A simulation of the Neolithic transition in Western Eurasia

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Abstract

Farming and herding were introduced to Europe from the Near East and Anatolia; there are, however, considerable arguments about the mechanisms of this transition. Were it the people who moved and either outplaced or admixed with the indigenous hunter-gatherer groups? Or was it material and information that moved—the Neolithic Package—consisting of domesticated plants and animals and the knowledge of their use? The latter process is commonly referred to as cultural diffusion and the former as demic diffusion. Despite continuous and partly combined efforts by archaeologists, anthropologists, linguists, palaeontologists and geneticists, a final resolution of the debate has not yet been reached. In the present contribution we interpret results from the Global Land Use and technological Evolution Simulator (GLUES). This mathematical model simulates regional sociocultural development embedded in the geoenvironmental context during the Holocene. We demonstrate that the model is able to realistically hindcast the expansion speed and the inhomogeneous space-time evolution of the transition to agropastoralism in western Eurasia. In contrast to models that do not resolve endogenous sociocultural dynamics, our model describes and explains how and why the Neolithic advanced in stages. We uncouple the mechanisms of migration and information exchange and also of migration and the spread of agropastoralism. We find that (1) an indigenous form of agropastoralism could well have arisen in certain Mediterranean landscapes but not in northern and central Europe, where it depended on imported technology and material; (2) both demic diffusion by migration and cultural diffusion by trade may explain the western European transition equally well; (3) migrating farmers apparently contribute less than local adopters to the establishment of agropastoralism. Our study thus underlines the importance of adoption of introduced technologies and economies by resident foragers.

Keywords: Europe, Linearbandkeramik, cultural diffusion, demic diffusion, agriculture, adaptation, migration, modelling

1. Introduction

The transition to agropastoralism in western Eurasia between 10000 and 3000 cal BC was associated with enormous cultural, technological and sociopolitical changes. Growing crops and herding animals have profoundly changed and continue to change global human history (e.g. Roth 1887; Westropp 1872; Diamond 2002; Mithen 2004; Barker 2006; Ruddiman 2006; Kaplan et al. 2010; Kuzbach et al. 2010). These changes may have been interpreted as a trajectory of progress in the way it had been seen by nineteenth and early twentieth century evolutionists (Westropp 1872; Childe 1936), or it may be seen as a road to perdición as it was, for instance, considered by J. Diamond (1997): “... a catastrophe from which we have never recovered. With agriculture came the gross social and sexual inequality.” However the interpretation, the transition to agropastoralism, often termed Neolithisation, constitutes a major period of change in the history of humankind.

1.1. Archaeology

Neolithisation is believed to have begun during the early Holocene in the Fertile Crescent, a mountainous region between the Levantine coast and the Zagros ridge (Flannery 1973). Archaeobotanical, archaeozoological and archaeogenetic work has demonstrated that all food crops and animals—except the dog—have their origins in and around the Fertile Crescent as a single founder region. The assemblage making up the Neolithic Package includes wheat, barley, rye, lentils, peas (Wilcox 2005), and cattle, sheep, goat and pigs (Luikart et al. 2001; Edwards et al. 2007; Larson et al. 2007; Zeder 2008).

While tendencies towards sedentism and storage of wild plants may already be interpreted from the Natufian data (Boyd 2006), intensive cultivation and domestication of both plants and animals gradually began during the Younger Dryas and only fully developed during the early Holocene (Zeder 2008; Wilcox et al. 2009). European agropastoralism is allochthonous and its most likely origins are in the Fertile Crescent, where farming and herding began—still in mixture with a broad spectrum of foraging practices—during the tenth millennium cal BC (Flannery 1973; Kuijt and Goring-Morris 2002).
The wider expansion of agropastoralism started around 8500 cal BC, approximately 1000 years after the first appearance of domesticated cereals in the Levant. The first clear evidence for colonist farmers was found on Cyprus (Peltenburg et al., 2000; Colledge et al., 2004; Wilcox, 2005); the expansion ended after 4000 cal BC, when Neolithic sites emerged on the British isles and throughout northern Europe (Sheridan, 2007; Whittle, 2007). Details of the intermediate region specific accounts of transitions have been collected, for example, by Price (2000), Whittle (2007), and Gronenborn and Petsas (2010), including the prominent sixth millennium linear pottery cultures of central Europe (LBK, e.g., Lüning and Stehli, 1994) and the funnel beaker culture of the northern European plains (TRB, after 4500 cal BC, Midgeley, 1992). Not only did agropastoralism spread to the northwest from the Near East centres but also eastward as far as the Indus valley (Fuller, 2006).

The question as to why agropastoral life spread has been recently connected to environmental variations and conflict resolution: (Dohukhanov, 1973; Weninger et al., 2009) and Gronenborn (2009a) suggested an emergence and spread of farming as a result of climate induced crises periods, during which it may have become necessary for groups to fission, i.e. to move from one location to the other to escape conflicts.

Two contrasting concepts on the mechanism of the spread of farming across western Eurasia have existed side by side. One suggests the introduction of the new agropastoral technologies through migrations of people—migrations of any form; the other suggests a technology shift through indigenous adaptations and inventions fostered by culture contact—information dispersal of any form. Zvelebil (1998) discriminates seven spreading modes, for example elite exchange or leap-frog colonisation, as combinations or intermediate forms of the two opposite spread mechanisms.

The acculturation or cultural diffusion model corpus has, in the more recent past, been applied by a number of processual archaeologists—more typically for the British isles but also for the continent (Hodder, 1990; Thomas, 1991). It may go back to a critique by, for example, Zvelebil and Zvelebil (1988) of a migrationist model proposed by Renfrew (1987) and later by others (e.g. Bellwood, 2005). In a way connected to these models are those of more complex scenarios of migrations and local acculturation notably in western central Europe and France (e.g. Jeunesse, 2000; Bentley et al., 2002; Gronenborn, 2007b), but acknowledges that long-distance contacts across western Eurasia did exist during the mid-Holocene and should, at least partly, have been maintained by the migration of people. It is yet unclear exactly when migrations began and what the relative importance of acculturation and movement of people was. It may not be ruled out that the large-scale population replacements around the Neolithic began with the onset of the sixth millennium cal BC (Gronenborn, 2007a, 2011).

1.2. Mathematical Models

The spatiotemporal structure of the advance of farming in Europe was first and very coarsely quantified by Edmonson (1961), who estimated the speed of the agropastoral transmission frontier at 1.9 km a⁻¹. Later, Clark (1965) and Ammerman and Cavalli-Sforza (1971, 1973) based their analysis on radiocarbon dates (in three areas, at 53 sites, 103 sites, respectively) to calculate the velocity of the appearance of farming practice in Europe along a southeast-northwest gradient. All three studies found an approximately linear relationship between temporal and spatial distance of European Neolithic sites to four Near Eastern sites, with a slope of approximately 1 km a⁻¹. Pinhasi et al. (2005) confirmed this finding on a more extended data set of 765 sites; they calculated a spreading rate between 0.8 and 1.3 km a⁻¹; even when shortest-path distances are considered (longer than great circle distances because of the detour necessary from the Near East to Anatolia and from central Europe to Iberia), a similar rate (0.6–1.1 km a⁻¹) is found. A data set of 477 sites, including boreal European sites, was used by Davison et al. (2006, 2007, 2009) who simulate for a noninteracting agropastoral subsistence style Neolithisation and its speed with a reaction-diffusion model. They too arrive at a mean speed of 1 km a⁻¹ into Europe.

