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RESILIENCE OF SMALL-SCALE SOCIETIES' LIVELIHOODS: A FRAMEWORK FOR STUDYING THE TRANSITION FROM FOOD GATHERING TO FOOD PRODUCTION

1. ABSTRACT

2. 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. Archaeologists 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 non-linear 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 archaeological 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
19. state (from one livelihood strategy to another).
20. Key words: transition to agriculture; social-ecological dynamics; ABM; subsistence strategies;
21. resources

INTRODUCTION
23. The adoption of agriculture is regarded as one of the major changes of the past and has been
24. intensively studied by both archaeologists and anthropologists (see e.g. the special issue on the
25. origins of agriculture in Current Anthropology edited by Leslie C. Aiello in 2011, Rindos 2013,
26. Barton and An 2014). However, due to the nature of the archaeological record whereby this process
27. becomes visible only once its practice is clearly established (see Fuller 2007 for discussion),
28. transitional phases between foraging groups and fully developed food-producing societies are much
29. less easily unfolded (notable exceptions are represented by the work of Zvelebil and Dolukhanov
30. 1999, and Smith 2001). Recent studies have shown that such transitional phases and the emergence of
31. 'mixed subsistence economies', based on the use of both wild and domesticated animal and plant
32. species, lasted at least several hundreds and in some cases thousands of years (Larson et al. 2014
33. and references therein). Further, these changes fundamentally shaped the development of agricultural
34. societies that emerged around the world (Hayden 1990, Denham et al. 2003, Weiss et al. 2006, Kuijt
36. methodological and technological advances, as well as an increase of archaeological excavations in
37. areas not investigated before, have produced large amounts of empirical data on forager-farmer
38. transitions worldwide (Fuller et al. 2014, and references therein). However, the resulting
39. interpretations are hampered by the many taphonomic problems related to archaeological material,
40. whereby differential preservation (especially of biological remains) impinges on our reconstructions
41. of past processes. Conversely, Gremillion et al. (2014) have argued that this hyper reliance on
42. empirical data has contributed to the rejection of general explanations on the origins of
43. agriculture (OA) and the consequent loss of theoretically driven hypothesis testing. Moreover,
44. scholars tend to explain this transition either as a necessity (e.g. due to climate change) or as an
45. opportunity (e.g. because domesticates offer more reliable food sources) (see as Ullah et al. 2015).
46. However, it is becoming clearer that both these mechanisms often acted in concert and at the same
47. time or at different chronological or spatial locations and the challenge is to distinguish between
48. these two occurrences. Recent advances in modeling and simulation approaches in archaeological
49. research (Madella et al. 2014) provide an opportunity for a detailed study of both the processes and
50. transitions associated with agricultural production (Allaby et al. 2008, 2010; van Etten and Hijmans
51. 2010; Ullah et al. 2015), and thus offer a formal tool to help close the 'gap' in our understanding
52. of the transition between hunter-gatherer (HG) and agro-pastoral (AP) societies.

53. In this paper we propose a theoretical conceptual model to study the transition to agriculture using resilience and social-ecological systems (SESs) theory. This is conceived as a way to clarify the

54. meaning of concepts and terms adopted as well as to make explicit the connections between these

55. different concepts. The ultimate aim is to advance general theoretical understanding of the origins

56. of agriculture through the creation of a model that will then be implemented in Agent-Based

57. Simulations. However we believe that, before proceeding to the implementation phase, a theoretical

58. introduction of our proposed approach that frames transitions within resilience theory is required,

59. and delivered in the current paper. Taken alone, none of the concepts presented here are new to

60. archaeology (see for example Redman 2005, Gronenborn et al. 2014). However, their combined use and

61. application to understanding the 'resilience of livelihood strategies', is a valuable and novel

62. contribution. The concept of 'livelihood strategy' refers to the combination of activities that

63. people develop to achieve their subsistence goals. These usually depend on the ecological settings

64. (Environmental Resources), productive strategies (Economic Resources) and social choices (Social

65. Resources), for which, in this article, we propose a parameterization (cf. Wilson 2012).

66. Resilience theory and transitions

67. The concept of resilience is used here sensu 'ecological resilience' (Holling 1973), indicating a

68. measure of how much a system can be perturbed without shifting to a new regime. When we talk about

69. transitions, we intend a slow change in the system that can potentially, but not necessarily, lead

70. to a transformation (or critical transition, Scheffer 2009). The system might gradually lose

71. resilience until even a minor perturbation can push it over a tipping point (ibid p.24). Resilience

72. theory is a particularly well-suited framework to study the nature of transitions for several

73. reasons. First, 'resilience' is a neutral framework, i.e. it does not have a positive or negative

74. connotation per se but it can be one or the other depending on the circumstances (Cumming et al.

