Exploring the Common Ground of Landscape Ecology and Landscape Archaeology Through a Case Study from Eastern Anatolia, Turkey

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Abstract

Context. Landscape archaeology has a lot to offer to landscape ecology, being an interdisciplinary approach that emphasizes the study of long-term human–environment dynamics.

Objectives. We outline different conceptualizations of landscape in landscape archaeology and illustrate the potential of the approach for collaborating with landscape ecologists by describing a case study from the multi-period site of Arslantepe, located in the Malatya province of eastern Anatolia, Turkey.

Methods. We use an agent-based modeling platform to understand the socio-economic transformations at Arslantepe during the Early Bronze Age-I.

Results. These simulations revealed long-term dynamics of grassland and woodland under different climate and population scenarios. It was found that both grassland and woodland responded most strongly to changes in population, with woodlands being more sensitive. Further, it becomes evident that the adapted site-tethered pastoralism could have brought more sustainable land use practices.

Conclusions. The example shows the tremendous potential landscape archaeology has for studying long-term sustainability issues, especially related to modes of production. The landscape archaeological perspective can be linked with expertise provided by landscape ecologists, and we propose more in-depth collaboration of these two fields that offer diverse yet complementary perspectives.

Keywords: abandonment, agent-based modeling, Arslantepe, climate change, Early Bronze Age, landscape archaeology, sustainability

Introduction

The debate about the Anthropocene and sustainable development has generated interest in research on long-term dynamics of socio-ecological systems to gain insights into issues like rates of change, safe operating spaces, and tipping points (Dearing et al. 2015). Landscapes are prime spheres to study such sustainability issues, as they are the result of multidimensional relationships between ecological and societal processes (Wu 2013; Bürgi et al. 2017). Consequently, landscape ecology has a rich tradition of looking into the historical dynamics of landscapes and related ecological – and to a lesser degree, societal – issues (see, e.g., Tappeiner et al., this issue).

Landscape archaeology on the other hand, complements landscape ecology by providing expertise on human activities in the (distant) past and related land use and land cover changes. Through the studies going further back in time, landscape archaeology has a lot to offer studying the long-term human–environment dynamics through interdisciplinary approaches as landscape archeology aims to correlate human societies with their natural settings while assessing emergent adaptive behaviors due to natural and anthropogenically induced environmental changes (Altaweel 2008; Barton et al. 2012). In this paper, we evaluate how landscape ecology could benefit from increased collaboration with landscape archaeology. We start by outlining how archaeological findings have been integrated into landscape ecological research so far, and we discuss the different conceptualizations of 'landscape' in landscape archaeology. At the example of the renown and well-researched archaeological site of Arslantepe and its landscape development during the Early Bronze Age, we illustrate how agent-based modeling can help to investigate long-term sustainability at the landscape level even for prehistoric times. We conclude the article by discussing the potential for collaboration between landscape ecology and landscape archaeology based on the presented case study that offers promising venues for joint research initiatives.

Role of archaeology in landscape ecology

In a conceptual contribution, Scharf (2014) specified the interest of landscape ecologists in a deep-time perspective for (a) tracing land-use legacies, (b) revealing the interplay of long- and short-term ecological processes, and (c) providing input for restoration and management plans, such as evaluating the sustainability of land-use practices. Archaeological evidence has been used in landscape ecological studies to analyze settlement patterns and landscape changes from a long–term perspective (Silbernagel et al. 1997), which can provide relevant background information to build more informed future scenarios (van der Leeuw et al. 2011). To more explicitly address the ecological dimension of long-term changes in socio-ecological systems, it is possible to combine archaeological data with paleoecological data, such as pollen and plant macrofossils (e.g., Mercuri 2014; Florenzano 2019), for more accurate assessments. When interpreting archaeological and paleoecological records, we have to remember the limitations of such data sets, as they reach us only after taphonomic processes have occurred.

Conceptualizations of landscape in landscape archaeology

Archaeologists study landscapes mainly because they are habitats of past societies (i.e., human shaped landscapes). Consequently, they hold numerous clues about management and design intentions. The similar concept of landscapes as the expression of an interplay between people and the environment corresponds well overall to the concept of cultural landscapes (Förster et al. 2012). However, the specific conceptualizations of landscape vary significantly between the different scientific traditions within archaeology and the associated research questions (Gillings and Pollard 2016). These traditions differ mainly in the discipline they are rooted in (i.e., natural sciences, human geography, and social science or cultural studies). Settlement archaeology addresses landscapes as the physical setting for the dwelling and economic actions of past societies (Knopf 2013), with a focus on economic and ecological topics like resource management or location factors. Tools and approaches from the natural sciences, such as GIS or soil analysis, are often used (Gramsch 2003). Agent-based models allow us to study the long-term impacts of socio-ecological systems on the local environment by simulating dynamics that are not tangible in the archaeological record (Barton et al. 2012) (see also the Arslantepe case study presented in this paper).

In contrast, archaeologists working with theories and methods from human geography and social science view landscape foremost as a space of social interaction. One of the critical concepts acknowledged today from Tuan's (1979) concept of space and place: by living in a landscape, people continuously reproduce their surroundings, or - more precisely - their interpretation of the perceived surrounding. This perspective means that by physically engaging with the local environment, the idea of the landscape, intimately entangled with the collective cultural memory of a community, is not only confirmed continuously but also transformed over time (Ingold 2000; Tilley 2010). Consequently, both the archaeological record and paleoenvironmental reconstructions are remnants of past landscapes that also reflect social structure (Gramsch 2003). Finally, archaeologists using theories from cultural studies often focus on perceptual experience and the symbolic meaning of landscapes, which holds especially true for archaeologists working with a phenomenological approach (Thomas 2008; Tilley 2010). In practice, the different conceptualizations are not mutually exclusive (Gillings and Pollard 2016). In a recent study, for example, Ballmer (2018) discussed the various theoretical and methodical approaches in archaeology to study the spatial arrangement of burial mounds in the landscape.

Case study Arslantepe

To further explore the common ground of landscape ecology and landscape archaeology, we present a case study from the multi-period site of Arslantepe, located in the Malatya province of eastern Anatolia (Fig. 1). Long-term interdisciplinary research at Arslantepe allows for a detailed reconstruction of landscape changes. By analyzing archaeological evidence in a landscape context, we are able to explore the reasons for significant social, economic, and political transformations during the Early Bronze Age (EBA). Agent-based modeling (ABM hereafter) and simulations based on different scenarios in climate, population density, and habitat conditions make it possible to assess the long-term impact of site-tethered pastoralism under given conditions and to determine the sensitivity of the model to variability in various input parameters. Consequently, the ABM approach will allow us to test various socio-ecological scenarios to understand the sustainability of social systems under well-defined parameters.

Study area – archaeological context

Arslantepe has been studied intensively by the Italian Arslantepe Archaeological Mission, who have been carrying out excavations and surveys in the region for more than five decades. Arslantepe is a 30-meter-tall mound covering approximately four hectares and containing eight levels that span from the Late Chalcolithic (ca. 6200 cal. BP, see Vignola et al. 2019 for a revised chronology) to the Iron Age (ca. 2660 cal. BP) periods (Frangipane 2010a; Restelli 2012; Frangipane 2012a). Situated on the Tohma River, a major tributary of the Euphrates (Fig. 1), Arslantepe had an advantageous location, not only for agriculture but also for semi-nomadic pastoralism due to the undulating topography around the site and

Beydağ Mountain nearby (Palumbi 2012). Additionally, Arslantepe was at the intersection of a land route that connected Mesopotamia, the Caucasus, and Central Anatolia. Consequently, from the earliest times on, Arslantepe has acted as a hub of cultural, technological, and economic exchange (Stein 2012).