Ackland et al. (2007) simulated the spread of farming by including a ‘hitchhiking’ advantageous trait in their reaction-diffusion model. This new lifestyle addition could either reflect the immigration of farmers, or a dynamical conversion of foragers into farmers upon contact. Their model predicts that Neolithic farmers outplaced the indigenous population up to a line approximately connecting today’s Venice–Prague–Warsaw–Moscow. To the north
Available evidence, in part originating from isotopic and genetic studies, points to a discontinuous expansion sequence for western Eurasia (Guilaine, 2001; Gronenborn, 2009; Bocquet-Appel et al., 2009; Schier, 2009) during which short dynamic phases of long distance rapid expansions were followed by periods of stand-still with local or regional colonisation. Discontinuities in the Neolithic advance, however, have not been hindcasted by the aforementioned models. One possible reason is that in the frameworks provided by Ackland et al. (e.g. 2007) or Davison et al. (2006, 2009) important aspects are missing. These may comprise more detailed descriptions of the resources needed and used by the people, the influence of the local biogeographic suitability for farming or herding, and of temporal variation in resource availability. Their models do not simulate any endogenous cultural, technical or agrarian development. All these factors may in principle accelerate or slow down the process of Neolithisation and lead to a more complex spatiotemporal pattern than may be predicted by simple reaction-diffusion models.

In this study, we employ the Global Land Use and technological Evolution Simulator (GLUES), which resolves local innovation, migration and cultural diffusion of traits (Wirtz and Lemmen, 2003; Lemmen, 2009; Lemmen and Wirtz, 2010). Although GLUES has been developed for the global domain, we restrict our analysis in this study to western Eurasia, where radiocarbon dates from Neolithic sites are abundant and of high quality, and where the issue of migration versus cultural diffusion is most intensively debated. The model is chosen because it allows us to differentiate between exchange (i.e. information exchange as cultural diffusion) and migration (demic diffusion) as important vectors of the expansion of agriculture.

In the following section, we shortly introduce the GLUES model and the radiocarbon site data which are used for validation; a full description of the algorithms used in GLUES can be found in the supplementary online material (SOM). The spatiotemporal pattern of the emergence and advancement of agropastoralism in western Eurasia is reconstructed and analysed in detail. This is achieved through a model-data comparison for ten focus regions along a southeast-northwest trajectory, from the Levant to north Germany; model-based expansion rates are put into the context of prior estimates from radiocarbon dates. A major part of our discussion concentrates on the discrimination of migration versus trade and the maximum contribution of immigrants to emerging agropastoral communities in Europe.

2. Material and Methods

GLUES mathematically resolves the dynamics of local human populations’ density and characteristic sociocultural traits in the context of a changing biogeographical environment. A local sociocultural coevolution is described by changes in mean population density, technology, share of agropastoral activities, and economic diversity, within a simulation region of approximately country-size extent (Figure 1). Each local population utilises its regional natural resources, which are described by vegetation productivity and climatic constraints. Each local population interacts with its geographical neighbours via trade and migration. The conceptual model is outlined below, for details on the algorithms used and the mathematical implementation we refer the reader to Wirtz and Lemmen (2003), summarised in the SOM.

2.1. Characteristic traits

For pre-industrial human societies, we define three characteristic traits:

1. Technology is a trait which describes the efficiency of food procurement—related to both foraging and farming—and improvements in health care. In particular, technology as a model describes the availability of tools, weapons, and transport or storage facilities. It aggregates over various relevant characteristics of early societies and also represents social aspects related to work organisation and knowledge management. It quantifies improved efficiency of subsistence, which is often connected to social and technological modifications that run in parallel. An example is the technical and societal skill of writing as a means for cultural storage and administration, with the latter acting as an organisational lubricant for food procurement and its optimal allocation in space and among social groups.

2. A second model variable represents the share of farming and herding activities, encompassing both animal
husbandry and plant cultivation. It describes the allocation of energy, time, or manpower to agropastoralism with respect to the total food sector. We define a local population as Neolithic when this share is larger than the share of foragers—regardless of its technology, economic diversity, or population density.

3. Economic diversity resolves the number of different agropastoral economies available to a regional population. This trait is closely tied to regional vegetation resources and climate constraints. We do not, however, attribute specific plants and animals to each economy. As an example, a value of four would be obtained when (1) domestic pigs and (2) goats and the growing of (3) barley and (4) wheat were present in a given population. A larger economic diversity offering different niches for agricultural or pastoral practices enhances the reliability of subsistence and the efficacy in exploiting heterogeneous landscapes.

The temporal change of each of these characteristic traits follows the direction of increased benefit for success (i.e., growth) of its associated population; this concept had been derived for genetic traits in the works of Fisher (1930), and was recently more stringently formulated by Metz and colleagues (Metz et al., 1992; Dieckmann and Law 1996; Kisdi 2010) as adaptive dynamics (AD). In AD, the population averaged value of a trait changes at a rate which is proportional to the gradient of the fitness function evaluated at the mean trait value. The AD approach was extended to functional traits of ecological communities (Wirtz and Eckhardt 1996; Merico et al., 2009; Smith et al., 2011), and was first applied to cultural traits of human communities by Lemmen (2001) and Wirtz and Lemmen (2003).}

2.2. Local resources

Each simulation region is defined by a largely homogeneous vegetation productivity (measured as net primary productivity, NPP), resulting in an average size of 130 \( \text{km}^2 \) (Figure 1). We reconstruct past distributions of NPP with a global climate model coupled to a vegetation module. Climber-2 (Claussen et al., 1999) temperature and precipitation anomalies from the NASA climatological data base (International Institute for Applied Systems Analysis, Leemans and Cramer, 1991) are converted to NPP according to the climate constraints on NPP from Lieth (1975); we do not use soil maps to constrain vegetation productivity.

From NPP, both the regional utility of natural food resources and the number of potential domesticates are derived. According to Braidwood and Braidwood (1949; 1950) hilly flanks hypothesis, potential domesticates were most abundant in open woodlands at low to intermediate NPP. The number of potential domesticates furthermore depends on a continental aggregation to account for the area-biodiversity relationship (e.g. Begon et al., 1993).

2.3. Exchange of information and people between regions

Information exchange and migration are vectors of the spread of technology, economic diversity, and farming practice from the founding centres to adjacent simulation regions. We discriminate the diffusion of traits without involving resettlement of people (cultural diffusion by information exchange), and the diffusion of traits via migration (demic diffusion). In GLUES, both mechanisms are driven by differences in influence between neighbouring local populations.

We assume that information travels two orders of magnitude faster than people. Exchange networks extend over distances of up to 1000 km, in the later Mesolithic and Neolithic (Mauvilly et al., 2008; Gronenborn, 1999); these networks were crossed many times during the active time—say ten years—of a Neolithic trader. Within this time span, a migration model like the one by Ammerman and Cavalli-Sforza (1973), would allow for an advance of only ten km. This parameterisation leads to diffusivities for migration on the order of ten km\(^2\)a\(^{-1}\), a value which is comparable to the diffusivities employed by other model studies of demic diffusion (e.g. Davison et al., 2006; Ackland et al., 2007; Patterson et al., 2010).

2.4. Reference data and simulated time scale

Our reference data set is the comprehensive data collection of 765 sites by Pinhasi et al. (2005). These authors used site data provided by the United Kingdom Archaeology Data Service, the Central Anatolian Neolithic e-Workshop (CANeW), the radiocarbon CONTEXT database, and the Radiokarbondaten Online (RADON) database. In their compilation, they included only sites with small dating uncertainty (< 200 a); they report dates as calibrated calendar years before present (relative to 1950) based on calibration of original \(^{14}\)C measurements with CalPal 2004. This data set was created by the Pinhasi et al. to provide a high quantity of dates and good spatial coverage at the expense of chronologic uncertainties, which could have been avoided, if for example only AMS-dated (accelerator mass spectroscopy) samples had been used; only few of the 765 sites, however, have been AMS dated. For our purpose, this data set with many (possibly uncertain) dates represents the expansion of agropastoralism at a satisfactory level of detail. Future simulations at a refined spatial scale would benefit from a data set with better chronologic control, where local and regional events are presented in higher resolution and where the regionally patchy nature of the expansion of agropastoralism is better represented.