75. 2005). Early literature tends to consider resilience as a positive state, because it is typically

76. associated with 'sustainability' (see a review of the use of the term resilience in Miller et al.

77. 2010). However, these are two different -albeit sometimes related- concepts, and resilience is not

78. always positive. Occasionally, a change at a larger scale might be beneficial and systems that do

79. not pass a certain threshold at a lower scale might be resilient, but at the same time create

80. problems in the surrounding environment or in the social structures that define them (Walker et al.

81. 2004).

82. Another aspect of resilience theory that fits well within transition studies (as proposed by Wilson

83. 2012) is the formalization of several adaptive cycles. Specifically, the synchronous interaction of

84. small-and-fast, intermediate and slow-and-large cycles seems particularly well-suited to constitute
86. A framework for studying the transition to agriculture. It is highly probable that during a long
87. phase transition to fully-committed agriculture, shifts in diet between HG and AP were common. These
88. might have included small changes in the dependency on one type of resource or another, as well as
89. 'reverses' from AP to HG. Such examples are evident in the archaeological record, stressing the
90. fluid nature of food procurement and preferences towards both domesticated and wild resources, such
91. as in areas of central and northern Europe (e.g. Bishop et al. 2009, Schibler and Jacomet 2010,
92. Kirleis et al. 2011, Colledge and Conolly 2014, Whitehouse et al. 2014) as well as southern Europe
93. (Antolin and Jacomet 2015, Valamoti 2015) during the transition period. Several modern HG
94. examples also show that these strategies often are complementary and reversions from one to the
95. other are not uncommon (e.g. Greaves and Kramer 2014). In addition, social, technological and
96. ecological changes may have been crucial for full reliance on agro-pastoralism. These changes might
97. have ranged from the introduction of the ard and tilling technology for increasing productivity
98. (Kerig 2013), irrigation in areas of limited rainfall (Kirch 1995, Doolittle 2014) and sophisticated
99. storage techniques (de Saulieu and Testart 2015). Reorganization of social structures may also have
100. been necessary to ensure food productivity and storage were reliable and available (Bar-Yosef 1988;
101. Zapata et al. 2005). In cooler areas, more marginal to agriculture and distant from the origin
102. centers of many cultivars, ecological and genetic changes were also required to ensure that crop
103. seeds were suited to the local growing conditions. For instance, genetic modifications that occurred
104. during the spread of cereal crops across Europe, allowed species to adapt to the wetter and cooler
105. climates and shorter growing seasons of central and northern Europe compared to the crops' original
106. regions (Jones et al. 2008, 2012). Conversely, crop failure may have been more frequent during this
107. adaptation phase, especially considering the apparent rapidity with which agriculture spread to some
108. of these northerly areas (Whitehouse et al. 2014).
109. The concept of resilience is associated with, and encompasses the concepts of 'Adaptability',
110. 'Vulnerability', and 'Transition' (Wilson 2012, 2013, Callo-Concha and Ewert 2014). Adaptability can
111. be described as the collective capacity of the actors of a system to influence resilience, i.e high
112. adaptation to perturbation contributes to high resilience of the system. Adaptability is used here
113. to refer to functional outcomes and not necessarily in a Darwinian sense. Vulnerability relates to
114. the possible changes that a system undergoes once stressed and implies that a system might be
115. vulnerable to some perturbations but not others (Adger 2006). Transition in resilience theory is
116. connected with the cycle of adaptive change and its four phases of transformation (Growth,
117. Conservation, Release and Reorganization - Holling 1987). The concepts of Adaptability,
118. Vulnerability and Resilience have been largely applied to the study of agricultural systems
119. (Callo-Concha and Ewert 2014, and references therein). In contrast, the notion of Transition has
120. been less thoroughly explored and is frequently associated with the internal transitions between
121. stages of the adaptive cycle, rather than to change from one system to another. These transitions
122. are governed by several fast and slow variables, the most critical and important for the system's
123. resilience being a low rate and a low frequency of change (Walker et al. 2006, 2012).
124. Some researchers have criticized the expression 'social resilience' because the term has been almost
125. directly adopted from environmental sciences and psychology, without appropriate modifications for
126. other social sciences (see Keck and Sakdapolrak 2013, Lorenz 2013, and the special issue being
127. edited by Stone-Jovicich et al. for discussion, and references therein). Within archaeology,
128. resilience provides a useful conceptual framework for the study of long term historical ecology,
129. emphasizing the inevitability of both stability and change in social-ecological systems (Redman
130. 2005). In other words, this framework provides an opportunity to move away from deterministic
131. narratives of change in past societies and to explore social, economic and ecological changes within
132. the same sphere of investigation. Most research based on this approach has focused on the resilience
133. of the entire social-ecological system and the relationship between society and the environment (see
134. Butzer and Endfield 2012). Other researchers who do not explicitly use resilience theory have
135. focused on developing the specific social mechanisms that allow societies to absorb external
136. disturbances (e.g. promoting the inherent flexibility of the system, see Head and Fullagar 1997,