Arslantepe is well known for its Hittite (Late Bronze Age, ca. 3700 cal. BP) and Neo-Hittite (Iron Age ca. 3150 cal. BP) phases, due to extensive textual and archaeological evidence. However, discoveries in the last couple of decades suggest that the site had already become a significant hub in the Late Chalcolithic (ca. 5300–4950 cal. BP) period as a result of the Uruk expansion from southern Mesopotamia. This expansion was related to the aim of establishing long-distance trade networks (Frangipane 2010b; Restelli 2012). During the transition into the EBA, an intensive fire destroyed the settlement; major social (i.e., de-centralization) and economic (from specialized agricultural production to specialized pastoralism) transformations took place. Although various hypotheses exist to explain such changes (e.g., warfare, invasion by a new group, or social unrest), archaeological evidence does not provide sufficient proof to support any of them. Based on archaeological evidence, EBA-I has become recognized as a phase where a new mode of production (i.e., pastoralism) emerged along with a social group that had a different organization (i.e., heterarchical tribal groups) than the hierarchic society of the Late Chalcolithic.

Study period

The period of interest for this research (EBA-I, 4950–4700 cal. BP, grey columns in Table 1) is between the 5.2 ka and the 4.2 ka climate events, both of which represent episodes of drought in the archaeological record of the Near East (Staubwasser and Weiss 2006; Weiss et al. 1993). Although the drastic changes recorded for Arslantepe between the Late Chalcolithic period and EBA (especially EBA-I) might have been the result of such wide-ranging climatic changes, the evidence for climatically induced socio-economic transformations is sporadic and limited in the archaeological record (Kuzucuoglu and Marro 2007). Previous research on the paleoclimate of the region clearly illustrated that the climate of the region was going through a phase of instability around the transition from the Late Chalcolithic to EBA (Arıkan 2014). At Arslantepe, intensive agriculture was the primary subsistence type during the Late Chalcolithic period, which might have caused some environmental degradation. However, according to Redman (2005), it is hard to judge whether environmental degradation changed the functioning of the societies or whether the change in land use took place as the former administration stopped working.

Long-term anthropogenic impacts, coupled with the climatic instability, might have necessitated specific adaptive measures in the EBA-I phase, resulting in changes in social organization (hierarchy vs. heterarchy) and/or subsistence system (intensive agriculture vs. pastoralism) to adjust the reliability and resilience of the socio-ecological system (sensu Redman and Kinzig 2003; Redman 2005). Following the corporate/network spectrum for social organization proposed by Feinman (2000), we argue that the Late Chalcolithic society fits the definition of the network type of organization. Network organization focuses on the concentration of wealth and its distribution under an exclusionary (hierarchical) structure, as opposed to EBA-I social, political, and economic transformations that brought the corporate organization through staple finance with corporate labor (Feinman 2000). In order to reduce environmental stress on society, such systems tend to include different segments of society as their focus shifts to survival, e.g., during a climatically unstable period (Feinman 2000). However, the corporate organization does not necessarily mean an egalitarian structure. These shifts in organizational scales may be perceived as adaptive behaviors and may explain how various modes of pastoralism (e.g., transhumant, site-tethered) became the predominant subsistence types for the remainder of the EBA in the upper Euphrates Basin. Based on the lack of centralized structures and trade evidence, we accept that the EBA-I settlement had the corporate mode of social organization.

Economy, society, and political organization during the Late Chalcolithic and EBA-I periods

The growing influence of Uruk culture in southern Mesopotamia started to penetrate the northern extremities of the Fertile Crescent after 5850 cal. BP (Stein 2012), which corresponds to Level VII (5850–5300 cal. BP) at Arslantepe (Table 1). The settlement might have covered the whole mound, and Temple B dominated the site (Frangipane 2010a). Social differentiation among the members of the community was evident from the chief's residence (Frangipane 2010a; Restelli 2012). In the following phase of the Late Chalcolithic, Level VI A (5300–4950 cal. BP), the "Palace" became an imposing structure at the site (Fig. 2), which implies that the social and economic power of the elites had increased considerably and had become more permanent than in the preceding phase (Frangipane 2010a; 2012b). The increase in the number of standardized vessels, seal impressions, and storage facilities suggests a redistributive economy and specialized agricultural production in this phase (Frangipane 2010b; Restelli et al. 2010).

The settlement during the first phase of the EBA-I (Level VI B-1, 4950–4850 cal. BP) was much smaller than in the previous phase (Fig. 3) (Frangipane 2012a). The wattle and daub architectural style might point to a seasonal settlement at Arslantepe, which also implies a de-centralized social organization (Alvaro 2010; Frangipane 2010b). The results of agent-based modeling presented in this paper inform us about the fate of this seasonal settlement Later in the EBA-I (Level VI B-2, 4850–4750 cal. BP), an extensive transformation resulted in the emergence of a village (Fig. 4) (Alvaro 2010) organized under a chief (Frangipane 2012b). Level VI B-2 ended with destruction of the settlement by fire, and a mostly nomadic population settled at the site during the final decades of the EBA-I (Level VI B-3, 4750–4700 cal. BP) (Frangipane 2012b), which emerged as a specialized transhumant nomadic pastoralist society in the EBA-II (Level VI C, 4700–4450 cal. BP) (Siracusano and Bartosiewicz 2012).

In summary, following the breakdown of the Late Chalcolithic culture, people started to practice site-tethered pastoralism that gradually evolved towards a specialized nomadic pastoralist society in the EBA-I. In this socio-economic evolutionary scheme, the EBA-I was a transitional period, with its de-centralized social organization that practiced site-tethered pastoralism (Frangipane 2012b; Palumbi 2012; Siracusano and Bartosiewicz 2012).

The paleoenvironment of Arslantepe

Geoarchaeological research at Arslantepe has focused on the Holocene paleosols, which helped to date an increased erosional activity to the middle of the late Chalcolithic period (ca. 6150 cal. BP) (Table 1); however, the exact reasons for this process remain undetermined (Dreibrodt et al. 2012). Zooarchaeological analyses have revealed a decrease in the frequency of brown bear and red deer, and an increase in the population of hare, in Level VI A (Bartosiewicz 2010). These shifts implicate that the land cover changed from semi-open coniferous forest to open grassland around the site. This transformation was also visible from the temporal changes in the kinds of wood used for construction (Alvaro 2010; Bartosiewicz 2010). Nevertheless, the climate of this phase (Level VI A) was wetter and more humid, as suggested by the presence of predominantly hydrophilous plants (Masi et al. 2012a; 2012b). Their presence also pointed to a riparian environment around the site (Sadori and Masi 2012). Stable carbon isotopes from deciduous oak remains are consistent with this reconstruction and indicate that around 5200 cal. BP the climatic instability started with a dry phase (Masi et al. 2012a).

