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Resilience of small-scale societies' livelihoods: a framework for studying the transition from food gathering to food production

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ABSTRACT. The origins of agriculture and the shift from hunting and gathering to committed agriculture is regarded as one of the major transitions in human history. Archeologists and anthropologists have invested significant efforts in explaining the origins of agriculture. A period of gathering intensification and experimentation and pursuing a mixed economic strategy seems the most plausible explanation for the transition to agriculture and provides an approach to study a process in which several nonlinear processes may have played a role. However, the mechanisms underlying the transition to full agriculture are not completely clear. This is partly due to the nature of the archeological record, which registers a practice only once it has become clearly established. Thus, points of transitions have limited visibility and the mechanisms involved in the process are difficult to untangle. The complexity of such transitions also implies that shifts can be distinctively different in particular environments and under varying historical and social conditions. In this paper we discuss some of the elements involved in the transition to food production within the framework of resilience theory. We propose a theoretical conceptual model in which the resilience of livelihood strategies lies at the intersection of three spheres: the environmental, economical, and social domains. Transitions occur when the rate of change, in one or more of these domains, is so elevated or its magnitude so large that the livelihood system is unable to bounce back to its original state. In this situation, the system moves to an alternative stable state, from one livelihood strategy to another.

Key Words: *ABM; resources; social-ecological dynamics; subsistence strategies; transition to agriculture*

INTRODUCTION

The adoption of agriculture is regarded as one of the major changes of the past and has been intensively studied by both archeologists and anthropologists (see, e.g., Price and Bar-Yosef 2011, Rindos 2013, Barton and An 2014). However, because of the nature of the archeological record whereby this process becomes visible only once its practice is clearly established (see Fuller 2007 for discussion), transitional phases between foraging groups and fully developed food-producing societies are much less easily unfolded (notable exceptions are represented by the work of Zvelebil and Dolukhanov 1991, and Smith 2001). Recent studies have shown that such transitional phases and the emergence of mixed subsistence economies, based on the use of both wild and domesticated animal and plant species, lasted at least several hundreds and in some cases thousands of years (Larson et al. 2014, and references therein). Further, these changes fundamentally shaped the development of agricultural societies that emerged around the world (Hayden 1990, Denham et al. 2003, Weiss et al. 2006, Kuijt and Finlayson 2009, Asouti and Fuller 2012, 2013, Fuller et al. 2012, Smith 2015). Recent methodological and technological advances, as well as an increase of archeological excavations in areas not investigated before, have produced large amounts of empirical data on forager-farmer transitions worldwide (Fuller et al. 2014, and references therein). However, the resulting interpretations are hampered by the many taphonomic problems related to archeological material, whereby differential preservation, especially of biological remains, impinges on our reconstructions of past processes. Conversely, Gremillion et al. (2014) have argued that this hyper reliance on empirical data has contributed to the rejection of general explanations on the origins of agriculture (OA) and the

consequent loss of theoretically driven hypothesis testing. Moreover, scholars tend to explain this transition either as a necessity, e.g., due to climate change, or as an opportunity, e.g., because domesticates offer more reliable food sources (see as Ullah et al. 2015). However, it is becoming clearer that both these mechanisms often acted in concert and at the same time or at different chronological or spatial locations and the challenge is to distinguish between these two occurrences. Recent advances in modeling and simulation approaches in archeological research (Madella et al. 2014) provide an opportunity for a detailed study of both the processes and transitions associated with agricultural production (Allaby et al. 2008, 2010, van Etten and Hijmans 2010, Ullah et al. 2015), and thus offer a formal tool to help close the gap in our understanding of the transition between hunter-gatherer (HG) and agro-pastoral (AP) societies.

In this paper we propose a theoretical conceptual model to study the transition to agriculture using resilience and social-ecological systems (SES) theory. This is conceived as a way to clarify the meaning of concepts and terms adopted as well as to make explicit the connections between these different concepts. The ultimate aim is to advance general theoretical understanding of the origins of agriculture through the creation of a model that will then be implemented in agent-based simulations. However, we believe that before proceeding to the implementation phase, a theoretical introduction of our proposed approach that frames transitions within resilience theory is required, and delivered in the current paper. Taken alone, none of the concepts presented here are new to archeology (see for example Redman 2005, Gronenborn et al. 2014). However, their combined use and application to understanding the resilience of livelihood strategies, is a valuable and novel contribution. The concept of livelihood strategy refers

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to the combination of activities that people develop to achieve their subsistence goals. These usually depend on the ecological settings (environmental resources), productive strategies (economic resources) and social choices (social resources), for which we propose a parameterization (cf. Wilson 2012).

