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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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## Research

### Special Feature: Small-Scale Societies and Environmental Transformations: Coevolutionary Dynamics

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

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1.

### **ABSTRACT**

2. The origins of agriculture and the shift from hunting and gathering to committed agriculture is
3. regarded as one of the major transitions in human history. Archaeologists and anthropologists have
4. invested significant efforts in explaining the origins of agriculture. A period of gathering
5. intensification and experimentation and pursuing a mixed economic strategy seems the most plausible
6. explanation for the transition to agriculture and provides an approach to study a process in which
7. several non-linear processes may have played a role. However, the mechanisms underlying the
8. transition to full agriculture are not completely clear. This is partly due to the nature of the
9. archaeological record, which registers a practice only once it has become clearly established. Thus,
10. points of transitions have limited visibility and the mechanisms involved in the process are
11. difficult to untangle. The complexity of such transitions also implies that shifts can be
12. distinctively different in particular environments and under varying historical and social
13. conditions. In this paper we discuss some of the elements involved in the transition to food
14. production within the framework of resilience theory. We propose a theoretical conceptual model in
15. which the resilience of livelihood strategies lies at the intersection of three spheres: the
16. environmental, economical and social domains. Transitions occur when the rate of change, in one or
17. more of these domains, is so elevated or its magnitude so large that the livelihood system is unable
18. 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
- 22.

## 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  
35. and Finlayson 2009, Asouti and Fuller 2012, 2013, Fuller et al. 2012, Smith 2015). Recent  
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 also 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  
54. resilience and social-ecological systems (SESSs) theory. This is conceived as a way to clarify the  
55. meaning of concepts and terms adopted as well as to make explicit the connections between these  
56. different concepts. The ultimate aim is to advance general theoretical understanding of the origins  
57. of agriculture through the creation of a model that will then be implemented in Agent-Based  
58. Simulations. However we believe that, before proceeding to the implementation phase, a theoretical  
59. introduction of our proposed approach that frames transitions within resilience theory is required,  
60. and delivered in the current paper. Taken alone, none of the concepts presented here are new to  
61. archaeology (see for example Redman 2005, Gronenborn et al. 2014). However, their combined use and  
62. application to understanding the 'resilience of livelihood strategies', is a valuable and novel  
63. contribution. The concept of 'livelihood strategy' refers to the combination of activities that  
64. people develop to achieve their subsistence goals. These usually depend on the *ecological settings*  
65. (Environmental Resources), *productive strategies* (Economic Resources) and *social choices* (Social  
66. Resources), for which, in this article, we propose a parameterization (cf. Wilson 2012).

#### 67. **Resilience theory and transitions**

68. The concept of resilience is used here *sensu* 'ecological resilience' (Holling 1973), indicating a  
69. measure of how much a system can be perturbed without shifting to a new regime. When we talk about  
70. transitions, we intend a slow change in the system that can potentially, but not necessarily, lead  
71. to a transformation (or critical transition, Scheffer 2009). The system might gradually lose  
72. resilience until even a minor perturbation can push it over a tipping point (*ibid* p.24). Resilience  
73. theory is a particularly well-suited framework to study the nature of transitions for several  
74. reasons. First, 'resilience' is a neutral framework, i.e. it does not have a positive or negative  
75. connotation *per se* but it can be one or the other depending on the circumstances (Cumming et al.  
76. 2005). Early literature tends to consider resilience as a positive state, because it is typically  
77. associated with 'sustainability' (see a review of the use of the term resilience in Miller et al.  
78. 2010). However, these are two different -albeit sometimes related- concepts, and resilience is not  
79. always positive. Occasionally, a change at a larger scale might be beneficial and systems that do  
80. not pass a certain threshold at a lower scale might be resilient, but at the same time create  
81. problems in the surrounding environment or in the social structures that define them (Walker et al.  
82. 2004).

83. Another aspect of resilience theory that fits well within transition studies (as proposed by Wilson  
84. 2012) is the formalization of several adaptive cycles. Specifically, the synchronous interaction of  
85. 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. (Antolín 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,  
137. Trosper 2003, Nelson et al. 2006).