The climate of Level VI B-1 (4950–4850 cal. BP) was reconstructed based on the most commonly found non-arboreal, hygrophilous species (Masi et al. 2012a; 2012b). In VI B-2 (4850–4750 cal. BP), the population of these hygrophilous species increased significantly, suggesting that woodland steppe replaced the riparian environment of the Late Chalcolithic (Sadori and Masi 2012). Although the exact reasons for this transformation remain unclear, such changes could have been due to a significant drop in humidity or to overexploitation (Masi et al. 2012a). The climate of Level VI C (EBA-II, 4700–4450 cal. BP) featured an increase in humidity, and it was relatively stable between 4700 and 4250 cal. BP (Masi et al. 2012a; Sadori and Masi 2012).

Interdisciplinary research at Arslantepe implies that changes in the paleoenvironment (e.g., the amount of precipitation and humidity) triggered behavioral adaptations of Arslantepe society (Sadori and Masi 2012). These changes led to the drastic economic transformations and the apparent decentralization in the political organization during the onset of the EBA. Stochastic and ABM platforms make it possible to simulate the dynamics of the newly introduced economic system of site-tethered pastoralism and to explore the plausibility of different possible developments (Arıkan 2012).

MedLanD Modeling Laboratory (MML)

The Mediterranean Landscape Dynamics (MedLanD) Modeling Laboratory (MML hereafter) is a platform that enables exploration of different impacts that past socio-ecological systems had on the environment and assessments of how these might have reached a critical long-term transition in the, from sustainable to high-risk systems. MML is not a tool to reconstruct the past; it is a hybrid modeling platform that simulates social, economic, and environmental dimensions of long-term land-use decisions, along with the natural changes in the environment (e.g., surface processes) (Mayer and Sarjoughian 2007; Barton et al. 2015). Consequently, MML has become a laboratory to assess past socio-ecosystems, their dynamics, and interrelated decisions about land-use through simulations. This method is an effective tool to explore potential reasons behind past societies' decisions, as well as the long-term effects of these decisions on the environment when coupled with natural changes (Kohler and van der Leeuw 2007; Ullah 2013; Barton et al. 2015).

The fact that MML computes multiple, independent entities according to a set of decision-making logic and connects the social processes with the natural processes makes it an ABM platform. ABMs are especially valuable in coupled systems research, as they take into account emergent properties: phenomena that cannot be predicted at the start of the model and develop within the system over time (Bonabeau 2002). Whereas other ABM platforms efficiently simulate natural or social processes (Kohler et al. 2007; Altaweel 2008; Cioffi-Revilla et al. 2010), MML has proven to connect these two separate processes in one platform successfully. Moreover, MML uses open-source scripts, which can be easily modified to customize the simulations for a specific case (Kim et al. 2009).

The spatial structure of MML uses GRASS GIS, which means simulations are run with high-resolution settings (e.g., 5–15 meters). Social (i.e., land use) and natural processes (e.g., erosion and deposition) are fully integrated, which makes it possible to establish full feedback cycles of a dynamic nature in order to accurately simulate the impacts of natural and social factors on a given landscape. MML simulates events at an annual scale, combining discrete events, such as population growth and the selection of plots, and time-averaged processes, such as landscape evolution or changes in vegetation.

In MML simulations, households constitute the smallest economic unit of past societies (Kramer 1982; Wilk and Rathje 1982; Kamp 2000). Several households form a village, and although MML is a hierarchical model where individual decisions, such as the allocation of land, take place at the level of the village, there are many levels where agency plays a significant role (e.g., decisions related to subsistence). Currently, MML only simulates societies that practiced dry farming and site-tethered pastoralism for self-subsistence, as the ethnographic data from the Mediterranean illustrate (Watson 1979; Kramer 1982; Kamp 2000; Al-Jaloudy 2006). In addition to agropastoral production and landscape evolution, the population of each household becomes the third variable in simulations, as the intensity of economic activities and the physical range of human impact depend on population numbers. Table 2 summarizes the parameters used in MML, and Ullah (2013) provides a more detailed explanation for the associated algorithms.

At the start of an MML simulation, households randomly choose plots to use according to their population size. Households develop subsistence plans concerning how many plots will be dedicated yearly to farming, grazing, and firewood gathering, i.e., the model does not adopt the concept of tenured plots. MML also accounts for the real-life situation of farmer/herder biases about production and rates of yield (Christensen and McElyea, 1988; Rhoton and Lindbo, 1997; Koriat et al., 2000) by randomly introducing bias in decision-making related to these economic activities.

The agents pick the farming and herding plots according to several criteria, i.e., distance to the village to maintain cost efficiency (i.e., the minimum cost of movement on the terrain and the maximum yield from that plot), the degree of slope to ensure the presence of deep and fertile soil, and the type of land cover to determine the amount of vegetation on the plot. Since farming is the only land-use practice in these simulations that disrupts the natural connection between vegetation, soil, and nutrient flow, soil fertility is assumed to be 100% at the start, and it decreases or increases depending on the impact of farming on the plot (e.g., erosion, de-vegetation) (Khresat et al. 1998; Oba 2012). Although the Late Chalcolithic agriculture caused some loss in soil fertility, we assume that this had a negligible impact on the pastoralist economy of the EBA-I group. Consequently, MML simulates feedback relationships between the changes in soil fertility and the farming returns from patches.

The Application of MML for Arslantepe

Arslantepe represents a prime opportunity to apply ABM to understand ancient land use and human decision-making. Intensive and long-term research at the site has resulted in diverse sets of archaeological, paleobotanical, zooarchaeological, and geoarchaeological data. In these respects, the site is a "natural laboratory" for collecting evidence about varied human behavior over a long period. The rich database makes it possible to prepare experimental protocols for modeling the effects of an agropastoral type of economy on habitat diversity. Through ABMs, it is also possible to test the effects of a specific type of land use under changing climatic conditions. The MML scenarios simulated for the EBA-I at Arslantepe presented here differ in terms of three main variables, i.e., climate, population density, and land cover (Table 3). Long-term archaeological and paleoenvironmental research at Arslantepe suggests that during the EBA-I, the site had a relatively *wet* climate (no major droughts but seasonality changes from homogeneous rain events to sudden discharge events), *woodland* environment, and normal population density (italicized scenarios in Table 3; see Table 4 for population density definitions).

To feed the climate module, we obtained average annual precipitation and temperature values for the Middle Holocene paleoclimate of the Malatya region from the Macrophysical Climate Model (MCM). The data suggest that the seasonality of precipitation changed from the end of the Late Chalcolithic period onwards from homogeneous rain events to sudden discharge events distributed over the year (Arıkan et al. 2016), defining what we called *wet* climate conditions in our simulations. For the *dry* climate scenario, precipitation values were reduced by 10%. A transitional climate scenario, i.e., a shift from wet conditions throughout the first half of the simulation to dry conditions during the second half, was applied to simulate effects of sudden climate changes.

To estimate the population data, we combined the average size of a habitation unit from Level VI B-1 at Arslantepe with ethnoarchaeological comparisons across the Near East (Watson 1979; Kramer 1982; Kamp 2000). Based on this assessment, we assumed that four individuals lived in each household unit at Arslantepe, corresponding to 24 individuals for the *normal* population density at the site at the start of the simulation (Table 4). There is a cap on the population increase in MML in order to maintain computational efficiency. The number of calculations increases as population increases in a village, and CPU time required to simulate all the relationships makes a single run take much longer. Table 4 shows the maximum population and the year that it was reached in the simulation.