Resilience theory and transitions

The concept of resilience is used here *sensu* ecological resilience (Holling 1973), indicating a measure of how much a system can be perturbed without shifting to a new regime. When we talk about transitions, we intend a slow change in the system that can potentially, but not necessarily, lead to a transformation, or critical transition (Scheffer 2009). The system might gradually lose resilience until even a minor perturbation can push it over a tipping point (Scheffer 2009). Resilience theory is a particularly well-suited framework to study the nature of transitions for several reasons. First, resilience is a neutral framework, i.e., it does not have a positive or negative connotation *per se* but it can be one or the other depending on the circumstances (Cumming et al. 2005). Early literature tends to consider resilience as a positive state, because it is typically associated with sustainability (see a review of the use of the term resilience in Miller et al. 2010). However, these are two different, albeit sometimes related, concepts, and resilience is not always positive. Occasionally, a change at a larger scale might be beneficial and systems that do not pass a certain threshold at a lower scale might be resilient, but at the same time create problems in the surrounding environment or in the social structures that define them (Walker et al. 2004).

Another aspect of resilience theory that fits well within transition studies (as proposed by Wilson 2012) is the formalization of several adaptive cycles. Specifically, the synchronous interaction of small-and-fast, intermediate, and slow-and-large cycles seems particularly well suited to constitute a framework for studying the transition to agriculture. It is highly probable that during a long-phase transition to fully committed agriculture, shifts in diet between HG and AP were common. These might have included small changes in the dependency on one type of resource or another, as well as reverses from AP to HG. Such examples are evident in the archeological record, stressing the fluid nature of food procurement and preferences toward both domesticated and wild resources, such as in areas of central and northern Europe (e.g., Bishop et al. 2009, Schibler and Jacomet 2010, Kirleis et al. 2011, Colledge and Conolly 2014, Whitehouse et al. 2014) as well as southern Europe (Antolín and Jacomet 2015, Valamoti 2015) during the transition period. Several modern HG examples also show that these strategies often are complementary and reversions from one to the other are not uncommon (e.g., Greaves and Kramer 2014). In addition, social, technological, and ecological changes may have been crucial for full reliance on agropastoralism. These changes might have ranged from the introduction of the ard and tilling technology for increasing productivity (Kerig 2013), irrigation in areas of limited rainfall (Kirch 1995, Doolittle 2014), and sophisticated storage techniques (de Saulieu and Testart 2015). Reorganization of social structures may also have been necessary to ensure food productivity and storage were reliable and available (Bar-Yosef 1998, Zapata et al. 2004). In cooler areas, more marginal to agriculture and distant from the origin centers of many cultivars, ecological and genetic changes were also required to ensure that crop seeds were suited to the local growing conditions. For

instance, genetic modifications that occurred during the spread of cereal crops across Europe, allowed species to adapt to the wetter and cooler climates and shorter growing seasons of central and northern Europe compared to the crops' original regions (Jones et al. 2008, 2012). Conversely, crop failure may have been more frequent during this adaptation phase, especially considering the apparent rapidity with which agriculture spread to some of these northerly areas (Whitehouse et al. 2014).

The concept of resilience is associated with, and encompasses the concepts of adaptability, vulnerability, and transition (Wilson 2012, 2013, Callo-Concha and Ewert 2014). Adaptability can be described as the collective capacity of the actors of a system to influence resilience, i.e., high adaptation to perturbation contributes to high resilience of the system. Adaptability is used here to refer to functional outcomes and not necessarily in a Darwinian sense. Vulnerability relates to the possible changes that a system undergoes once stressed and implies that a system might be vulnerable to some perturbations but not others (Adger 2006). Transition in resilience theory is connected with the cycle of adaptive change and its four phases of transformation, growth, conservation, release, and reorganization (Holling 1987). The concepts of adaptability, vulnerability, and resilience have been largely applied to the study of agricultural systems (Callo-Concha and Ewert 2014, and references therein). In contrast, the notion of transition has been less thoroughly explored and is frequently associated with the internal transitions between stages of the adaptive cycle, rather than to change from one system to another. These transitions are governed by several fast and slow variables, the most critical and important for the system's resilience being a low rate and a low frequency of change (Walker et al. 2006, 2012).

Some researchers have criticized the expression "social resilience" because the term has been almost directly adopted from environmental sciences and psychology, without appropriate modifications for other social sciences (see Keck and Sakkapolrak 2013, Lorenz 2013, Stone-Jovicich et al. in progress, and references therein). Within archeology, resilience provides a useful conceptual framework for the study of long-term historical ecology, emphasizing the inevitability of both stability and change in social-ecological systems (Redman 2005). In other words, this framework provides an opportunity to move away from deterministic narratives of change in past societies and to explore social, economic, and ecological changes within the same sphere of investigation. Most research based on this approach has focused on the resilience of the entire social-ecological system and the relationship between society and the environment (see Butzer and Endfield 2012). Other researchers who do not explicitly use resilience theory have focused on developing the specific social mechanisms that allow societies to absorb external disturbances, e.g., promoting the inherent flexibility of the system (see Head and Fullagar 1997, Trosper 2003, Nelson et al. 2006).