From this data set, we choose for comparison those 631 sites which are located in the spatial model domain (10°W–42°E and 31°N–57°N) and the period of interest (8000–3500 cal BC). For each site, we use the age range computed from the reported calibrated radiocarbon age and the reported standard deviation.
For the mathematical model, we introduce the age scale ‘simulated time BC’ (sim BC) to distinguish between empirically determined age models and the model time scale. Ideally, sim BC should be numerically equal to cal BC.

We set up the eight global model parameters such that the simulation is able to hindcast an accurate timing and location of the early farming centres Fertile Crescent, northern China, and Mesoamerica [Smith (1997)], and a reasonable global pattern of the subsequent Neolithisation. The simulation is started at 9500 sim BC. All of the 685 biogeographically defined regions (including 71 in western Eurasia) are initially set with farming activity at 4% and established agropastoral communities at 0.25, what represents a low density Mesolithic technology population and a broad spectrum foraging lifestyle with low unintentional farming activity. The latter is assumed to represent early animal harvesting, selective seed gathering, and the active use of fire.

3. Results

In the GLUES simulation, farming originates in the Levant (focus region A, cmp. Figure 1) around 7000 sim BC and penetrates into Europe in a northwest direction. By 3500 sim BC all of continental Europe has converted to farming as the predominant subsistence style. This emergence of farming in western Asia and Europe is shown as a series of snapshots in Figure 2 (see SOM for an animated version with finer temporal resolution).

3.1. Expansion of agropastoralism

The initial development progresses slowly and at a low level. It begins during the first century of the seventh millennium sim BC in a region encompassing today’s Lebanon, coastal Syria and a small part of the adjacent coastal Anatolia. In the 67th century sim BC, northern Greece converts to agropastoral subsistence with rapid extension into the central Balkan. Over the next four hundred years, these agropastoral nuclei spread out further, encompassing the whole of Greece and the southern Balkan, and the coast of Anatolia by the 63rd century sim BC.

A rapid expansion of agropastoralism occurs between 6200 and 6000 sim BC, transforming the entire Balkan region and Anatolia. By 5750 sim BC, the new subsistence mode has reached the northwestern and the easternmost coasts of the Black Sea. In the 57th century sim BC, independent agropastoralism arises in north Africa in the region around the Strait of Gibraltar, and it emerges on the Italian peninsula.

The 55th century sim BC sees a rapid expansion of farming and herding into the area of the central LBK, and its spread into the south coast of the Iberian peninsula. By the 54th century, the LBK has expanded west- and eastwards and covers a vast stretch of land from southern Germany to the Ukraine; this central–eastern European area intensifies agropastoral activity without notable expansion until 5100 sim BC.

Around 5000 sim BC, forager societies on the north coast of the Black Sea, in north Africa and on the Iberian peninsula have converted to predominantly agropastoralism. At 4750 sim BC, the Neolithic package reaches the Baltic Sea at the Oder river mouth; this coastal agropastoralism expands eastward until 4500 sim BC and resembles the rise of the eastern TRB culture. By this time, farming and herding have—in the model—reached the south coast of France and the north coast of Portugal.

An agropastoral area resembling the western TRB appears by 4400 sim BC, also in southern Germany the new life style becomes dominant. The later half of the fifth millennium sees a slow expansion towards the northeast of Europe, and the gap closure in central and northern France. After 4000 sim BC, agropastoralism reaches the British isles.
Figure 3: Timing of the transition to agropastoralism in Western Eurasia. The simulated transition (background pastel shading) is contrasted with the radiocarbon ages of Neolithic sites from Pinhasi et al. (2005, solid colour triangles). The lower right inset image shows the transition for a scenario without migration or exchange, i.e., it shows the propensity of regions to endogenously develop agropastoralism.

3.2. Timing of agropastoralism in model and data

A summary description of the timing of agropastoralism between 7500 and 3500 sim BC is illustrated by Figure 3. Shown alongside are the median radiocarbon dates of Neolithic sites within this period from the data compilation by Pinhasi et al. (2005). From this time-integrated perspective, the simulated centres of agropastoralism in the Fertile Crescent, in northern Greece and at the Strait of Gibraltar are evident, as well as the southeast to northwest temporal gradient of the Neolithic transition. The model-data comparison shows many good matches between radiocarbon dates and simulated transition dates. We can clearly see, however, the spatial scale difference between simulation region and site data. The spatial distribution of radiocarbon dated sites has good coverage along the transect from the Levant to northwestern Europe discussed below, it provides few or no information on central and eastern Europe, or in north Africa.

To assess the quality of the simulated onset of agropastoralism, we compare in Figure 3 the change in fractional agropastoralism to the radiocarbon site statistics for ten focus regions A–H (a transect from the the Levant A to north Germany H) and radiocarbon dated sites within the region, or within 200 km distance of the region centre for small regions. We also indicate by colour selected cultural attributions.

Seventeen sites within or near region A are dated between 8000 and 5500 BC, of which the most frequent cultural attribution is Pre Pottery Neolithic (PPN X, 9 sites) and Pottery Neolithic (6 sites). The most frequent century is the 68th cal BC (4 sites); the simulated change in agropastoral activity is greatest in the 70th century sim BC.

Ten sites are found in or near region B, most of which are assigned to the Pottery Neolithic (6 sites). All sites date to before 6000 cal BC, with a maximum around 6400 cal BC; the largest simulated change to farming occurs in this region and in region C, around 6300 sim BC. Near or in C, 15 sites cover a wide temporal range from 6500 to 4400 cal BC. The site statistic within or around region D is poor with only six sites, which date to 5800–5000 cal BC. The timing of the largest simulated change is 6100 sim BC; this simulated transformation resembles the occurrence of the Körös culture.

Like region D, most sites near region E are attributed to Körös; the second most frequent cultural complex in region E is the LBK, which is also the dominant attribution at sites around regions F to I. In regions H to J, the site histogram is bimodal with the latter peak assigned to funnel beaker sites. Many site dates near region E fall within the period 6000–4800 cal BC, whereas the simulated change is greatest at 6100 sim BC; around region F, the simulated transition occurs around 5800 sim BC. The most frequent date is the 52nd century cal BC, with a large range of 1500 years.

Radiocarbon dates for region G range from 6600 to 3500 cal BC; a maximum occurs between the 53rd and 47th century, which is concurrent with the largest simulated change at 5200 sim BC. Seven LBK sites around region H are dated to 5600–5000 cal BC, coterminous with
the simulated shift at 5500 sim BC. For region I, with mostly LBK-attributed sites and radiocarbon dates (5200–4400 cal BC), the simulated subsistence change culminates around 4600 sim BC. The respective model transition for region J appears at 4400 sim BC. Here, the site histogram can be divided into two modes, where the first encompasses radiocarbon dates between 5800 and 4600 cal BC (incl. 9 LBK sites) and the latter dates from 4200 cal BC (incl. 10 TRB sites).

3.3. Time lag–distance relationships

The average speed of the expansion of agropastoralism can be estimated from the time lag–distance relationship relative to an assumed founding centre of agropastoralism (e.g. Ammerman and Cavalli-Sforza 1973). Figure 5 shows this relationship for all regions and radiocarbon dated sites within the model domain. Here, the assumed agropastoral centre is near today’s Beirut, which lies in the middle of focus region A. The (great circle) distances and time differences to this assumed centre extend over 4000 km and 4000 a, respectively.

