interpretive potential for future archaeological research. This includes more detailed comparison of fundamental vs. actualized land use zones to identify key areas of discontinuity. Examination of long-term changes in actualized land use will permit more systematic identification of temporal shifts in the exploitation of different land use zones. One example of such a shift where more data would be particularly valuable is the expansion of settlement during the 3rd millennium BCE into zones that had not previously been systematically exploited, representing a key shift in land use practices. This includes the expansion of arboricultural zones in upland areas of the Levant, and increased exploitation of steppe environments in northern Syria (Wilkinson et al., 2014). Another example is the significant shifts in settlement in the Arabian peninsula that occurred in the late 2nd-early 1st millennia BCE following the domestication of the camel, with notable expansion into the desert zone (Magee, 2014). Our study has also identified areas of discontinuity where mismatches exist between reconstructed land use needs and available land (Fig. 5), indicating potential overexploitation of land resources and a need to consider site population sizes in estimating land use zones via a buffer-based approach. Greater scrutiny of these areas, particularly in the context of long-term shifts in land use patterns, has the potential to contribute to better understanding of the relationship between political and economic changes, shifting subsistence practices and the implementation of resource management strategies.

In addition to being a valuable tool for archaeological research, the reconstruction presented here holds significant utility for the climate modelling community; it can be an input for systematic testing of the impact of LULC scenarios on climate reconstructions. This is true particularly when it is combined with the efforts of the PAGES-LandCover6k initiative to create similar land use reconstructions for other regions of the globe. Finally, this study clearly demonstrates that archaeological data can not only be profitably incorporated into LULC reconstructions, but that its explicit integration both constrains their current variability and improves their empirical basis; we therefore call for increased archaeological data input into global LULC reconstruction efforts.

CRediT authorship contribution statement

Lynn Welton: Conceptualization, Data curation, Methodology, Visualization, Supervision, Writing – original draft, Writing – review & editing. **Emily Hammer:** Conceptualization, Data curation, Methodology, Supervision, Writing – review & editing. **Francesca Chelazzi:** Data curation, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Michelle de Gruchy:** Data curation, Methodology, Formal analysis, Writing – review & editing. **Jane Gaastra:** Data curation, Writing – review & editing. **Dan Lawrence:** Conceptualization, Data curation, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2024.109142.

Data availability

Data is included with supplementary data

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