In order to simulate land cover change with MML, several variables are of importance. MML requires that the climax stages for each land cover type are specified, as well as the length of time that any specific vegetation class would need to reach climax from bare land (Table 5). In simulating the changes in land cover, one has to consider that vegetation classes differ in biomass. However, by using the coefficient of variation (CV hereafter), i.e., the ratio of the standard deviation to the mean, it is possible to compare the effects on classes with widely differing amounts of biomass. Higher CV values stand for higher variability in biomass. We use CV because it provides a unitless number for comparing biomass with different volumes. For the woodland environments a maximum of 35 classes, ranging from bare land (class 1) to tall brush steppe and sparse trees (class 35), are distinguished in the model, whereas for the grassland environments a maximum of 25 classes and corresponding amounts of biomass are modeled, i.e., from bare land (class 1) to tall grass steppe and brush (class 25). Additionally, each land cover type has a specific C-factor value (land cover management index), which expresses the degree of protection against erosion.

Modeled habitat changes

We present simulations using a wet climate and woodland environment, in combination with three different population densities (i.e., low, normal, high) in order to reflect the scale and intensity of impacts that vary with population density. Out of nine scenarios for the woodland environment, three scenarios reflect the range of developments (Fig. 5). Population density emerges as the most influential variable. Overall, woodlands started to decline after 20 to 40 years and levelled off 90 to 100 years into the model run, whereas biomass diversity dropped even further after population stabilized (Fig. 5). In a low-population-density scenario, woodlands showed minimal change for 250 years (CV = 5.25), and the most dramatic decline in woodlands took place under high population density (CV = 3.25).

Out of nine scenarios simulating the grassland environment, again, the three with varying population density show the range of developments (Fig. 6). The most dramatic decline in biomass diversity again occurred with high population density. Although the vegetation went through a similar change with woodland scenarios, variability at the end of the simulations was much lower for grassland scenarios. In other words, biomass diversity of grassland environments was less affected by differences in population density (CV= 4.2–4.4).

Anthropogenic impacts on the landscape of Arslantepe

Using GRASS GIS, it is possible to map the spatial extent and intensity of human activities and the effects on land cover. Changes in a woodland environment under low population density and related low levels of anthropogenic land use turn out to be limited in terms of the area affected, even after 250 years, as grasses replaced woodlands only around the settlement site (located at the center of the impact zone, Fig. 7). Under high population conditions, however, the size of the core impact zone expanded relative to the increase in intensity and scale of anthropogenic activities. This led to a more extensive conversion of woodlands and intensive grazing activities, which caused erosion especially on the slopes of to the south of Arslantepe (Fig. 8). The simulations of a grassland environment under the wet climate and low-population-density scenario (Fig. 9) and under the wet climate and high-population-density scenario (Fig. 10) revealed unexpected patterns. The size of the anthropogenic impact zone around the core site differed depending on the population size; however, grazing seemed to de-vegetate a considerable area. This is especially true for the mountainous area just south of Arslantepe, where many steeps slopes eroded due to grazing (Barton et al. 2010).

Insights from the Arslantepe case study

ABM of the socio-ecological dynamics at Arslantepe during the EBA-I provides invaluable insights concerning the range and intensity of anthropogenic impacts under different climatic, land cover, and population conditions. The changes in habitat reflect the sensitivity of different types of land cover to anthropogenic impacts. Woodland, the dominant vegetation type at Arslantepe during the EBA-I, offered more diverse habitat types; however, it was more heavily affected by long-term anthropogenic impacts than the grassland environment, as shown by the wider range of CV values for woodland under three different population densities. Regardless of the level of population density, CV values for grassland scenarios remained close to each other at the end of simulations. The higher susceptibility of woodland environments to higher levels of human impacts is due to higher values of biomass at the start of the simulations, resulting in a more substantial loss if impacts reached a certain threshold.

In low-population-density scenarios, spatial simulations of grassland environments resulted in land cover classes that did not emerge in woodland environments, i.e., bare soils, which occur in all grassland environments (Fig. 9 & Fig. 10). Similarly, in high-population-density scenarios, the size of the anthropogenic impact zone in the woodland environment (Fig. 8) was much larger than in the grassland environment (Fig. 10). This result suggests that, in the long-term, grassland was more heavily affected by increased anthropogenic activity: biomass kept declining even when the population stabilized in simulations. The CV values for grassland (Fig. 6) seem to confirm these results because they kept declining even with a stagnating population. This pattern is in contrast with that for the woodland environment (Fig. 5), where CV values reached a plateau after around 100 years.

When looking at the CV values of the most likely EBA-I conditions at Arslantepe – a wet climate, normal population, woodland environment scenario following observations can be made: it is clear that 250-year-long, site-tethered pastoralism with self-sufficient agriculture did not cause significant changes in biomass and its variability. At the beginning of simulations (ca. 4950 cal. BP), CV was 6.0 for the EBA-I (Level VI B-1) settlement (Fig. 1). After 100 years, ca. 4850 cal. BP, the anthropogenic transformation of the native vegetation around the immediate vicinity of Arslantepe was complete, and it reached a plateau (Fig. 6 top) at a CV of around 4.5. At this point, the small settlement had grown to what might have been the EBA-I village (Level VI B-2, Fig. 2). The overall production capacity did not change until the end of the simulations. In other words, if the Level VI B-2 village had not burnt down or if people had rebuilt it, it could well have sustained a more substantial population.

The population of the post-destruction EBA-I settlement (Level VI B-3, 4750–4700 cal. BP) is known to have had a mostly nomadic character (Frangipane 2012a). Based on the results of agent-based, socio-ecological modeling, there does not seem to be an environmental reason, such as vegetation degradation or soil depletion, that would necessitate such an economic transformation. Consequently, non-environmental conditions may have necessitated the shift to fully nomadic lifeways.

Finally, the results of agent-based, socio-ecological modeling show that in a climatically unstable period, the residents at Arslantepe managed to survive and thrive by adapting to site-tethered pastoralism. Such adaptations required certain social transformations, such as the shift from hierarchic to heterarchic structure, accompanied by shifts in the mode of production (from intensive agriculture to mainly pastoralist economies). Under such transformations, the EBA-I population of Arslantepe grew into a village within a century. This transformation implies that heterarchically-organized societies may also reach social complexity by following a different path than traditional, agriculturalist societies with a hierarchical organization.

As stated at the beginning of the article, Arslantepe offers a unique opportunity to perform a detailed reconstruction of an Early Bronze Age landscape. The data available additionally allow to address various questions concerning the past socio-ecological systems. For such studies, ABM has become a valuable method to test various scenarios and to observe the emergent properties. Integrating landscape ecology in our interpretations of the ABM results allowed us to specifically discuss thresholds, ecological processes, and the long-term sustainability of the Early Bronze Age-I society at Arslantepe.

Landscape ecology and landscape archaeology – ways ahead

The interest of landscape ecologists in a deep-time perspective, as outlined in two of the three dimensions distinguished by Scharf (2014), includes tracing land-use legacies and revealing the interplay of long- and short-term ecological processes. Cegielski and Rogers (2016) see human ecology as one of the core themes within archaeology, where ABMs have a great potential to be applied and provide insights into the long-term human–environment dynamics, such as agropastoral land use and related landscape evolution. The link between these two perspectives is clearly illustrated in the case study of Arslantepe, where ABMs also facilitate study of the phenomenon, which is of interest to both landscape ecology and landscape archaeology alike.