Time lag and distance from the sites are highly correlated ($r^2 = .61$) but also indicate a stair-case like distribution around a linear regression line with slope $0.72$ km a$^{-1}$ (cmp. Guilaine, 2001; Gronenborn, 2009a; Schier, 2009). This means that in the data collection the spread of Neolithisation is slower in spatial proximity of the founder region than is predicted by a linear correlation; between 6000 and 4500 cal BC, however, the graph of the majority of sites lies above the regression line, which
indicates a more rapid wave of advance from the Balkan towards central Europe. Lag and distance for GLUES-simulated regions are also correlated to a marked degree ($r^2 = 0.40$) and are similarly scattered around the regression line. Of the ten focus regions, regions A and B develop more slowly than expected from the regression and regions E–G develop agriculture faster than the linear regression. The average speed for the expansion of agropastoralism from the Levant into Europe calculated from the model is 0.81 km a$^{-1}$.

4. Discussion

The Global Land Use and technological Evolution Simulator is able to hindcast a realistic spatiotemporal pattern of the introduction of farming and herding into Europe between 8000 and 3500 sim BC. The simulated expansion speed of agropastoralism compares well to a large dataset of radiocarbon dated Neolithic sites; the inhomogeneous spatial distribution of Neolithisation is reproduced.

4.1. spatiotemporal onset and expansion of agriculture

The differences we observe between simulated timing and the radiocarbon age of sites within a simulation region (Figures 3 and 4) are less than 1000 a for almost all sites, for the majority of sites less than 500 a; only a handful of sites show differences greater than 1000 a. These differences are similar in magnitude to those obtained by Davison et al. (2007) between their numerical model and radiocarbon dated sites in Europe. At this scale of model uncertainty, the radiocarbon dating uncertainty of individual sites (< 200 a) can be neglected: the mismatch between the onset definitions in the data (presence of a Neolithic site, Figure 4) and in the model (50% agropastoral activity), as well as the spatial scale mismatch (local site data versus country-size simulation region, Figure 3) introduce larger temporal differences. To overcome the spatial scale problem, Zimmermann (2004) argued for a landscape approach to archaeology, whereby a multitude of local sites are used to infer the archaeological context at the regional scale or larger. The landscape approach can only succeed, however, if many sites within a region are excavated, as was the case for the lignite mining area of the Aldenhovener Platte studied by Lüning and Stehli (1994) and Zimmermann (2004). From a model perspective, more studies on methodologies to scale up the site (or many sites) information to the landscape are highly desirable. The scale difference illuminates the resolution limits of our model: GLUES resolves societal dynamics in larger environmental contexts rather than the history at individual sites.

We find a marked correlation between the timing of first agropastoralism and the distance from a founding centre in the model ($r^2 = 0.40$), and an average speed of agropastoralism in western Eurasia of 0.81 km a$^{-1}$. Using radiocarbon data, a marked or high correlation was also found by Gkiasta et al. (2003, $r^2 = 0.53, n = 510$), Ammerman and Cavalli-Sforza (1971, $r^2 = 0.79, n = 103$), and Pinhasi et al. (2005, $r^2 = 0.64, n = 765$). Differences between these empirical results can be attributed to the number of sites under consideration, to the location of the assumed founding centre, to site selection, or to the consideration of the shortest land route versus great circle distance (Pinhasi et al. 2005). For calibrated dates, Pinhasi et al. calculate a speed range of 0.6–1.3 km a$^{-1}$ when these differences are taken into account. The validity of comparing the onset of agropastoralism between simulated regions (with large areal extent) and (local) radiocarbon dated sites, despite the different scales, is supported by our simulation in two ways: (1) the marked correlation obtained between lag and distance of first agropastoralism to an assumed founding centre; (2) a calculated speed of 0.81 that agrees closely with other published estimates.

Our simulations do not take coastal expansions into account, which would seem a major model deficiency at first glance. The independent Moroccan model centre, however, acts for the Iberian peninsula similar as an explicit fast migration process (like leapfrogging, on the order of 20 km a$^{-1}$, Zilhão 1993; Zilhão 2000) along the Mediterranean coast and islands. GLUES does not currently account for rivers: we attribute the late transition of northern France in the simulation to a missing pathway from the Mediterranean coast through the Rhone valley. Indeed, Davison et al. (2006) found in their model a significant role of waterways in the Neolithisation of Europe, whereas our results only indirectly (through the definition of regions by homogeneous vegetation) include river basins; GLUES performs well despite the lack of explicit river pathways like the Rhine or Danube valleys for all regions of Europe except central France.

In the simulation, as well as in the data, the expansion of farming occurs in stages with periods of rapid spread followed by periods of local intensifications. The rapid Neolithisation from Greece to the central Balkan in the 67th century sim BC is followed by a 400 a period of relative stagnation. A very similar pattern is hindcasted for the LBK-like Neolithisation in the 55th and 54th century cal BC, and for the relative stagnation before the onset of a TRB-like Neolithic further north. Several regions exhibit a slow conversion to agropastoralism: according to Bellwood and Oxenham’s (2008) classification of zones in Neolithic Europe, France (see discussion of rivers above) would represent rather a friction than a spread zone. Another friction zone, where the Neolithic is introduced gradually, exists in the northern European lowlands, where empirical data supports the simulated late arrival of farming (Middleton 1992; Zvelebil 2006; Hartz et al. 2007).

Our simulations predict a second and eastern expansion path around the Black Sea, which was archaeologically suggested by Kotova (2003, 2009). From a model perspective, Davison et al. (2007, 2009) suggested that to find a suitable simulation consistent with the radiocarbon dated site context, one needed an additional early wave.
of advance emanating around 8200 cal BC from an Eastern European centre; agropastoral expansion would then proceed via the steppe corridor and be responsible for the eastern version of the Neolithic in Europe. This steppe corridor is archaeologically visible from the spread of pottery across Eurasia and the expansion of farming from eastern Anatolia into the Caucasus (Dolukhanov et al. 2005; Gronenborn 2009b; Kotova 2003; 2009). In the reaction-diffusion migration model by Ackland et al. (2007), a circular expansion from a single Mesopotamian centre is simulated; the geographical bottlenecks between the Mediterranean and the Black Sea, and between the Black and the Caspian sea act as successive wave centres and thus the arrival of the farming wave in Europe “appears to come from two sources: north and south of the Black Sea” (Ackland et al. p. 8715). GLUES exhibits the same behaviour, with a southern and eastern path along the Black Sea based on a single Mesopotamian source area; for central Europe, however, our model suggests that the secondary centre is rather located in northern Greece and the central Balkan. Archaeologically, the land route bottleneck may have not been too important for the Mediterranean coast, where the many islands provided a fast sea route from the Levant to Cyprus, Greece, and as far as Portugal (Poltenburg et al. 2000; Theoharis and Bökonyi 1973; Arias 1999; Zilhão 2000).

A separate non-Eurasian independent centre of agropastoralism is simulated by GLUES in the Maghreb. From there, agropastoralism enters Europe via the Strait of Gibraltar around 5500 cal BC (cmp. Manen et al. 2007). Archaeological records to show this are sparse; it is clear, however, that the strait had been in use as a migration path long since pre-Neolithic times, which is evident in gene pool analyses (e.g. Currat et al. 2010). Not only people but also domesticates crossed the strait in prehistory. This was verified in a study by Anderung et al. (2005), who found mitochondrial DNA of Bronze age (1800 cal BC) Iberian cattle, of which a significant number possessed African haplotypes.

4.2. Demic or cultural diffusion

The relative contribution of demic versus diffusive processes can be calculated by following the streams of migration and trade in the model. We find that exchange processes contribute much less to local Neolithisation than adoption does. In Figure 6 we show this for the fraction of immigrant agropastoralists: for some (mostly Mediterranean) regions, immigrants are unimportant; for most regions, immigrants constitute one fourth of the agropastoral community; for a few northern and alpine regions, immigrants dominate.