Why the need for another model for the transition to food production?

The literature available on models for the OA, either using ABM or not, is vast and its full review is outside the scope of this paper. Recent and detailed reviews can be found in Barlow (2006), Winterhalder and Kennett (2006), Bettinger et al. (2010), Gremillion et al. (2014), and Zeder (2015), among others, and the

numerous works by Tim Kohler, Michael Barton and Stephen Shennan. For what concerns the present work we find a passage of Ullah et al. work (2015:9579) critical: “Simply put, there is currently no sufficient theory to explain the nonlinear and contingent worldwide transitions from foraging to farming.” We need theoretically driven hypothesis-testing and a combination of both general explanations and local narratives depending on the data used as advocated by Gremillion et al (2014). The model we propose has two important characteristics that can advance our understanding of the transition to food production: (1) it can be applied to both in situ transitions and diffusion processes; and (2) it considers a broad range of factors that collectively played a role in this transition.

Although the demic/cultural diffusion processes underlying some agricultural transitions are still debated (Fort 2012, 2015), it is now clear that the OA took a multitude of paths depending on local conditions (Abbo et al. 2010, and references therein). The ability of members of the same functional group to diversify their response to external disturbance is a key aspect of resilient livelihood strategies (Walker et al. 2006). Early agricultural systems likely enhanced the general biodiversity of ecosystems (Zeder 2008), especially through intermediate disturbance (see, for example, Colombaroli et al. 2013, Siebert and Belsky 2014). However, farming can concurrently reduce the spectrum of available foods because of selection pressures on favored plants or crop choices (Walker et al. 2006). Therefore, efforts to increase resource management efficiency might actually lead to loss of resilience of a subsistence system. The links between biodiversity loss and the maintenance of ecosystem functioning are well known (Cardinale et al. 2012), and may eventually result in water eutrophication, increasing habitat homogeneity, and species loss (Storkey et al. 2012). These, in turn, lead to ecosystem service losses and less resilient ecosystems. Monocropping with a single genotype is a modern example of extreme biodiversity loss and the end point of a trajectory that started with production of domestic cereals. From these premises, it follows that agriculturalists should have, generally speaking, lower resilience than HG (although we are aware that there are several past and present examples where agro-ecological systems show great flexibility and high dynamism). Many researchers argue that the spatial and organizational flexibility typical of hunter-gatherers or foragers can be termed resilience because it promotes a continuous readaptation of their strategies (Ames 1981, Kent 1992). Indeed, it has been hypothesized that the resilience of HG groups is greater than that of farming societies because response diversity, mobility strategies, and reliance on a wider spectrum of resources enhances resilience (Bender 1978, Winterhalder 1990, Diamond 2002, Hamilton et al. 2014 and references therein). Few examples of HG systems’ failure, e.g., starvation, exist in the ethnographic record and these are mostly related to extreme climatic conditions (Jones et al. 1999, Williams et al. 2010) or the influence of a distinct population (Swift 1982, McGranaghan 2012, Friesen 2013). The model we present explores modifications introduced in the HG strategy that ultimately led to agriculture. At the same time, it also considers the weaknesses that might result in vulnerability to diffusion pressure. For example, it is unlikely that certain short-term ecological effects, such as biodiversity loss, had immediate impacts on early agriculturalists. However, they are likely to have been increasingly important in how shifts to

agriculture developed through time and may also help explain situations where such transitions did not occur.

With respect to the many existing models, we believe that the one presented here contributes the following:

- Addresses the lack of recognition of the many important processes that may be modeled from current ethnographic data on mixed economies and small-scale cultivation;
- Removes the linearity that has been implied in the transition to agriculture;
- Provides an explanation for the presence of intermediate stages, or mixed economies where cultivation did not inevitably lead to agriculture;
- Provides the basis for the formalization and implementation of a model that can be used in agent-based model simulations.

Crossing one threshold, in this case reliance on foraging versus farming products, often produces a cascading effect with several other thresholds breached at different spatial and temporal scales. To focus strongly on one single domain is likely to result in missing the interactions between domain shifts (Kinzig et al. 2006). For this reason, the model we propose explicitly links subsistence change to other aspects of environment, economic strategies, and social shifts.

THE MODEL

The three domains of the system

The model follows the conceptualization proposed by Wilson (2012) that places community resilience at the intersection of three complementary domains: environmental, economic, and social. Wilson uses transition theory as an approach to the study of resilience. Here, we take an opposite point of view, linking resilience and transition theory but using the former as a framework to explain the latter. Placing resilience at the intersection of three domains has previously been suggested (see, for example, Kinzig et al. 2006 and references therein), by considering how regime shifts in one domain impact upon other domains, and then in general on the whole social-ecological system.