In landscape ecology, legacy effects are receiving increasing attention, as present conditions often are a result of ecological processes or land-use practices which took place a long time ago, or regime shifts occurring as thresholds are passed due to cumulative effects, and not merely the present conditions, e.g., land-use intensity (Li et al. 2017). If the available data allow, ABMs can contribute to genuinely long-term integrative assessments of ecological processes, such as net erosion and deposition rates, and resulting feedbacks on the suitability of the land for specific land-use types and intensities in a spatially specific manner (Barton et al. 2012).

A long-term perspective on sustainability foremost helps set current challenges in perspective. Moreover, landscape archaeology confronts landscape ecology with the relevance of considering organizational structures, which, to a certain degree, go along with specific land-use practices. For analyzing the long-term sustainability of society–environment interactions, organizational structures certainly have to be considered but are often not on the radar of researchers interested in landscapes. By providing an example from the distant past, we show the potential of landscape archaeology and discuss its relevance for landscape ecology.

For the more direct application of the insights gained on, e.g., present land management decisions, studies making use of archaeological and paleoecological findings concerning the less distant past and on more recent phenomena will be necessary. However, the basic principles remain: interdisciplinary collaboration of landscape ecologists and landscape archaeologists makes it possible to study past land–society interactions in a spatially explicit manner. Whereas landscape ecologists can contribute by specifying the resulting ecological shifts and providing insights into potential feedbacks on socio-ecological systems from the ecological domain, landscape archaeologists provide expertise in interpreting the archaeological records and parameterizing the spatial societal impact and organizational context. Knitter et al. (2015) propose seeing landscape archaeology as a pillar built on expertise taken from the humanities and sciences, i.e., going beyond the usual picture of a bridge surpassing the gap between different communities. We indeed see the potential for a similar interdisciplinary pillar based on landscape ecology and landscape archaeology.

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Tables

Table 1. The archaeological record of Arslantepe from 6150 BP to 4450 BP and related environmental parameters. The model presented addresses the Early Bronze Age period EBA-I (columns shaded in grey). References are provided in the main text.

Duration	*5850–5300 cal. BP*	*5300–4950 cal. BP*	*4950–4850 cal. BP*	*4850–4750 cal. BP*	*4750–4700 cal. BP*	*4700–4450 cal. BP*
Period	*Late Chalcolithic*	*Late Chalcolithic*	*EBA-I*	*EBA-I*	*EBA-I*	*EBA-II*
Stratigraphy	*Level VII*	*Level VI A*	*Level VI B-1*	*Level VI B-2*	*Level VI B-3*	*Level VI C*
Interpretation of traditional excavation results	**The settlement covers the whole mound; temple functions as socio-economic focus**; social differentiation assumed based on **chiefs' residence;** growing influence of Uruk culture (southern Mesopotamia)	Redistributive economy, specialized agricultural production; a palace structure, **standardized vessels, seal impressions & storage facilities** indicate the increase of social and economic power of the elite; assumed fire destruction of palace approx. 5000 cal. BP	**A much smaller settlement**, buildings made by "wattle and daub", maybe seasonal? Probably de-centralized social organization	**A small village,** mudbrick architecture, narrow streets, fortification wall, possibly organized around a chief; destroyed by fire	Mostly nomadic population	Specialized transhumant (or nomadic) **pastoralist society**
Geo-/ Zoo-archaeological evidence	More brown bear and red deer compared to Level VI A suggest a **semi-open coniferous forest**	The analysis of construction wood confirms a decrease of brown bear and red deer, whereas an increase in hare points to **open grassland**;	Increase in ovicaprid population	A larger amount of seed remains from the site,	Increase in ovi-caprid population	
Climate	A wetter and more humid climate	5.2 ka event: reduction of precipitation in the headwater of Euphrates /Anatolia, deciduous oak remains as evidence that climatic instability starts with a dry phase	A phase of instability; no major drought but seasonality changes from homogeneous rain events to sudden discharge events spread apart over time in a year	Unstable climate	Unstable climate	Stable during 4700–4250 cal. BP, followed by 4.2 k event, triggering severe droughts & displacement of Mediterranean westerlies
Expected environment based on plant residues		**Riparian environment around the site** based on the presence of hydrophilous plants.	**Woodland steppe** based on non-arboreal / hygrophilous species.			

Table 2. Model parameters used in MedLanD Modeling Laboratory (MML).

Module	Sub-module	Parameters	Variables / units used	
Economy	Farming	Wheat	kg/ha	
		Barley	kg/ha	
		Environmental impact	amount of biomass removed or altered in cells (1 cell=100 m^2)	
		Total no. of plots	total = $w_{pop} + b_{pop} + w_{seed} + b_{seed}$	
		Distance to village	cost-efficiency	
		Deep and fertile soils	slope°	
		Type of land cover	plot	
		Environmental impact	plot – $veg_{nat} + veg_{cereal}$	
		Farming returns	kg $grain_{harv}$ = $((grain_{type} = a + bX_{precipitation}) + ((graintype = c + dX_{soildepth}) + ((graintype = e + fX_{soilfertility}))/3$	
	Herding	Ovicaprids	number	
		Total no. of plots	$total_{plot} = (matter_{needed} - matter_{crop-barely})/matter_{produced\ per\ plot}$	
		Distance to village	cost-efficiency	
		Environmental impact	net vegetation change	
		Herding returns	kg/h = edible biomass + grazing impact factor + land cover value	
	Wood gathering	Total no. of plots	$total_{plot} = (wood_{needed} - wood_{clearance})/firewood_{per\ plot}$	
		Distance to village	cost-efficiency	
		Dense woody material	number of cells (1 cell=100 m^2)	
		Environmental impact	net vegetation change	
		Wood gathering returns	kg/m = no. raster cells “dense wood” * gathering intensity	
	Natural setting	Climate	wet, normal, dry	
		Topography	alluvial floodplain with lacustrine sediments	
		Geology	limestone and andesite	
		Land use	50% agricultural, 50% pastoralist	
		Phytogeography	open woodland	
Population dynamics		Annual kilocalorie farming	kg yield * caloric yield	
		Number of animals (goats / sheep) fed	amount fodder = number animals fed/(goats*sheep)	
		Number goats / number sheep	ratio	
		Annual kilocalorie herding	$No._{sheep}$ * specific caloric yield + $No._{goats}$ * specific caloric yield	
		Probability Birth	10% over-production	
		Probability Death	10% under-production	
Landscape evolution		Impact precipitation (Unit Stream Powered Erosion Deposition – USPED)		
		Erosion / deposition (Revised Universal Soil Loss Equation – RUSLE)	Rainfall intensity factor (r-factor)	Monthly precipitation amounts
			Soil erosion resistance factor (k-factor)	% inclusion in soil
			Vegetation erosion protection factor (C-factor)	Ability of different vegetation to hinder water, cause sediment transportation
		Bedrock	Soil map	
		Transport capacity	Topographic relief, watershed geometry, area	

Table 3. MML simulations for the EBA-I at Arslantepe, addressing variations in the three variables climate, population, and land cover. Italicized scenarios reflect a combination that has been indicated by scientific research to exist at the site during this period. Shaded cells indicate further scenarios discussed in the results section.