We assessed the model sensitivity to different configurations for the speed of both information exchange and migration. We find that (1) the model does not show sensitivity to either of these two parameters for a wide range of values, and that (2) the substitution fraction of agropastoralists with immigrants generally remained around 25% for most regions; local invention and adoption of ideas dominate the Neolithisation, irrespective of whether people or information moved.

Is demic diffusion a sufficient explanation for the European Neolithic? This has been suggested by many authors (Ammerman and Cavalli-Sforza 1971; 1973; Sokal et al. 1991; Richards 2003; Edwards et al. 2007; Bramanti et al. 2009; Balaresque et al. 2010; Haak et al. 2010). We can confirm this finding from a model simulation where cultural diffusion was deactivated. Demic processes alone can reproduce the timing and lag-distance relationship seen in the radiocarbon data.

But is demic diffusion necessary for explaining the radiocarbon record? Pinhasi et al. (2005) answered this question positively and pointed out that, at present, no working model existed that could explain the European Neolithic without demic diffusion. Unlike the demic diffusion-only experiment, we set up a simulation experiment where only information was allowed to diffuse, and where migration was inhibited: we could successfully reproduce the spatiotemporal emergence of the Neolithic in Europe with purely cultural diffusion processes. To the question of necessity of demic diffusion for the explanation of the radiocarbon record, our answer is no. This shows that the recently published evidence for major population transfers around the time of the Neolithisation process (Haak et al. 2010) may have to be functionally disconnected from the spread of agropastoralism: apparently, people did move at greater scales during the sixth and fifth millennium but these movements were not triggered by the spread of farming. It may entirely be possible that early—yet hypothetical—migrations already occurred before and during the seventh millennium and were
undertaken by hunter-gatherers or mixed hunter-gatherer-horticulturalists originating from Anatolia. These immigrants then gradually pushed the original Mesolithic hunter-gatherer population of Europe towards the continental margins. Later, this migratory stream was complemented with farmers from Anatolia who then interacted with those hunter-gatherers who had arrived earlier (Gronenborn 2011). This scenario would explain the archeogenetic evidence for migrations as well as the archeological evidence of interactions by disconnecting the spread of farming from the mid-Holocene migratory processes.

The insensitivity of the simulation results to the absence of either trade or migration processes prevents us from constraining the parameters for these processes quantitatively. Even more, it tells us that from the phenology (the timing of agropastoralism) we cannot infer which of the two processes was responsible, or to which degree. For the interpretation of radiocarbon dates of sites with an attribution to farming subsistence, one cannot find out whether demic or cultural diffusion was responsible for the apparent distribution in space and time of these sites. Or, put differently, the question on demic or cultural vectors may be not the most critical one for understanding the Neolithisation of Europe as a whole.

What was the contribution of local adoption and invention? From Figure 3 it is evident that for most regions conversion of resident foragers to farmers played a larger role than immigration. We quantitatively examined the relative importance of different sources (demic diffusion, cultural diffusion and local adoption or invention) to local Neolithisation in different model configurations (Table 1). Even in a scenario where demic diffusion is the only active process, migration as a source does not explain 100% of the agropastoralists in any focus region along the transect A–H but at most 85% (in region H), less in regions closer to the Mediterranean coast (e.g. 54% in region F). The local source (adoption and innovation) for an exchanged commodity like technology is in all configurations and focus regions more important (70–90%) than migration or exchange.

| Region F | Region H | Region H |
|----------|----------|----------|
|          | agropastoralism | agropastoralism | technology |
|          | migr:adopt | migr:adopt | migr:exch:adopt |
| demic    | 54:46     | 85:15     | 22:0:78     |
| mixed    | 22:78     | 41:59     | 6:13:79     |
| cultural | 0:100     | 0:100     | 0:21:79     |

Table 1: Contributions (in percent) to local agropastoralism and technology from three different sources (1) demic diffusion (labelled migr), (2) cultural diffusion (exch), and (3) local adoption and invention (adopt) for three different model configurations with demic only, mixed (our standard configuration discussed in Figures 2–6), and cultural only diffusion. Simulation results are shown for model regions corresponding to today’s Hungary (focus region F) and southern Poland (focus region H).

4.3. Independent agropastoralism

Was regional exchange (via migration or trade) necessary at all for the onset of agropastoralism everywhere in western Europe? In Figure 3 (lower right panel) we show the result of a simulation where both exchange processes were suppressed, thus endogenous transitions to agropastoralism become visible. The timing of the onset of agropastoralism around the Mediterranean Sea exhibits—next to the Levantine, Greek, and Moroccan centres which also appear in the reference simulation—many centres of hypothetical independent agropastoralism. This independent agropastoralism is solely predicted on the basis of suitable environmental conditions (open vegetation type, not too cold) and internal development of sociocultural traits and demography; it corresponds to indigenist scenarios proposed in the older literature, for example for southern France (Geddès 1980, Courtin and Erroux 1974) or Greece (Theocharis and Bokony 1973, Winiger 1998). The indigenous agropastoralism hypothesis is, however, currently disregarded in archaeology because the genetic evidence points to the Near East as the centre for all Neolithic cultigens and nearly all domestic animals. For northern Europe, GLUES does not simulate the emergence of agropastoralism without the contribution of migration; these regions critically depended on the introduction of technologies and economies through the actual movement of people, commodities, and information.

4.4. Model comparison and outlook

In addition to the prior approaches to simulating the European Neolithic (Davison et al. 2006, 2007, 2009, Ackland et al. 2007) which use geographic and topographic constraints for describing environmental heterogeneity, our model considers vegetation. Vegetation production is directly coupled to the carrying capacity and it determines the economic potential of a given environment. Already many regions, mainly around the Mediterranean Sea, have a high propensity for developing independent agricultures based on the palaeoecological background (Figure 3 lower right panel). We couple the diffusion rates of traits and migration of people not only to the background geography but also to the (evolving) technology. With these assumptions we can realistically reproduce the spatiotemporal pattern of Neolithisation in greater detail than was done for the front speed of Neolithisation by Davison et al. (2006, 2007) and Ackland et al. (2007). Ackland et al. (2007) and more recently Patterson et al. (2010) for the Indian transition to agropastoralism use the concept of converts to describe resident foragers which have converted to agropastoralism. We have shown that these converts may have played a larger role in the European Neolithisation than immigrant farmers. Our model provides additional insight into the processes responsible for local adoption—often, a small share of introduced technology is sufficient to spark local invention.
and trigger the transition. Alternatively, a few immigrant farmers and the technologies and economic possibilities they carry along may suffice to stimulate the local transition.

Our regional prediction for western Eurasia emerges in the context of a global simulation: not only is the subcontinental prediction embedded in the larger spatial scale, but every local transition occurs within the temporal context of preceding predominant foraging subsistence with continuous innovation and succeeding intensification periods. While we have shown that the model realistically reproduced the European Neolithisation, where archaeological data is plenty and most reliable, the model’s spatiotemporal consistency gives us confidence to draw conclusions about regions outside Europe in further studies.

With the expected availability of more reliable palaeoclimatic and palaeovegetation reconstructions from both models and data (Kutzbach et al., 2010; Gaillard et al., 2010), we expect to refine the large-scale biogeographic context of cultural evolution and the impact of local environmental disturbances (Wirtz et al., 2010). We will then be able to assess better the degree to which the environment determined the potential transition to farming. This potential should, however, be interpreted in G. Ackland et al.’s way as providing a “historical null hypothesis. Its predictions can be taken as requiring no special explanation, and its failures can be taken as evidence of rare events that had significant and long-lived consequences”. Numerical modelling of culture as a (natural) ecosystem may help to isolate the significant and non-deterministic events and concentrate our historical interpretation on those events where culture was most emancipated from the environment.