**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

155. strategies (Walker et al. 2006). Early agricultural systems likely enhanced the general biodiversity  
156. of ecosystems (Zeder 2008), especially through intermediate disturbance (see for example Colombaroli  
157. et al. 2013, Siebert and Belsky 2014). However, farming can concurrently reduce the spectrum of  
158. available foods due to selection pressures on favoured plants or crop choices (Walker et al. 2006).  
159. Therefore, efforts to increase resource management efficiency might actually lead to loss of  
160. resilience of a subsistence system. The links between biodiversity loss and the maintenance of  
161. ecosystem functioning are well known (Cardinale et al. 2012), and may eventually result in water  
162. eutrophication, increasing habitat homogeneity and species loss (Storkey et al. 2012). These, in  
163. turn, lead to ecosystem service losses and less resilient ecosystems. Monocropping with a single  
164. genotype is a modern example of extreme biodiversity loss and the end point of a trajectory that  
165. started with production of domestic cereals. From these premises, it follows that agriculturalists  
166. should have, generally speaking, lower resilience than HG (although we are aware that there are  
167. several past and present examples where agro-ecological systems show great flexibility and high  
168. dynamism). Many researchers argue that the spatial and organizational flexibility typical of  
169. hunter-gatherers or foragers can be termed resilience as it promotes a continuous re-adaptation of  
170. their strategies (Ames 1981; Kent 1992). Indeed, it has been hypothesized that the resilience of HG  
171. groups is greater than that of farming societies because response diversity, mobility strategies and  
172. reliance on a wider spectrum of resources enhances resilience (Bender 1978, Winterhalder 1990,  
173. Diamond 2002, Hamilton et al. 2014 and references therein). Few examples of HG systems' failure  
174. (e.g. starvation) exist in the ethnographic record and these are mostly related to extreme climatic  
175. conditions (Jones et al. 1999, Williams et al. 2010) or the influence of a distinct population  
176. (Swift 1982, McGranaghan 2012, Friesen 2013). The model we present explores modifications introduced  
177. in the HG strategy that ultimately led to agriculture. At the same time, it also considers the  
178. weaknesses that might result in vulnerability to diffusion pressure. For example, it is unlikely  
179. that certain short-term ecological effects, such as biodiversity loss, had immediate impacts on  
180. early agriculturalists. However, they are likely to have been increasingly important in how shifts  
181. to agriculture developed through time and may also help explain situations where such transitions  
182. did not occur.

183. With respect to the many existing models, we believe that the one presented here:  
184. - Addresses the lack of recognition of the many important processes that may be modeled from current  
185. ethnographic data on mixed economies and small-scale cultivation;  
186. - Removes the linearity that has been implied in the transition to agriculture;  
187. - Provides an explanation for the presence of intermediate stages, or mixed economies where  
188. cultivation did not inevitably lead to agriculture;

189. - Provides the basis for the formalization and implementation of a model that can be used in  
190. Agent-Based Model Simulations.  
  
191. Crossing one threshold (in this case reliance on foraging *versus* farming products) often produces a  
192. cascading effect with several other thresholds breached at different spatial and temporal scales. To  
193. focus strongly on one single domain is likely to result in missing the interactions between domain  
194. shifts (Kinzig et al. 2006). For this reason, the model we propose explicitly links subsistence  
195. change to other aspects of environment, economic strategies, and social shifts.

196.

## THE MODEL

### 197. The three domains of the system

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

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

217. Considering the multiscalar, complex nature of the resilience framework, defining variables to be  
218. operationalized is extremely difficult, as also suggested by Cumming et al. (2005). In addition,  
219. when addressing resilience of social-ecological systems, which are complex systems, additional

220. challenges are posed when approaching their formalization and parameterization as more than one  
221. attractor can play a significant role (Davidson 2010). Moreover, given the impossibility of  
222. replicating and analyzing real-world systems, it must be assumed that some level of subjectivity is  
223. inevitable in any study related to resilience of social-ecological systems. We argue that the  
224. variables selected are those that impact the system most, although recognize that they do not  
225. represent the entire spectrum of possible variables. We draw particular attention to the fact that  
226. it is not the absolute value of each variable that matters, but their variation and relative weight  
227. in respect to the other domains. In other words, rather than the absolute resource availability, it  
228. is the amount of variation in a particular resource and the rate of production of new resources that  
229. characterizes any particular system.

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

**232. Parameter 1: Environmental resources**

233. Humans are one of between 5 and 30 million animals species present on our planet (Erwin 1982), but  
234. use approximately 40% of the current productivity of terrestrial ecosystems (Vitousek et al. 1986).  
235. Therefore, environmental resources are fundamental in our model. We define this parameter as the  
236. biodiversity and geodiversity available for human exploitation, and we choose two specific  
237. variables: productivity and variability, as they are non-context dependent (they can be applied to  
238. any environmental/economic setting) but can be strictly specified if needed (for example, looking at  
239. single resource productivity). Furthermore, this approach can accommodate different scales: single  
240. elements (e.g. temperature) or pools of elements (e.g. seasonality) and non-linear trajectories,  
241. looking at both resilient and non-resilient systems

**242. Variable 1: Ecosystem productivity**

243. This represents the entire pool of resources in the system or the rate of biomass generation. A  
244. rather straightforward way to quantify the available resources is to calculate an environment's Net  
245. Primary Production (NPP) and Net Secondary Production (NSP).