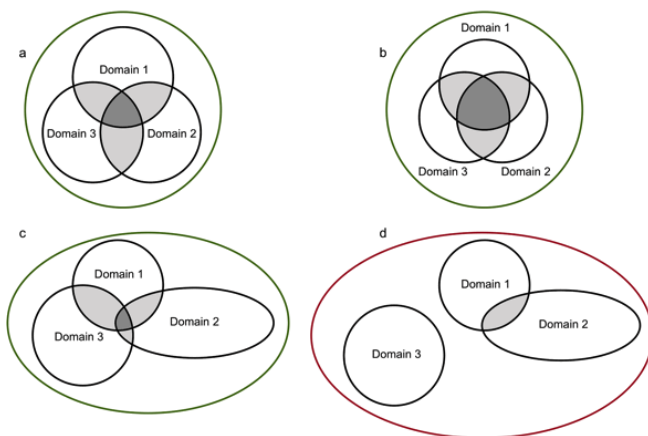
The model is therefore regulated by the interplay of the environmental, economic, and social resources, whereby a resilient system occurs when the three domains overlap, representing the resilient state of the SES system, or, in the present work, the capacity of a society to maintain the same livelihood strategy (Fig. 1a). The expansion of this area (representing greater or lesser resilience), can change both by modifying the overlapping part of the three areas (Fig. 1b) or the shape of one or more of the domains (Fig. 1c). The livelihood strategy ceases to be resilient when the system cannot counteract changes in the domains and when transition to a different livelihood strategy takes place (Fig. 1d). Below, is a description of how we define the domains in the model, and what factors we include in each of the three domains. Specifically, we concentrate on explaining the parameters and variables that we select as influential in the transition to food production and why we think each are important in this context.

Table 1. Summary of the variables presented in the paper, with an indication on proxies for measuring them in past social-ecological systems.

Parameter	Variable	Measure	Paleo proxies
Environmental resources	Ecosystem productivity	NPP/NSP	Micro- and macrobotanical remains Micro- and macrozoological remains Chemical and trace elements/nutrients Temperature and moisture proxies Proxies that measure quantified temperature or that indicate climate (e.g., chironomids; beetles; leaf waxes, tree rings, ice cores, ocean and lake sediments, plant isotopes)
	Variability of system productivity	Temperature Moisture/rainfall Seasonality Nutrient status	
Economic resources	Diet	Nutrient status Caloric intake	Archeobotany (macro- and microremains) Archeozoology Stable isotopes Residue analysis Chemical analysis on human bones
	Technology	Production/extraction/preservation efficiency	Geoarcheology Archeobotany (weeds) Typological studies Use-wear on lithics/bone tools Storage structures and technologies
Social resources	Population distribution	Demography	Density of sites Size of sites Gene flow Chronology/radiocarbon dates
	Social networks	Relationships and flows between and within groups	Patterns/distribution of the sites Appearance of exotic materials (trade)

NPP, Net Primary Production; NSP, Net Secondary Production.

Fig. 1. Schematic representation of the model. The external circle represents the livelihood system, which comprises three domains: environmental, social, and economic resources (not named in the figure to indicate that the change is not dependent on the domain). Whenever the three domains overlap, the system can be considered resilient (a, b, and c - green circle). The degree of resilience depends on the size of the overlapping areas: the more the three domains overlap (bigger area) the more resilient the system is. When one or more of the domains do not overlap with the others, the system is not resilient and the transition to a new system takes place (d - red circle).



Considering the multiscale, complex nature of the resilience framework, defining variables to be operationalized is extremely difficult, as also suggested by Cumming et al. (2005). In addition, when addressing resilience of social-ecological systems, which are complex systems, additional challenges are posed when approaching their formalization and parameterization because more than one attractor can play a significant role (Davidson 2010). Moreover, given the impossibility of replicating and analyzing real-world systems, it must be assumed that some level of subjectivity is inevitable in any study related to resilience of social-ecological systems. We argue that the variables selected (Table 1) are those that impact the system most, although recognize that they do not represent the entire spectrum of possible variables. We draw particular attention to the fact that it is not the absolute value of each variable that matters, but their variation and relative weight in respect to the other domains. In other words, rather than the absolute resource availability, it is the amount of variation in a particular resource and the rate of production of new resources that characterizes any particular system.

Parameter 1: Environmental resources

Humans are one of between 5 and 30 million animal species present on our planet (Erwin 1982), but use approximately 40% of the current productivity of terrestrial ecosystems (Vitousek et al. 1986). Therefore, environmental resources are fundamental in our model. We define this parameter as the biodiversity and geodiversity available for human exploitation, and we choose two specific variables, productivity and variability, because they are noncontext dependent, i.e., they can be applied to any environmental/economic setting, but can be strictly specified if

needed, for example, looking at single resource productivity. Furthermore, this approach can accommodate different scales: single elements (e.g., temperature) or pools of elements (e.g., seasonality) and nonlinear trajectories, looking at both resilient and nonresilient systems

Variable 1: Ecosystem productivity: This represents the entire pool of resources in the system or the rate of biomass generation. A rather straightforward way to quantify the available resources is to calculate an environment's net primary production (NPP) and net secondary production (NSP).