5. Conclusion

We presented a spatially explicit mathematical model of the Neolithisation of western Eurasia from 8000 BC to 3500 BC. Our model incorporates endogenous sociotechnological dynamics, where culture is represented by the adaptation of characteristic population traits (technology, fraction of farmers, and economic diversity) and their interaction with demographics. The study resolved the spatial expansion of Neolithic culture via indigenous development, migration and information exchange and reproduced the chronology of agropastoral onset observed in field data across western Eurasia, particularly reproducing and explaining the discontinuous speed of the “wave of advance”.

Our results encourage us to rethink possible indigenous centres along the northeastern shore of the Mediterranean: these might have not been able to develop since they were overrun by Near Eastern populations. Alternatively, the evidence for independent agropastoralism may have gotten lost in the admixture with the Fertile Crescent Neolithic package. According to our simulations, a north African contribution to the European Neolithic should equally not be discounted.

The assessment of the relative importance cultural diffusion and demic diffusion in the model shows that either of these processes can explain the spatiotemporal pattern of agropastoral onset in Europe equally well. The phenomena of the spatiotemporal pattern of agropastoral onset cannot discriminate the underlying process. Furthermore, even if only migration was considered and the diffusion of traits occurred only via immigrants, the prevalence of immigrant farmers in any of the emerging agropastoral regions was much less than the prevalence of foragers who adopted the agropastoral life style. To the long-lasting dispute between cultural and demic diffusionists our novel interpretation offers a balanced explanation of predominant adoption despite migration. Whether the adopting population, however, did not also ultimately originate from Anatolia needs to be investigated by further archaeogenetic studies.

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References

Ackland, G., Singitzer, M., Stratford, K., Cohen, M., 2007. Cultural hitchiking on the wave of advance of beneficial technologies. Proceedings of the National Academy of Sciences 104 (21), 8714.

Ammerman, A., Cavalli-Sforza, L., 1971. Measuring the rate of spread of early farming in Europe. Man 6 (4), 674–688.

Ammerman, A., Cavalli-Sforza, L., 1973. A population model for the diffusion of early farming in Europe. In: Renfrew, C. (Ed.), The explanation of cultural change. Duckworth, London, pp. 343–57.

Anderung, C., Bouwman, A., Persson, P., Carretero, J., Ortega, A., Elburg, R., Smith, C., Arsuaga, J., Ellegrén, H., Götherström, A., 2005. Prehistoric contacts over the Straits of Gibraltar indicated by genetic analysis of Iberian Bronze Age cattle. Proceedings of the National Academy of Sciences 102 (24), 8431.

Arias, P., 1999. The origins of the Neolithic along the Atlantic coast of continental Europe: A survey. Journal of World Prehistory 13 (4), 403–464.

Balaresque, P., Bowden, G., Adams, S., Leung, H., King, T., Ross, Z., Goodwin, J., Moisan, J., Richard, C., Millward, A., et al., 2010. A predominantly Neolithic origin for European paternal lineages. Public Library of Science Biology 8 (1), e1000285.

Barker, G., 2006. The Agricultural Revolution in Prehistory. Why did Foragers become Farmers? Oxford University Press, Oxford, United Kingdom.

Begon, M., Harper, J. L., Townsend, C. R., 1993. Ecology—Individual. Populations and Communities, 2nd Edition. Blackwell Scientific Publications, Oxford.

Bellwood, P., 2005. First Farmers: The Origins of Agricultural Societies. Blackwell Publishers.

Bellwood, P., Oxburn, M., 2008. The expansions of farming societies and the role of the Neolithic Demographic Transition. In: Bocquet-Appel, J., Bar-Yosef, O. (Eds.), The Neolithic Demographic Transition and its consequences. Springer, pp. 13–34.
Bentley, A., Price, T., Luning, J., Gronenborn, D., Wahl, J., Ful- lagar, P., 2002. Prehistoric migration in Europe: strontium isotope analysis of early Neolithic skeletons. Current Anthropology 43 (5), 799–804.

Bocquet-Appel, J.-P., Naji, S., van der Linden, M., Kozlowski, J. K., 2009. Detection of diffusion and contact zones of early farming in Europe from the space-time distribution of $^{14}$C dates. Journal of Archaeological Science 36, 807–820.

Boyd, B., 2006. On ‘sedentism’ in the Later Epipalaeolithic (Natufian) Levant. World Archaeology 38 (2), 164–178.

Braidwood, L., Braidwood, R., 1949. On the treatment of the prehis- toric near Eastern materials in Steward’s “cultural causality and law”. American Antiquity 51 (4), 665–669.

Braidwood, R., Braidwood, R., 1950. Jarno: A village of early farm- ers in Iraq. Antiquity 24 (96), 189–195.

Bramanti, B., Thomas, M., Haak, W., Unterlaender, M., Jores, P., Tambets, K., Antanaitis-Jacobs, I., Haidle, M., Jankauskas, R., Kind, C., et al., 2009. Genetic discontinuity between local hunter-gatherers and central Europe’s first farmers. Science 326 (5949), 137.

Childe, V. G., 1925. The Dawn of European civilization. Kegan Paul, Trench, Trubner, London.

Childe, V. G., 1936. Man makes himself. Watts, London.

Childe, V. G., 1942. What happened in history. Pelican/Penguin.

Childe, V. G., 1949. The social process: a derivation from stochastic ecological processes. Journal of Mathematical Biology 34, 579–612.

Clark, J. D., 1965. Radiocarbon dating and the spread of farming economy. Antiquity 39, 45–48.

Claussen, M., Kubatza, C., Brovkin, V., Ganopolski, A., Hoelzmann, P., Pachur, H., 1999. Simulation of an abrupt change in Saharan vegetation at the end of the mid-Holocene. Geophysical Research Letters 24, 2037–2040.

Colledge, S., Conolly, J., Shennan, S., 2004. Archaeobotanical evi- dence for the spread of farming in the eastern Mediterranean. Current Anthropology 45 (suppl), S35–S58.

Courtin, J., Erroux, J., 1974. Aperçu sur l’agriculture préhistorique dans le sud-est de la France. Bulletin de la Société Préhistorique Française 71 (1), 321–334.

Curtat, M., Poloni, E., Sanchez-Mazas, A., 2010. Human genetic differen- tiation across the Strait of Gibraltar. BMC Evolutionary Biology 10 (1), 237.

Davey, K., Dolukhanov, P., Sarson, G., Shukurov, A., 2006. The role of waterways in the spread of the Neolithic. Journal of Archaeo- logical Science 33 (5), 641–652.

Davey, K., Dolukhanov, P., Sarson, G., Shukurov, A., Zaitseva, G., 2009. Multiple sources of the European Neolithic: Mathematical modelling constrained by radiocarbon dates. Quaternary Interna- tional 203 (1-2), 10–18.

Davey, K., Dolukhanov, P. M., Sarson, G., Shukurov, A., Zaitseva, G. I., 2007. A pan-European model of the Neolithic. Documenta Praehistorica XXXIV, 641–652.

Diamond, J., 1997. The worst mistake in the history of the human race. Discover May, 64–66.

Diamond, J., Aug. 2002. Evolution, consequences and future of plant and animal domestication. Nature 418, 700–707.

Dieckmann, U., Law, R., 1996. The dynamical theory of coevolu- tion: a derivation from stochastic ecological processes. Journal of Mathematical Biology 34, 579–612, adapt.

Dolukhanov, P., 1973. The Neolithisation of Europe: a chronological and ecological approach. In: Renfrew, C. (Ed.), The explanation of cultural change. Duckworth, Gloucester, United Kingdom, pp. 329–342.