Climate	Population density	Land cover
Wet	*Normal*	*Woodland*
Dry	Low	Grassland
Transitional	High	Shrub

Table 4. The calculation of different densities of the population at the start of the simulations, the maximum population, and the simulation year when the maximum population emerged.

Population density	Number of households (start)	Number of people per household	Total population (start/end)	Year maximum population reached
Low	3	4	12/225	75
Normal	6	4	24/450	69
High	9	4	36/675	84

Table 5. Land cover types differing in the number of years required to reach climax stage from bare land, and corresponding C-factor values expressing how prone to erosion the land cover types are.

Land cover	Time to maturity	C-factor value (land cover strength to protect from erosion)
Woodland	35 years	0.006
Grassland	25 years	0.05

Figure captions

Fig. 1. Location of Arslantepe (marked with a star) in the eastern part of Turkey (map based on free vector and raster map data @ naturalearthdata.com).

Fig. 2. Late Chalcolithic (Level VI A) plan of Arslantepe (after Frangipane 2010b). The palace was located in the residential area.

Fig. 3. Early Bronze Age-I (Level VI B-1) plan of Arslantepe (courtesy of M. Frangipane).

Fig. 4. Early Bronze Age-I (Level VI B-2) plan of Arslantepe (courtesy of M. Frangipane).

Fig. 5. Changes in CV values and population for woodland scenarios after 250 years of simulation.

Fig. 6. Changes in CV values and population for grassland scenarios after 250 years of simulation.

Fig. 7. Changes in a woodland environment under a wet climate and low population density. The legend shows vegetation classes from moderately sparse grass (5) to tall brush steppe and sparse trees (35) after 250 years of simulation.

Fig. 8. Changes in a woodland environment under a wet climate and high population density. The legend shows vegetation classes from bare land (1) to tall brush steppe and sparse trees (35) after 250 years of simulation.

Fig. 9. Changes in a grassland environment under a wet climate and low population density. The legend shows vegetation classes from bare land (1) to tall grass steppe and brush (25) after 250 years of simulation.

Fig. 10. Changes in a grassland environment under a wet climate and high population density. The legend shows vegetation classes from bare land (1) to tall grass steppe and brush (25) after 250 years of simulation.

Figure1

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Figure2

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Figure3 Click here to access/download;Figure;fig3.tiff

Figure4


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Figure5

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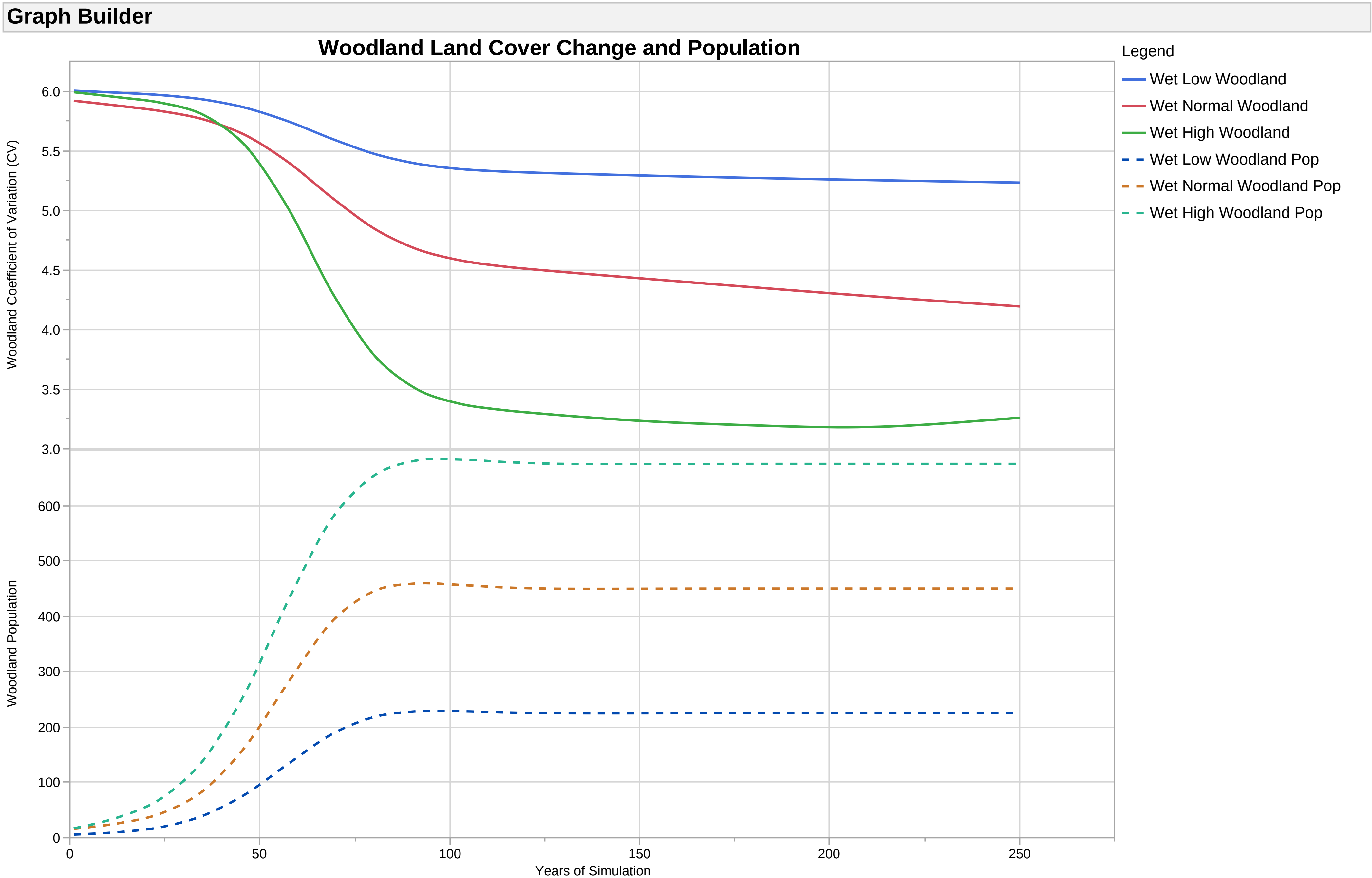