NPP is the rate at which all the plants in an ecosystem produce net chemical energy. This rate is equal to the difference between the rate at which the plants in an ecosystem produce chemical energy (gross primary production) and the rate at which they use some of that energy during respiration. NSP is the generation of biomass of heterotrophic (consumer) organisms in a system. This is characterized by the transfer of organic material between trophic levels and represents the quantity of new tissue (mostly animal) created by food assimilation. NSP is commonly defined to include all biomass generation by heterotrophs (herbivore consumers; carnivore consumers). The NPP and NSP are well-established measures for energy flow and they can be calculated for any environment, with higher or lower accuracy, including those for specific resources. These resources can originate from totally anthropic environments, such as a field of wheat, or from environments where the human influence is negligible, such as a tropical forest. Gross production in animals equals the amount of biomass or energy assimilated or biomass eaten less feces.

Using NPP and/or NSP offers the opportunity to estimate the level of energy potentially co-opted by humans (Kelly 1995, Binford 2001). It also allows the evaluation of possible consequences when there is an unsustainable use of resources, such as environmental degradation and species extinctions (loss of biodiversity), and altered climate. For the purpose of our model we can use NPP, NSP, or, more useful for resources potentially available to humans, the standing crop (the measure of the biomass of a system at a single point in time; calories/m²) as one of our parameters. The primary and secondary productions of an environment can be expressed as the rate of formation of new material in the environment or all biomass generated, per unit of surface and per unit of time (energy = calories/m²/year). The difference between primary production and standing crop is crucial when, for instance, we are interested in understanding delayed investments and management of the resource. The productivity of a field of wheat can be calculated simply by the standing crop because the resource is harvested at the end of the growing season in the same year. On the other hand, the productivity of a forest or a hazelnut grove should be calculated as primary production because it must include "time" because these systems are generally managed over an extended period. Indeed, the element "time" is very important when thinking about ecosystems; and understanding how much and how fast something is happening or changing is a critical aspect for properly understanding the system under study. NPP can be calculated for past systems through current data or models of past vegetation or plant production (see for example Sugita 2007, Gaillard et al 2010). Because NSP is positively correlated with

NPP, at least for what concerns herbivores (Coe et al. 1976), NPP can be used in the model to combine two values in one measure.

Variable 2: Variability of system productivity: This variable represents inter- and intra-annual changes in a system's productivity and assesses how much and how fast a system's productivity is changing. In this case we consider changes that happen within a system's phase, because of the inherent variance of the system characteristics, rather than changes of phases. A system can be destabilized depending on the scales and tempo of the decrease in system productivity, forcing human groups to deal with fewer or diminishing resources during particular periods, which in some cases can become critical for a group's survival. The importance of variability in systems' productivity has been highlighted, for instance, by a set of simulation experiments for HG populations in semiarid environments (Balbo et al. 2014). These have shown that, independently of the scale of the climatic variability, human populations increase as the variability in yearly precipitation (VYP) decreases. Here, yearly precipitation (YP) is taken as a rough proxy of NPP, valid at least in the specified climatic settings. Thus, the lower the interannual (annual, decadal) variation in precipitation, the better human populations perform in the simulation (population's growth). This is understandable in terms of human behavior because decreased short-term variability leads to improved predictability of resources (the system has more constant production) and continued availability from one year to the following. The opposite situation (high variance) reduces a population's growth capabilities because it requires a constant reconsideration of subsistence strategies that are dependent on the quantity of resources and their distribution in the landscape. These experiments also reveal that decadal patterns of resource availability affect reproductive strategies, i.e., the number of offspring any agent has (where the agent is a household comprising a couple and its offspring) depends on access to resources. It is interesting that similar responses are observed in current animal populations and that a higher variance of certain environmental parameters, e.g., temperature, impact the population performance (Vasseur et al. 2014). We therefore suggest that general models of ecosystem productivity should consider the amplitude and frequency of variations of ecosystems, especially in those study systems characterized by high seasonality or high fluctuations or variability in climatic parameters.

Parameter 2: Economic resources

We define this parameter as the subsistence strategy of a population, including the pool of resources that people choose to exploit among those available and by what means. Preindustrial subsistence strategies are normally divided into four major groups (Nanda and Warms 2011): (1) hunting and gathering; (2) horticulture, i.e., domestic plants and animals with low-level technology and absence of surplus; (3) pastoralism, i.e., domestic animals and animal products constitute the main resource base; and (4) agriculture, i.e., intensive or extensive cultivation of plants with high-level technologies. It now seems clear that in many cases this classification is too strict and some societies practice a mixed economy, combining elements of more than one of the above-mentioned strategies (Minzenberg and Wallace 2011, Greaves and Kramer 2014).