138. Why the need for another model for the transition to food production?
139. The literature available on models for the OA, either using ABM or not, is vast and its full review
140. is outside the scope of this paper. Recent and detailed reviews can be found in Barlow (2006),
141. Winterhalder and Kennett (2006), Bettinger et al. (2010), Gremillion et al. (2014), and Zeder
142. (2015), amongst others, and the numerous works by Tim Kohler, Michael Barton and Stephen Shennan.
143. For what concerns the present work we find a passage of Ullah et al. work (2015) critical: "Simply
144. put, there is currently no sufficient theory to explain the nonlinear and contingent worldwide
145. transitions from foraging to farming" (ibid, pp 9579). We need theoretically driven
146. hypothesis-testing and a combination of both general explanations and local narratives depending on
147. the data used as advocated by Gremillion et al (2014). The model we propose has two important
148. characteristics that can advance our understanding of the transition to food production: a) it can
149. be applied to both in situ transitions and diffusion processes; and b) it considers a broad range of
150. factors that collectively played a role in this transition.

151. Although the demic/cultural diffusion processes underlying some agricultural transitions are still
152. debated (Fort 2012, 2015), it is now clear that the OA took a multitude of paths depending on local
153. conditions (Abbo et al. 2010 and references therein). The ability of members of the same functional
154. 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 due to selection pressures on favoured 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 as it promotes a continuous re-adaptation 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:

- 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 impacts 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, of the adaptability of the livelihood 
strategy and the capacity of a society to persist - figure 1a). The expansion of this area 
(representing greater or lesser resilience), can change both by modifying the overlapping part of 
the three areas (figure 1b) or the shape of one or more of the domains (figure 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 (figure 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.

Considering the multiscalar, 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 as more than one
attractor can play a significant role (Davidson 2010). Moreover, given the impossibility of
copied 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 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.

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

Parameter 1: Environmental resources

Humans are one of between 5 and 30 million animals 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, as they are non-context dependent (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 non-linear trajectories,
looking at both resilient and non-resilient 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
c charact erized 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 faeces.

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/m$^2$) 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/m$^2$/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’ as 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 Gaillard et al 2010, Sugita 2007). As NSP is
positively correlated with NPP, at least for what concerns herbivores (Coe et al. 1976, Cole et al.
1991), 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 the
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 semi-arid 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 inter-annual (annual, decadal) variation in precipitation, the better human populations perform in the simulation (population's growth). This is understandable in terms of human behavior, as 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, as 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 composed by 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 characterised 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 amongst those available and by what means. Pre-industrial subsistence strategies are normally divided into four major groups (Nanda and Warms 2011): 1) hunting and gathering; 2) horticulture - domestic plants and animals with low-level technology and absence of surplus; 3) pastoralism - domestic animals and animal products constitute the main resource base; and 4) agriculture - 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 archaeologically. 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 archaeological record using archaeozoology (the study of vertebrate and invertebrate animal remains to reconstruct animal consumption and exploitation patterns), archaeobotany (the study of archaeological 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 archaeological 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 archaeology and ethnology. Indeed, technology and resource exploitation are suggested to be co-evolutionary (see Rammel et al. 2007 for a discussion on modern complex adaptive systems).