246. NPP is the rate at which all the plants in an ecosystem produce net chemical energy. This rate is  
247. equal to the difference between the rate at which the plants in an ecosystem produce chemical energy  
248. (Gross Primary Production) and the rate at which they use some of that energy during respiration.  
249. NSP is the generation of biomass of heterotrophic (consumer) organisms in a system. This is  
250. characterized by the transfer of organic material between trophic levels and represents the quantity  
251. of new tissue (mostly animal) created by food assimilation. NSP is commonly defined to include all  
252. biomass generation by heterotrophs (herbivore consumers; carnivore consumers). The NPP and NSP are

253. well-established measures for energy flow and they can be calculated for any environment (with  
254. higher or lower accuracy), including those for specific resources. These resources can originate  
255. from totally anthropic environments, such as a field of wheat, or from environments where the human  
256. influence is negligible, such as a tropical forest. Gross production in animals equals the amount of  
257. biomass or energy assimilated or biomass eaten less faeces.

258. Using NPP and/or NSP offers the opportunity to estimate the level of energy potentially co-opted by  
259. humans (Kelly 1995, Binford 2001). It also allows the evaluation of possible consequences when there  
260. is an unsustainable use of resources, such as environmental degradation and species extinctions  
261. (loss of biodiversity), and altered climate. For the purpose of our model we can use NPP, NSP or,  
262. more useful for resources potentially available to humans, the standing crop (the measure of the  
263. biomass of a system at a single point in time; calories/m<sup>2</sup>) as one of our parameters. The primary  
264. and secondary productions of an environment can be expressed as the rate of formation of new  
265. material in the environment or all biomass generated, per unit of surface and per unit of time  
266. (energy = calories/m<sup>2</sup>/year). The difference between primary production and standing crop is crucial  
267. when, for instance, we are interested in understanding delayed investments and management of the  
268. resource. The productivity of a field of wheat can be calculated simply by the standing crop because  
269. the resource is harvested at the end of the growing season in the same year. On the other hand, the  
270. productivity of a forest or a hazelnut grove should be calculated as primary production because it  
271. must include 'time' as these systems are generally managed over an extended period. Indeed, the  
272. element 'time' is very important when thinking about ecosystems; and understanding *how much* and *how*  
273. fast something is happening or changing is a critical aspect for properly understanding the system  
274. under study. NPP can be calculated for past systems through current data or models of past  
275. vegetation or plant production (see for example Gaillard et al 2010, Sugita 2007). As NSP is  
276. positively correlated with NPP, at least for what concerns herbivores (Coe et al. 1976, Cole et al.  
277. 1991), NPP can be used in the model to combine two values in one measure.

278. *Variable 2: Variability of System Productivity*

279. This variable represents inter- and intra-annual changes in a system's productivity and assesses the  
280. *how much* and *how fast* a system's productivity is changing. In this case we consider changes that  
281. happen within a system's phase, because of the inherent variance of the system characteristics,  
282. rather than changes of phases. A system can be destabilized depending on the scales and tempo of the  
283. decrease in system productivity, forcing human groups to deal with fewer or diminishing resources  
284. during particular periods, which in some cases can become critical for a group's survival. The  
285. importance of variability in systems' productivity has been highlighted, for instance, by a set of  
286. simulation experiments for HG populations in semi-arid environments (Balbo et al. 2014). These have