Variable 1: Diet: Diet, defined as the suite of resources that constitute the primary caloric intake of a community, can be traced both ethnographically and archeologically. The type and relative amounts of food items consumed can be explored ethnographically through interviews and direct observations. Past diets can be reconstructed from the archeological record using archeozoology (the study of vertebrate and invertebrate animal remains to reconstruct animal consumption and exploitation patterns), archeobotany (the study of archeological plant remains), as well as the study of human remains. These analyses offer a wealth of information on past subsistence strategies (literature on these subjects is abundant; an interesting effort to combine these techniques is represented by the work of Smith and Munro 2009). More recently, other dietary proxies, such as chemical, isotopic, and elemental signatures have been successfully used to reconstruct past diets (Fernandes et al. 2014, and references therein).

Changes in past and present subsistence strategies have been linked to climate and environmental change (e.g., Richerson et al. 2001), resource overexploitation (Williams et al. 2014), as well as modification of the social structure (e.g., McCabe et al. 2010). By modifying their diet, populations can offset the overexploitation of specific resources, but also increase their resilience. Indeed, HG are often characterized as resilient because of their diverse diet (Bender 1978) and flexible social organization (Colonese et al. 2014).

Variable 2: Technology: Technology is the means by which people access natural resources. The available technology determines the suite of resources that can be potentially procured. Technology may be viewed either as changing autochthonously in response to novel food opportunities, either environmentally generated or due to dietary shifts, or enabling new exploitive tasks through introduction. Many past archeological arguments about technological and dietary changes, especially among food producers, emphasized introductions of tools and techniques as critical (Kirch 1995, Doolittle 2014, de Saulieu and Testart 2015). Current understanding recognizes the potential complexities in identifying innovation, simple adoption, and modified use of new techniques in both archeology and ethnology. Indeed, technology and resource exploitation are suggested to be coevolutionary (see Rammel et al. 2007 for a discussion on modern complex adaptive systems).

Technological change is a key aspect of inferring subsistence shifts in archeology. Associated faunal and floral remains may not always be recovered from archeological sites to provide a secure understanding between technology and diet. Variation in tools may signal new subsistence activities, situational changes in extant dietary practices, or changes that affect resource exploitation in complex ways that can feedback into environmental availability or social organization. For example, technological innovation can drive change in the intensity with which resources are exploited, i.e., increased accessibility, reduced search, pursuit or handling time, increased return predictability (Bender 1978). For example, the introduction of firearms in Native Alaskan communities has dramatically increased the number of hunted caribou (Usher 1965).

It has been proposed that the introduction of the ox-drawn plough, whose archeological signatures can be at times studied

through soil micromorphology (Lewis 2012), initiates a series of social transformations that ultimately led to intensification of production (Kerig 2013). New food processing technologies can also result in resources intensification (Wright 1994). Thus food procurement and processing artefacts may reflect changes in strategies to increase their nutritional input. Other forms of technology, such as storage, allow the unbalanced temporal production of specific resources to remain available throughout the year, mitigating risk and uncertainty in resource availability (de Saulieu and Testart 2015, and references therein). Mobility can also be considered a technological strategy to manipulate the spatial distribution of resources and maintain the stability of the system (Binford 2001, Kelly 2013, Hamilton et al. 2014, and references therein).

Parameter 3: Social resources

We define social resources as the means by which societies respond to and cope with internal and external stresses and disturbances. According to ethnography, these mechanisms emerge at different social scales including the individual, household, and community level. Archeologically, the social scale may be a much more abstract set of events because the time depth and temporal resolution of the archeological record is not equivalent to relatively short-term ethnographic observations. Although many social factors influence the ability to cope with changing and variable conditions, for simplicity, most factors are expected to filter through population distribution and social networks. Because we are exploring the transition from HG to AP (even if cases of reversion from AP to HG are not uncommon), we concentrate on the social mechanisms that primarily regulate HG societies.

Variable 1: Population distribution: Although the environment imposes certain constraints on population size, hunter-gatherers may adjust group numbers through various mechanisms to balance resource density with population density. The distribution of individuals, households, and groups can be managed through mobility, camp composition (Williams and Hunn 1982, Kelly 1983, 2013, Binford 2001), dispersal and postmarital residence patterns (Alvarez 2004, Marlowe 2010, Kramer and Greaves 2011), and fusion/fission dynamics (Crema 2014). Population redistribution may occur at different temporal scales, for example, daily, seasonally, or annually, and may involve the aggregation and dispersal of different group members, e.g., bachelor foraging trips, female food processing parties). At its simplest, population redistribution serves to adjust consumers and producers, and the age and sex composition of groups for the purposes of resource procurement, mating, and information exchange.