Figure6

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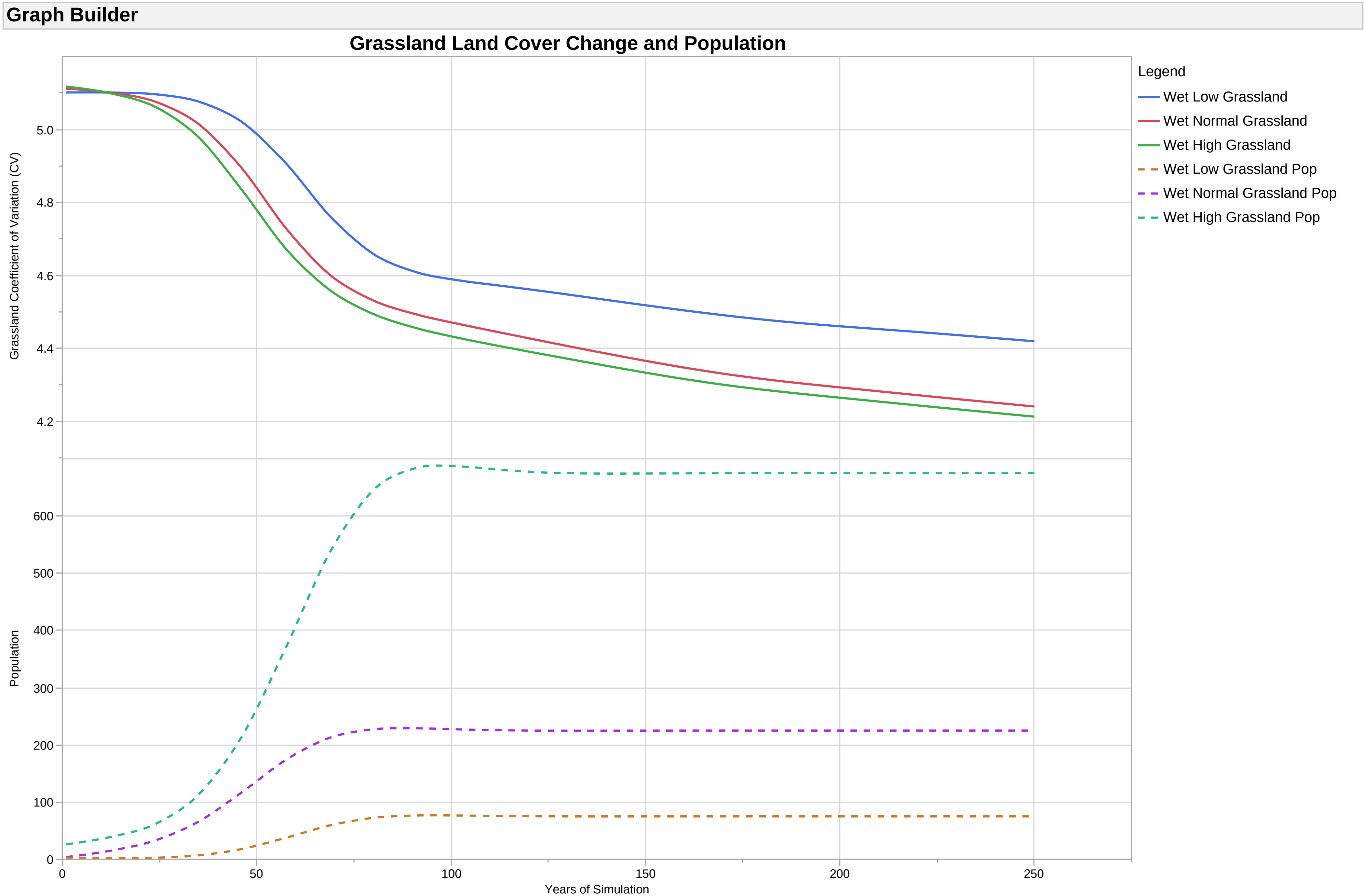