287. shown that, independently of the scale of the climatic variability, human populations increase as  
288. the variability in yearly precipitation (VYP) decreases. Here, yearly precipitation (YP) is taken as  
289. a rough proxy of NPP, valid at least in the specified climatic settings. Thus, the lower the  
290. inter-annual (annual, decadal) variation in precipitation, the better human populations perform in  
291. the simulation (population's growth). This is understandable in terms of human behavior, as  
292. decreased short-term variability leads to improved predictability of resources (the system has more  
293. constant production) and continued availability from one year to the following. The opposite  
294. situation (high variance) reduces a population's growth capabilities, as it requires a constant  
295. reconsideration of subsistence strategies that are dependent on the quantity of resources and their  
296. distribution in the landscape. These experiments also reveal that decadal patterns of resource  
297. availability affect reproductive strategies, i.e. the number of offspring any agent has (where the  
298. agent is a household composed by a couple and its offspring) depends on access to resources. It is  
299. interesting that similar responses are observed in current animal populations and that a higher  
300. variance of certain environmental parameters (e.g. temperature) impact the population performance  
301. (Vasseur et al 2014). We therefore suggest that general models of ecosystem productivity should  
302. consider the amplitude and frequency of variations of ecosystems, especially in those study systems  
303. characterised by high seasonality or high fluctuations or variability in climatic parameters.

304. **Parameter 2: Economic resources**

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

314. **Variable 1: Diet**

315. Diet, defined as the suite of resources that constitute the primary caloric intake of a community,  
316. can be traced both ethnographically and archaeologically. The type and relative amounts of food  
317. items consumed can be explored ethnographically through interviews and direct observations. Past  
318. diets can be reconstructed from the archaeological record using archaeozoology (the study of  
319. vertebrate and invertebrate animal remains to reconstruct animal consumption and exploitation  
320. patterns), archaeobotany (the study of archaeological plant remains) as well as the study of human

321. remains. These analyses offer a wealth of information on past subsistence strategies (literature on  
322. these subjects is abundant, an interesting effort to combine these techniques is represented by the  
323. work of Smith and Munro 2009). More recently, other dietary proxies, such as chemical, isotopic and  
324. elemental signatures have been successfully used to reconstruct past diets (Fernandes et al. 2014,  
325. and references therein).

326. Changes in past and present subsistence strategies have been linked to climate and environmental  
327. change (e.g., Richerson et al. 2001), resource overexploitation (Williams et al. 2014) as well as  
328. modification of the social structure (e.g., McCabe et al. 2010). By modifying their diet,  
329. populations can offset the overexploitation of specific resources, but also increase their  
330. resilience. Indeed, HG are often characterized as resilient because of their diverse diet (Bender  
331. 1978) and flexible social organization (Colonese et al. 2014).

332. *Variable 2: Technology*

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

343. Technological change is a key aspect of inferring subsistence shifts in archaeology. Associated  
344. faunal and floral remains may not always be recovered from archaeological sites to provide a secure  
345. understanding between technology and diet. Variation in tools may signal new subsistence activities,  
346. situational changes in extant dietary practices, or changes that affect resource exploitation in  
347. complex ways that can feedback into environmental availability or social organization. For example,  
348. technological innovation can drive change in the intensity with which resources are exploited, i.e.  
349. increased accessibility, reduced search, pursuit or handling time, increased return predictability  
350. (Bender 1978). For example, the introduction of firearms in Native Alaskan communities has  
351. dramatically increased the number of hunted caribou (Usher 1965, 137).

352. It has been proposed that the introduction of the ox-drawn plough, whose archaeological signatures  
353. can be at times studied through soil micromorphology (Lewis 2012), initiates a series of social

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

**363. *Parameter 3: Social resources***

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

**373. *Variable 1: Population Distribution***

374. While the environment imposes certain constraints on population size, hunter-gatherers may adjust  
375. group numbers through various mechanisms to balance resource density with population density. The  
376. distribution of individuals, households and groups can be managed through mobility, camp composition  
377. (Williams and Hunn 1982, Kelly 1983, 2013, Binford 2001), dispersal and postmarital residence  
378. patterns (Álvarez 2004, Marlowe 2010, Kramer and Greaves 2011), and fusion/fission dynamics  
379. (Crema 2014). Population redistribution may occur at different temporal scales (daily, seasonally or  
380. annually, for example), and may involve the aggregation and dispersal of different group members  
381. (e.g. bachelor foraging trips, female food processing parties). At its simplest, population  
382. redistribution serves to adjust consumers and producers, and the age and sex composition of groups  
383. for the purposes of resource procurement, mating and information exchange.  
  
384. Ethnographically, population distribution has been linked to resource availability and extensive  
385. studies exist about resource availability, mobility and population densities (Keeley 1988, Taylor  
386. 1998). For example, among Pumé mobile hunter-gatherers living on the Llanos of Venezuela,

387. camp membership includes bilateral kin and remains stable across all seasonal moves. This appears to  
388. be a response to their marginal environment by maximizing the number of producers and be as  
389. inclusive of male and female kin base as possible (Kramer and Greaves 2011). In contrast, among  
390. Hadza, hunter-gatherers living in the woodlands of Tanzania, individuals rotate among much smaller  
391. shorter-term camps (Marlowe 2006). Unlike the Venezuelan Llanos, the Hadza environment has a greater  
392. availability of game, tubers and reliable sources of honey, so that camp moves are seldom related to  
393. food shortages. Camps can include fewer producers partly because each has a greater assurance of  
394. daily foraging success (Woodburn 1972).