Ethnographically, population distribution has been linked to resource availability and extensive studies exist about resource availability, mobility, and population densities (Keeley 1988, Taylor 1998). For example, among Pumé mobile hunter-gatherers living on the Llanos of Venezuela, camp membership includes bilateral kin and remains stable across all seasonal moves. This appears to be a response to their marginal environment by maximizing the number of producers and to be as inclusive of male and female kin base as possible (Kramer and Greaves 2011). In contrast, among Hadza, hunter-gatherers living in the woodlands of Tanzania, individuals rotate among much smaller

shorter term camps (Marlowe 2006). Unlike the Venezuelan Llanos, the Hadza environment has a greater availability of game, tubers, and reliable sources of honey, so that camp moves are seldom related to food shortages. Camps can include fewer producers partly because each has a greater assurance of daily foraging success (Woodburn 1972).

An archeological example is represented by the Azapa Valley (northern Chile) where Varela and Cocilovo (2002) identified changes in population distribution dynamics over a period of about 6000 years. Their study highlighted that genetic changes in the population correlate well with population mobility, increase/decrease of endogamy in the kinship structure, and changes in the economy, i.e., beginning of plant cultivation. Population density and distribution in archeology has been inferred also through summed probability distribution of radiocarbon dates (e.g., Crema et al. 2016, Shennan and Edinborough 2007, Bamforth and Grund 2012, and references therein), through settlement pattern and distribution (Zimmermann et al. 2009), or habitable areas (see Gautney and Holliday 2015, and references therein). Some of the most recent results of this approach seem to indicate that demography had a crucial role in shaping the phase of incipient food-production in Europe (Shennan et al. 2013), although a different perspective is also emerging, that compares the demographic growth of HG to that of AP (Zahid et al. 2016).

Variable 2: Social networks: In addition to population distribution, HGs also utilize many strategies to establish social networks that link individuals with small familial units as well as across sometimes vast distances. Social networks involve obligations and responsibilities that may form among kin and nonkin for the purposes of reproduction, family formation, food and resource sharing, information exchange, protection, aggression, and other forms of cooperation. Social networks function as systems where hierarchies (elements at different scale) interact at different levels (Kohl 2008). Social networks include the number of individuals and the extent of a network (size of the network), as well as the intensity of interactions (frequency, periodicity, etc.). Because of the partiality of the archeological record, evidences for past social networks are difficult to assess. However, finding exotic materials in archeological assemblages might indicate the existence of exchange routes that possibly served as information exchange networks too (Zvelebil 2006, Otte 2009). In addition new approaches are being developed to understand population distribution across territories (Marwick 2003, Soares et al. 2010). Ethnographic data offer extensive information on social networks, which can be used to build general exchange and social networks models. Then, the complexity of the networks can be measured following specific methodologies, such as Horton-Strahler number (see an application to a social case study in Arenas et al. 2004).

Pumé hunter-gatherers, for example, frequently aggregate for all-night dances that reify group solidarity and membership across a broad social sphere (Kramer and Greaves 2016). Although food consumption does not occur during these gatherings, individuals participate by singing and dancing, activities known to promote cooperation (Adams 2004, Wiltermuth and Heath 2009). Information exchange at dances includes discussions of resource distributions, news of kin and individuals of interest for a range of economic and social reasons, and outside events that may affect

local communities. These weekly dances also include storytelling and performance of healing rites. Songs and stories typically reiterate kin and affine relations across multiple generations and large distances. Rarely does a camp member not attend these events, which often are followed by foraging and hunting bouts and other cooperative activities.

Gamble (1982) was one of the first scholars to use social network theories to interpret Paleolithic art and ornaments to formalize the link between archeological objects and social alliances and interactions. Moreover, the spread of different types of ornaments has been interpreted archeologically as a mechanism for reinforcing identities and delayed reciprocity (Trubitt 2003). A way of inferring social networks from livelihood practices has been introduced by Stiner and Kuhn (2006). Their work shows that during the Late Paleolithic, the decrease in ungulates prey size, alongside changes in the mortality patterns, could be interpreted as the consequence of higher demographic pressure (Stiner et al. 1999), which in turn forced a reorganization and intensification of social networks (Stiner and Kuhn 2006).

DISCUSSION

Because the dynamics of social-ecological systems are mostly driven by humans, some authors consider adaptability mainly as a function of the social component (Walker et al. 2004). However, it is the interplay of the three domains we identify in the model (environmental, economic, and social) that influences the resilience of any particular adaptive system. Focusing too intensely on one of the three risks underestimating the effects of the others, and of their interactions. This is the reason why we have conceptualized the intersection of each domain as representing a resilience measure. Certainly, SES are complex in that the effects of the interactions are more than the sum of the single parts. For example, in our model, any changes in one of those contributing domains can affect the area of overlapping between those domains (the systems' resilience) thus producing a cascading effect in the others that ultimately affects the whole system. Environments can be affected by the economic and social behaviors of humans, and obviously environments play an important role in determining effective economic and social strategies. For example, in the transition from HG to AP there may be associated soil impoverishment and in some cases biodiversity loss (Denevan 1995, Haberle 2007), but the various forms of traditional landscape engineering can also be beneficial creating, in fact, higher biodiversity (Zeder 2008). On the other hand, in some ecosystems removing one element might create a cascade effect that impinges on the entire trophic system (Chapin et al. 2000). Normally, the higher the biodiversity, the more resilient the system. Generally, environmental effects are better understood or hypothesized than the diverse outcomes from changing subsistence responses of humans as economies change and social behaviors shift, making systemic resilience measures problematic. This concept has been explored in the study of livelihood strategies and it is mostly accepted that HGs, who consume a wide spectrum of food products and share and divide their foodstuff to minimize vulnerability, are more resilient than many agricultural adaptations (Bender 1978, Winterhalder 1990, Diamond 2002).