Dolukhanov, P., Shukurov, A., Gronenborn, D., Sokoloff, D., Timofeev, V., Zaitseva, G., 2005. The chronology of Neolithic dis- persal in central and eastern Europe. Journal of Archaeological Science 32 (10), 1441–1458.

Edenroth, M., 1961. Neolithic diffusion rates. Current Anthropology 2, 71–102.

Edwards, C. J., Bollongino, R., Scheu, A., Chamberlain, A., Tresset, A., Vigne, J.-D., Baird, J. P., Larson, G., Ho, S. Y. W., Heupink, T. H., Shapiro, B., Freeman, A. R., Thomas, M. G., Arbogast, R., Arndt, B., Bartosiewicz, L., Benecke, N., Budja, M., Chaix, L., Choyke, A. M., Coqueugniot, E., Döhle, H.-J., Gödner, H., Hartz, S., Helmer, D., Herzig, B., Hongo, H., Mashlour, M., Özdoğan, M., Pucher, E., Roth, G., Scahde-Lindig, S., Schmölke, U., Schulting, R. J., Stephan, E., Uerpmann, H.-P., Vörös, I., Voytek, B., Bradley, D. G., Burger, J., 2007. Mitochondrial DNA analysis shows a Near Eastern Neolithic origin for domestic cattle and no indication of domestication of European aurochs. Philo- sophical Transactions of the Royal Society of London Series B 274, 1377–1385.

Fisher, R. A., 1930. The Genetical Theory of Natural Selection. Dover, New York.

Flannery, K. V., 1973. The origins of agriculture. Annual Review of Anthropology 2 (1), 271–310.

Fuller, D. Q., 2006. Agricultural origins and frontiers in south Asia: A working synthesis. Journal of World Prehistory 20 (1), 1–86.

Gaillard, M.-J., Sugita, S., Mazier, F., Trondman, A.-K., Broström, A., Hickler, T., Kaplan, J. O., Kjellström, E., Kookfet, U., Kunes, P., Lemmen, C., Miller, P., Olofsson, J., Poska, A., Rundgren, M., Smith, B., Strandberg, G., Fye, R., Nielsen, A. B., Alenius, T., Balakauskas, L., Barnekow, L., Birks, H. J. B., Bjune, A., Björkman, L., Giesecke, T., Hjelle, K., Kalnina, L., Kangur, M., van der Knaap, W. O., Koff, T., Lageris, P., Latalowa, M., Leyd- det, M., Lechterbeck, J., Lindbladh, M., Odgaard, B., Peglar, S., Szelese, J., von der Heydt, A., Seppä, H., 2010. Holocene land- cover reconstructions for studies on land cover-climate feedbacks. Climate of the Past 6 (4), 483–499.

Geddes, D., 1980. De la chasse au troupeau en Méditerranée Occi- dentale: les débuts de l’élevage dans le bassin de l’Aude. Bulletin of the Société préhistorique française. 81 (10-12), 370–378.

Gkiasta, M., Russell, T., Shennan, S., Steele, J., 2003. Neolithic transition in Europe: the radiocarbon record revisited. Antiquity 77 (295), 45–62.

Gronenborn, D., 1999. A variation on a basic theme: The transition to farming in southern central Europe. Journal of World Prehis- tory 13 (2), 123–210.

Gronenborn, D., 2007a. Beyond the models: Neolithisation in central Europe. In: Whittle and Cumming (2007), pp. 73–98, 73–98.

Gronenborn, D., 2007b. Climate change and socio-political crises: some cases from Neolithic central Europe. In: Pollard, T., Banks, I. (Eds.), War and sacrifice studies in the archaeology of conflict. Koninklijke Brill NV, Leiden, pp. 13–32.

Gronenborn, D., Petrov, L., Dobrzanski, R., Poczobut, M., Poczobut, M., 2010. The Spread of the Neo- lithic to Central Europe. Vol. 4 of RZGM Tagungen. Römisch- Germanisches Zentralmuseum, Mainz, Germany.

Guilaine, J., 2001. La diffusion de l’agriculture en Europe: une hy- pothèse arithmétique. Zephyrus 53 (4), 267–272.

Haak, W., Balanovsky, O., Sanchez, J. J., Koshe, S., Zaporojchenko, V., Adler, C. J., Der Sarkissian, C. S. I., Brandt, G., Schwarz, C., Nicklisch, N., Dresely, V., Fritsch, B., Bal- anosvka, E., Villems, R., Meller, H., Alt, K. W., Cooper, A., the Genographic Consortium, 2010. Ancient DNA from European early Neolithic farmers reveals their Near Eastern affinities. Public Library of Science Biology 8 (11), e1000536.

Hartz, S., Lübke, H., Terberger, T., 2007. From fish and seal to sheep and cattle: new research into the process of Neolithisation in northern Germany. Proceedings of the British Academy 144, 567–594.

Hodder, I., 1990. The Domestication of Europe: Structure and Con- tingency in Neolithic Europe. Basil Blackwell, Oxford.
Jeunesse, C., 2000. Les composantes autochtone et danubienne en Europe centrale et occidentale entre 5500 et 4000 av. J.-C.: contacts, transferts, acculturations. In: Les derniers chasseurs-cueilleurs d’Europe occidentale (13000-5500 av. J.-C.): actes du colloque international de Besançon. pp. 361–78.

Kaplan, J., Krumhardt, K., Ellis, E., Ruddiman, W., Lemmen, C., Klein Goldewijk, K., 2010. Holocene carbon emissions as a result of anthropogenic land cover change. The Holocene, prepublished Dec 30, 2010, doi: 10.1177/0123456789123456.

Kisdi, Éva and Geritz, S. A. H., 2010. Adaptive dynamics: a framework to model evolution in the ecological theatre. Journal of Mathematical Biology 61, 165–169.

Kotova, N. S., 2003. Neolithization in Ukraine. British Archaeological Reports Ltd.

Kotova, N. S., 2009. The Neolithization of northern Black Sea area in the context of climate changes. Documenta Praehistorica XXXVI, 159–174.

Kučjt, I., Goring-Morris, N., 2002. Foraging, farming, and social complexity in the pre-pottery Neolithic of the southern Levant: A review and synthesis. Journal of World Prehistory 16 (4), 361–440.

Kutzbach, J., Ruddiman, W., Vavrus, S., Philippon, G., 2010. Climate model simulation of anthropogenic influence on greenhouse-induced climate change (early agriculture to modern): the role of ocean feedbacks. Climatic Change 95 (3), 315–381.

Larson, G., Albarella, U., Dolney, K., Rowley-Conwy, P., Schibler, J., Tresset, A., Vigne, J. D., Edwards, C. J., Schluumber, A., Dinu, A., Balatas, C., Dolman, G., Tagliacozzo, A., Manasevian, N., Miracle, P., Van Wijngaard-Bakker, L., Masseti, M., Bradley, D. G., Cooper, A., 2007. Ancient DNA, pig domestication, and the spread of the Neolithic into Europe. Proceedings of the National Academy of Sciences 104 (39), 15276.

Leemans, R., Cramer, W. L., Nov. 1991. The IASA database for mean monthly values of temperature, precipitation and cloudiness of a global terrestrial grid. Research report, International Institute of Applied Systems Analyses, Laxenburg.

Lemmen, C., 2001. Understanding the regional rise of civilizations by means of a dynamic model. Master thesis, Carl von Ossietzky University, Oldenburg.

Lemmen, C., 2009. World distribution of land cover changes during pre-and protohistoric times and estimation of induced carbon releases. Gédéomorphologie: relief, processus, environnement 4, 303–102.

Lemmen, C., Wirtz, K. W., 2010. Socio-technological revolutions and migration waves re-examining early world history with a mathematical model. In: [Grunenborn and Petrasch] (2010), Vol. 4 of RGZM Tagungen, pp. 25–38.