Technological change is a key aspect of inferring subsistence shifts in archaeology. Associated faunal and floral remains may not always be recovered from archaeological 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, 137).

It has been proposed that the introduction of the ox-drawn plough, whose archaeological 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 Salieu 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. Archaeologically, the social
scale may be a much more abstract set of events because the time depth and temporal resolution of
the archaeological record is not equivalent to relatively short-term ethnographic observations.
While 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

While 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 (Álvarez 2004, Marlowe 2010, Kramer and Greaves 2011), and fusion/fission dynamics
(Crema 2014). Population redistribution may occur at different temporal scales (daily, seasonally or
annually, for example), 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 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 archaeological 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 archaeology has been inferred also through summed probability distribution of radiocarbon dates (e.g. Crema et al. in press, 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 archaeological record, evidences for past social networks are difficult to assess. However, finding exotic materials in archaeological 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 (Marvick 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, n.d.). 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 archaeological objects and social alliances and
interactions. Moreover, the spread of different types of ornaments has been interpreted
archaeologically 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 turns forced a reorganization and
intensification of social networks (Stiner and Kuhn 2006).

DISCUSSION AND CONCLUSIONS
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, SESs 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 III 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, Antolin 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’ (figure 1b and 1c) of the resilient area of the system, without the three domains separating (figure 1d). These cases
are important to gain a better understanding of transitions from foraging to horticultural and agricultural reliance where the archaeological 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, economic and social domains is influenced by emergent properties of societies that follow non-linear 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 (see Rubio-Campillo et al., this issue). Traditionally, modeling and simulation approaches are split between two different perspectives: a) ecologically influenced or b) 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 (Francès 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 in order to maintain the resilience of livelihood strategies (both HG and AP).

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>Measure*</th>
<th><em>Palaeo</em>proxies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental resources</td>
<td>Ecosystem productivity</td>
<td>NPP/NSP</td>
<td>Micro and macro-botanical remains</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Micro and macro-zoological remains</td>
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<td></td>
<td></td>
<td></td>
<td>Chemical and trace elements/nutrients</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Temperature and moisture proxies</td>
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<tr>
<td>Variability of</td>
<td>Temperature</td>
<td></td>
<td>Proxies that measure quantified temperature or that</td>
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<tr>
<td>system productivity</td>
<td>Moisture/rainfall</td>
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<td>indicate climate (e.g. chironomids; beetles; leaf</td>
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<tr>
<td></td>
<td>Seasonality</td>
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<td>waxes, tree rings, ice cores, ocean and lake sediments,</td>
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<tr>
<td></td>
<td>Nutrient status</td>
<td></td>
<td>plant isotopes)</td>
</tr>
<tr>
<td>Economic resources</td>
<td>Diet</td>
<td>Caloric intake</td>
<td>Archaeobotany (macro- and microreains)</td>
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<td></td>
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<td>Archaeozoology</td>
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<td>Stable isotopes</td>
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<td>Residue analysis</td>
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<td></td>
<td>Chemical analysis on human bones</td>
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<tr>
<td>Technology</td>
<td>Production/extraction / preservation efficiency</td>
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<td>Geoarchaeology</td>
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<td>Archaeobotany (weeds)</td>
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<td>Typological studies</td>
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<td>Use-wear on lithics/bone tools</td>
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<td>Storage structures and technologies</td>
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<tr>
<td>Social resources</td>
<td>Population distribution</td>
<td>Demography</td>
<td>Density of sites</td>
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<td>Size of sites</td>
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<td>Gene flow</td>
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<td>Chronology/radiocarbon dates</td>
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<tr>
<td>Social networks</td>
<td>Relationships and flows between and within groups</td>
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<td>Patterns/distribution of the sites</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Appearance of exotic materials (trade)</td>
</tr>
</tbody>
</table>
Fig. 1. Schematic representation of the model. The external circle represent the livelihood system, which is composed by 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).