Figure7

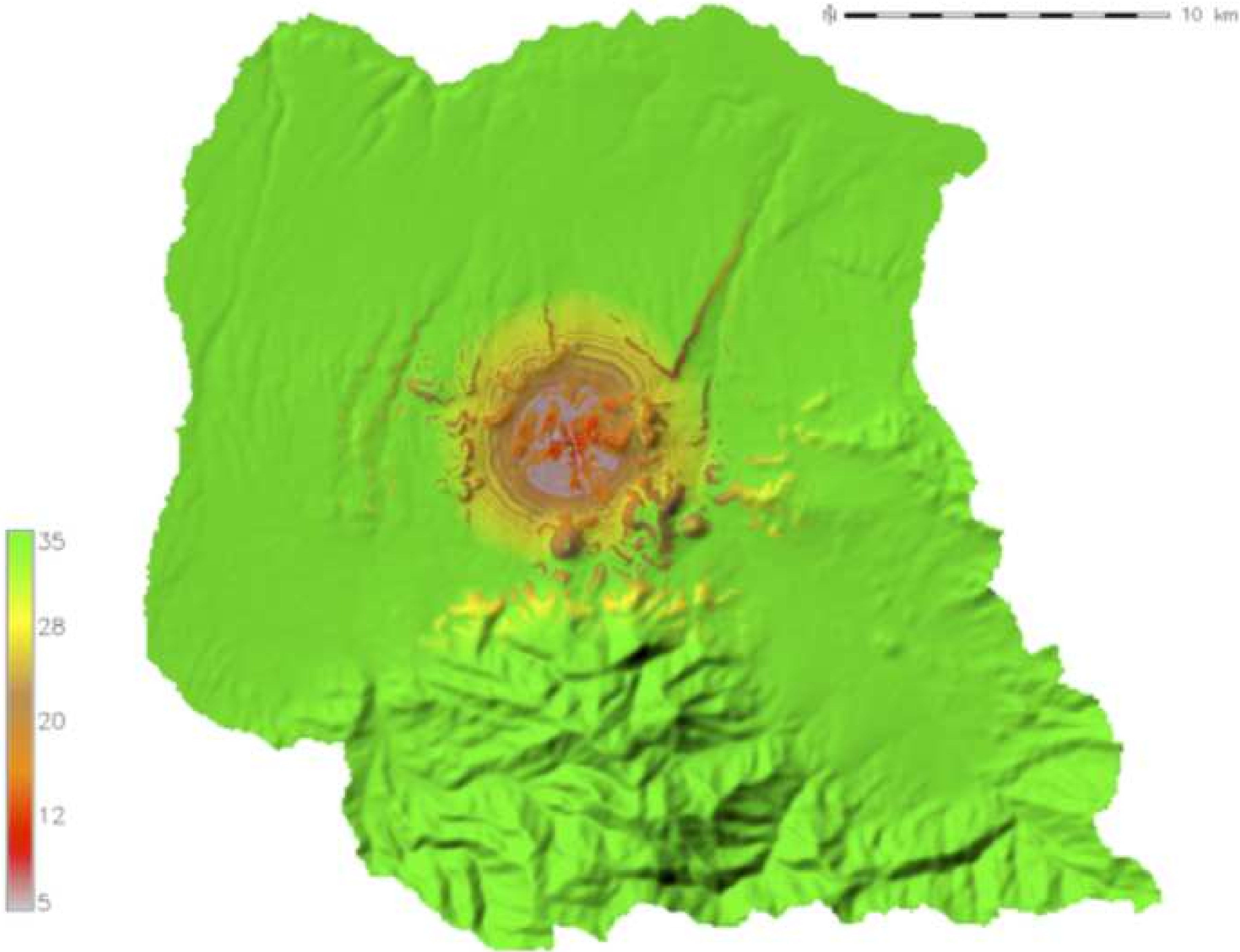

Figure8

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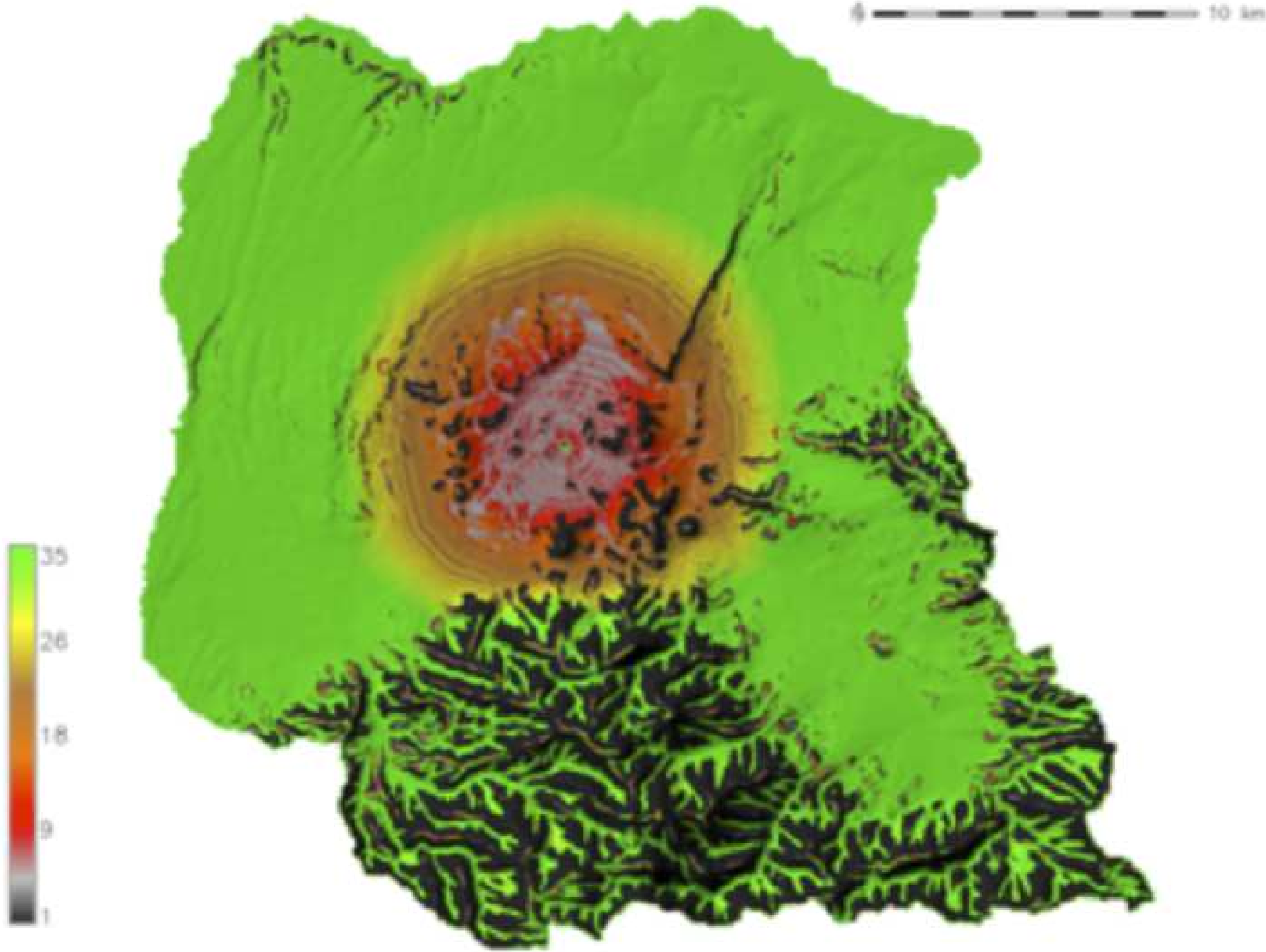

Figure9

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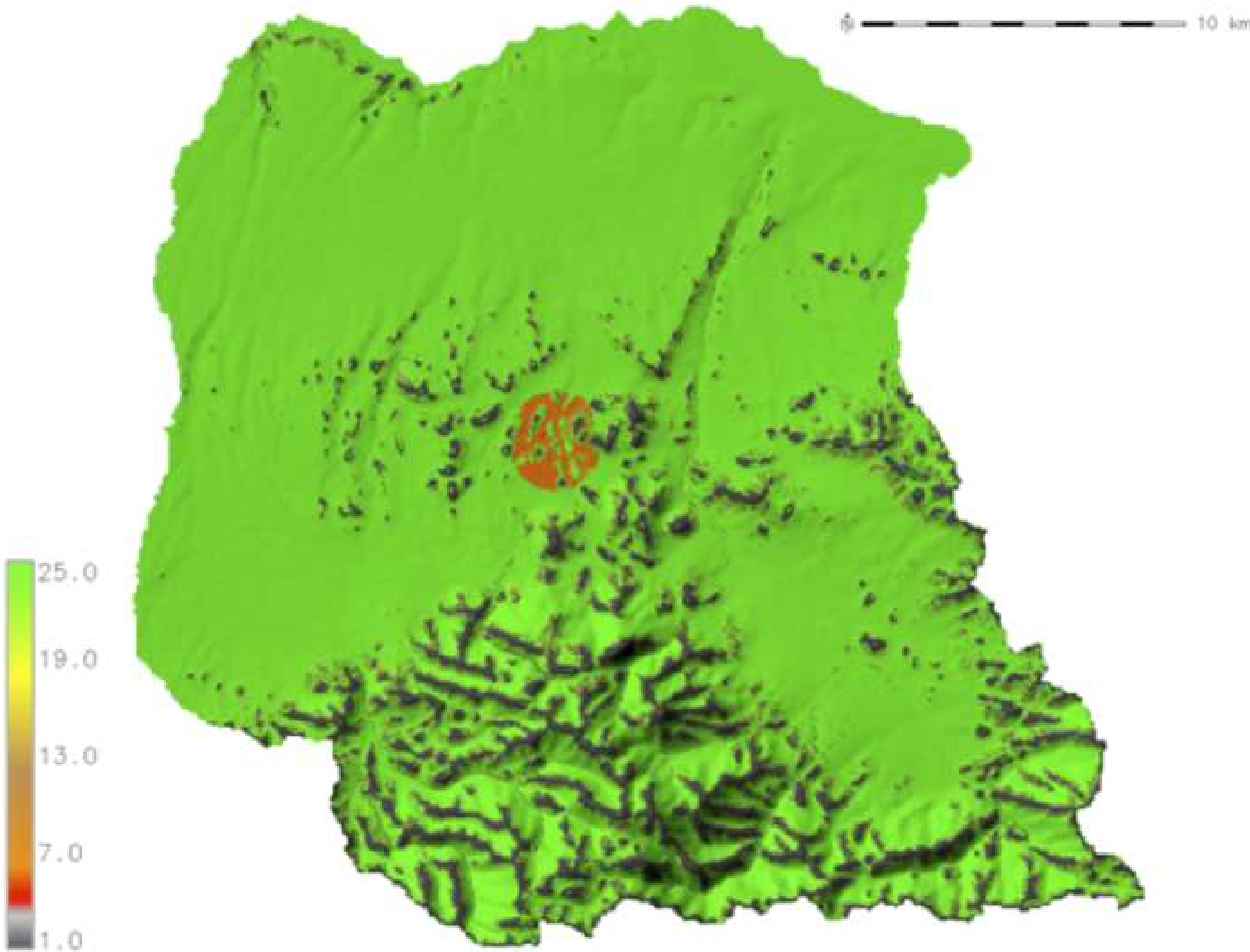

Figure10

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