Relevance of this model to the study of the transition to agriculture

The model we presented in this paper may be used to explain transitions in livelihood systems. In our expectations, transitions are most likely to occur when the pull of the environmental and the social domains is strong and populations do not have the possibility of mitigating it by changing some of the internal variables (technology, mobility, etc.). These may include, but are not limited to, the deliberate mixed use of wild and domesticated resources, a focus on more reliable food storage, and/or social mechanisms such as exchange and specialization (Whitehouse and Kirleis 2014, Antolín et al. 2015, García-Granero et al. 2015). As a result, the only, or most profitable, option is to completely change the subsistence strategy, i.e., the economic resources. This model offers the possibility to consider social-ecological prehistoric systems as dynamic and fluctuating. The value of this model is augmented by the additional consideration of selecting parameters that can also be examined in modern ethnographic contexts where populations exhibit stable or transitioning economies that include foraging, mixed subsistence, and agricultural reliance.

The proposed approach also removes the linearity of simply expecting most systems to lead to agricultural adaptations and provides the possibility of formalizing the model and using it for simulations. This potentially offers improved understanding of circumstances where HGs changed their strategy to include some aspects of cultivation that may or may not have led to a greater reliance on agriculture. Such instances would represent changes in the “shape” or “size” (Figs. 1b and 1c) of the resilient area of the system, without the three domains separating (Fig. 1d). These cases are important to gain a better understanding of transitions from foraging to horticultural and agricultural reliance where the archeological evidence indicates that significant periods of time separate initial appearances of cultivation and the move to reliance on those foods (Allaby et al. 2008, Piperno and Pearsall 1998, Richerson et al. 2001, Smith 2001). This also means that most transitions to agriculture occur from mixed economies, not directly from hunting and gathering.

ABM as a tool to explore resilience of livelihood strategies

The resilience of livelihood strategies as the consequence of the dynamics between complex social and economic domains is influenced by emergent properties of societies that follow nonlinear pathways and is based on a bottom-up approach to uncertainty and change (Wilson 2012, and references therein). In this perspective, agent-based models (ABM) and simulations (ABS) represent some of the most useful tools to investigate these wider processes, and specifically in small-scale societies. Traditionally, modeling and simulation approaches are split between two different perspectives: (1) ecologically influenced or (2) oriented to artificial societies (for a synthesis on this subject, see Epstein and Axtell 1996). The first perspective is primarily interested in environmental constraints and resource exploitation and management, often neglecting the importance of human behavior. The second perspective makes use of simplified virtual societies to investigate theoretical questions, thus removing what should be a basic component of the model: the environment where human interactions take place. ABM and simulation, provides the opportunity to integrate ecological and social aspects in realistic, heterogeneous scenarios (Rubio-Campillo et al. 2012,

and references therein). In addition, ABMS is able to deal with a wide range of assumptions (Balbo et al. 2014, Lake and Crema 2012) as well as with agent’s decision-making processes (Francés et al. 2015), opening the possibility to investigate subsistence shifts from both a theoretical and the empirical perspective. We consider that this model incorporates a number of useful interactions to evaluate the potential for the concept of resilience to improve alternative explanatory implications behind potentially complex pathways from hunting and gathering to agricultural lifeways.

CONCLUSIONS

The model we described in this paper constitutes a first conceptualization to be used as the basis for the implementation of formal ABM and ABMS. We stress that our work on the application of these ideas is at an early stage, and present this framework in the hope that it will be useful to future research on the question of OA and, more generally, of the resilience of social-ecological systems. The variables selected to explain the model can be easily converted into numerical values to be introduced in a computational model and adapted to any specific case study. The next step of the research will be the implementation of the proposed model to explore the mechanisms behind the transition to agriculture in a set of worldwide case studies. We believe that our approach can positively contribute to the challenge of understanding how this transition took place and the adaptive mechanisms that were put in place to maintain the resilience of livelihood strategies, both HG and AP.

AUTHOR CONTRIBUTIONS

All authors discussed the idea, the paper structure and the parameters to be included in the model. CL wrote a first draft, the general parts and the economic parameter. All other authors contributed to the general text and, more specifically, DZ and KLK contributed to the social parameters and NJW and MM to the ecological parameters.

Responses to this article can be read online at:

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