Lieth, H., 1975. Modeling the primary productivity of the world. Primary Productivity of the Biosphere 14, 237–263.

Lukart, G., Gielly, L., Excoffier, L., Vigne, J.-D., Bouvet, J., Taberlet, P., 2001. Multiple maternal origins and weak phylogeographic structure in domestic goats. Proceedings of the National Academy of Sciences 98 (10), 5927–5932.

Lüning, J., Stehl, P., 1994. Die Bandkeramik im Merzbachtal auf der Aldenhovenplatte. Rheinland-Verlag.

Manen, C., Marchand, G., Carvalho, A. F., 2007. Le Néolithique ancien de la péninsule Ibérique: vers une nouvelle évaluation du mirage africain? In: Évin, J., (Ed.), XXXVe Congrès préhistorique de France, Congrès du centenaire de la Société préhistorique française, Avignon, 21–25 Sept 2004. Vol. 3 of Aux conceptions d’aujourd’hui. Société Préhistorique Française, Paris, France, pp. 133–151.

Mauvilly, M., Jeunesse, C., 2003. Neolithization in France. Congrès préhistorique de France, Congrès du centenaire de la Société préhistorique française, Avignon, pp. 361–78.

Mauvilly, M., Jeunesse, C., Doppler, T., 2008. Ein Tonstempel aus der spätmesolithischen Fundstelle Arconciel/La Souche (Kanton Freiburg/Schweiz). Quartär 55, 151–157.

Merico, A., Bruggeman, J., Wirtz, K., 2009. A trait-based approach for documenting complexity in plankton ecosystem models. Ecological Modelling 220 (21), 3001–3010.

Metz, J., Nisbet, R., Geritz, S., 1992. How should we define fitness for general ecological scenarios. Trends in Ecology and Evolution 7, 198–202.

Migeoney, M. S., Nov. 1992. TRB culture: the first farmers of the North European Plain. Edinburgh University Press.

Mithen, S. J., 2004. After the Ice: A Global Human History, 20,000–5000 BC. Weidenfeld & Nicolson, London, United Kingdom.

Patterson, M., Sarson, G., Sarson, H., Shukurov, A., 2010. Modelling the Neolithic transition in a heterogeneous environment. Journal of Archaeological Science 37 (11).

Peltenburg, E., Collede, S., Croft, P., Jackson, A., McCutney, C., Murray, M. A., 2000. Agro-pastoralist colonization of Cyprus in the 10th millennium BP: initial assessments. Antiquity 74, 844–853.

Pinhasi, R., Fort, I., Ammerman, A., 2005. Tracing the origin and spread of agriculture in Europe. PloS Biology 3 (12), 410.

Price, T. D. (Ed.), 2000. Europe’s First Farmers. Cambridge University Press.

Renfrew, C., 1987. Archaeology and language. the puzzle of Indo-European origins. Current Anthropology 29, 437–441.

Richards, M., 2003. The Neolithic transition in Europe: archaeo- logical models and genetic evidence. Documenta Praehistorica 30, 159–68.

Roth, H. L., 1887. On the origin of agriculture. The Journal of the Royal Agricultural Society 98 (10), 5927–5932.

Ruddiman, W., 2006. The early anthropogenic hypothesis—challenges and responses. Geophysical Research Abstracts 8, 01749.

Schier, W., 2000. Extensive Brandfeldbau und die Ausbreitung der Neolithischen Wirtschaftsweise in Mitteleuropa und Südsiedl- inavien am Ende des 5. Jahrtausends v. Chr. Prehistorische Zeitschrift 84 (1), 15–43.

Sheridan, J., 2007. Scottish beaker dates: the good, the bad and the ugly. In: From Stonehenge to the Baltic: Living with Cultural Diversity in the Third Millennium BC. British Archaeological Reports Ltd, pp. 91–123.

Smith, B., 1997. The initial domestication of Cucurbita pepo in the Americas 10,000 years ago. Science 276 (5314), 932–934.

Smith, S. L., Pahlow, M., Merico, A., Wirtz, K. W., 2011. Optimality as a unifying concept for planktonic organisms and their ecology. Limnology and Oceanography submitted.

Sokal, R., Oden, N., Wilson, C., 1991. Genetic evidence for the spread of agriculture in Europe by demic diffusion. Nature 351 (6322), 143–145.

Theocharis, D. R., Bökényi, S., 1973. Neolithic Greece. National Bank of Greece Athens.

Thomas, J., 1991. Rethinking the Neolithic. Cambridge Press, Cambridge.

Weninger, B., Clare, L., Rohling, E. J., Bar-Yosef, O., Böhner, U., Budja, M., Bündschuh, M., Feurdean, A., Gebel, H.-G., Joris, O., Lackmaitter, J., Mayewski, P., Mienlenbruch, T., Reingruber, A., Rolleson, G., Schyle, D., Thissen, L., Todtoro, H., Zelhoefer, C., 2009. The impact of rapid climate change on prehistoric societies during the Holocene in the eastern Mediterranean. Documenta Praehistorica 902 (4-5), 551–583.

Westropp, H. M., 1872. Pre-historic phases: or, Introductory essays on pre-historic archaeology, 1st Edition. Bell & Dddy.

Whittle, A., 2007. The temporality of transformation: dating the early development of the southern British Neolithic. In: [Whittle and Cummings] (2007), Vol. 144 of Proceedings of the British Academy, pp. 377–398.

Whittle, A., Cummings, V., 2007. Going Over: the Mesolithic-Neolithic transition in North-West Europe. Vol. 144 of Proceedings of the British Academy. Oxford University Press.

Willcox, G., 2005. The distribution, natural habitats and availability of wild cereals in relation to their domestication in the near east: multiple events, multiple centres. Vegetation History and Archaeobotany 14 (4), 534–541.

Willee, C., Bufo, R., Verveux, L., 2009. Late Pleistocene and early Holocene climate and the beginnings of cultivation in northern Syria. Holocene 1 (1), 151–158.

Winiger, J., 1998. Ethnarchäologische Studien zum Neolithikum Südwesteuropas. British Archaeological Reports.

Wirtz, K., Lemmen, C., 8 2003. A global dynamic model for the
Neolithic transition. Climatic Change 59 (3), 333–367.
Wirtz, K., Lohmann, G., Bernhardt, K., Lemmen, C., 2010. Mid-Holocene regional reorganization of climate variability: Analyses of proxy data in the frequency domain. Paleogeography Palaeoclimatology Palaeoecology 298 (3–4).
Wirtz, K. W., Eckhardt, B., 1996. Effective variables in ecosystem models with an application to phytoplankton succession. Ecological Modelling 92, 33–54.
Zeder, M., 2008. Domestication and early agriculture in the Mediterranean basin: Origins, diffusion, and impact. Proceedings of the National Academy of Sciences 105 (33), 11597.
Zilhão, J., 1993. The spread of agro-pastoral economies across Mediterranean Europe: a view from the Far-West. Journal of Mediterranean Archaeology 6, 5–63.
Zilhão, J., 2000. From the Mesolithic to the Neolithic in the Iberian peninsula. In: Price (2000), pp. 144–182.
Zimmermann, A., 2004. Landschaftsarchäologie II. Überlegungen zu Prinzipien einer Landschaftsarchäologie. Vol. 85 of Bericht der Römisch- Germanischen Kommission. Philipp von Zabern, Mainz.
Zvelebil, M., 1998. What’s in a name: the Mesolithic, the Neolithic, and social change at the Mesolithic-Neolithic transition. In: Edmonds, M., Richards, C. (Eds.), Understanding the Neolithic of north-western Europe. Cruithne Press, pp. 1–36.
Zvelebil, M., Zvelebil, K. V., 1988. Agricultural transition and Indo-European dispersals. Antiquity 62, 574–583.