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

407. *Variable 2: Social Networks*

408. In addition to population distribution, HGs also utilize many strategies to establish social  
409. networks that link individuals with small familial units as well as across sometimes vast distances.  
410. Social networks involve obligations and responsibilities that may form among kin and nonkin for the  
411. purposes of reproduction, family formation, food and resource sharing, information exchange,  
412. protection, aggression and other forms of cooperation. Social networks function as systems where  
413. hierarchies (elements at different scale) interact at different levels (Kohl 2008). Social networks  
414. include the number of individuals and the extent of a network (size of the network), as well as the  
415. intensity of interactions (frequency, periodicity, etc.). Because of the partiality of the  
416. archaeological record, evidences for past social networks are difficult to assess. However, finding  
417. exotic materials in archaeological assemblages might indicate the existence of exchange routes that  
418. possibly served as information exchange networks too (Zvelebil 2006, Otte 2009). In addition new  
419. approaches are being developed to understand population distribution across territories (Marwick  
420. 2003, Soares et al. 2010). Ethnographic data offer extensive information on social networks, which

421. can be used to build general exchange and social networks models. Then, the complexity of the  
422. networks can be measured following specific methodologies, such as Horton-Strahler number (see an  
423. application to a social case study in Arenas et al. 2004).

424. Pumé hunter-gatherers, for example, frequently aggregate for all-night dances that reify  
425. group solidarity and membership across a broad social sphere (Kramer and Greaves, n.d.). Although  
426. food consumption does not occur during these gatherings, individuals participate by singing and  
427. dancing, activities known to promote cooperation (Adams 2004; Wiltermuth, and Heath 2009).  
428. Information exchange at dances includes discussions of resource distributions, news of kin and  
429. individuals of interest for a range of economic and social reasons, and outside events that may  
430. affect local communities. These weekly dances also include storytelling and performance of healing  
431. rites. Songs and stories typically reiterate kin and affine relations across multiple generations  
432. and large distances. Rarely does a camp member not attend these events, which often are followed by  
433. foraging and hunting bouts and other cooperative activities.

434. Gamble (1982) was one of the first scholars to use social network theories to interpret Paleolithic  
435. art and ornaments to formalize the link between archaeological objects and social alliances and  
436. interactions. Moreover, the spread of different types of ornaments has been interpreted  
437. archaeologically as a mechanism for reinforcing identities and delayed reciprocity (Trubitt 2003). A  
438. way of inferring social networks from livelihood practices has been introduced by Stiner and Kuhn  
439. (2006). Their work shows that during the Late Paleolithic, the decrease in ungulates prey size,  
440. alongside changes in the mortality patterns, could be interpreted as the consequence of higher  
441. demographic pressure (Stiner et al. 1999), which in turns forced a reorganization and  
442. intensification of social networks (Stiner and Kuhn 2006).

443.

## **DISCUSSION AND CONCLUSIONS**

444. Because the dynamics of social-ecological systems are mostly driven by humans, some authors consider  
445. adaptability mainly as a function of the social component (Walker et al. 2004). However, it is the  
446. interplay of the three domains we identify in the model (environmental, economic and social) that  
447. influences the resilience of any particular adaptive system. Focusing too intensely on one of the  
448. three risks underestimating the effects of the others, and of their interactions. This is the reason  
449. why we have conceptualized the intersection of each domain as representing a resilience measure.  
450. Certainly, SESs are complex in that the effects of the interactions are more than the sum of the  
451. single parts. For example, in our model, any changes in one of those contributing domains can affect  
452. the area of overlapping between those domains (the systems' resilience) thus producing a cascading

453. effect in the others that ultimately affects the whole system. Environments can be affected by the  
454. economic and social behaviors of humans, and obviously environments play an important role in  
455. determining effective economic and social strategies. For example, in the transition from HG to AP  
456. there may be associated soil impoverishment and in some cases biodiversity loss (Denevan 1995,  
457. Haberle 2007), but the various forms of traditional landscape engineering can also be beneficial  
458. creating, in fact, higher biodiversity (Zeder 2008). On the other hand, in some ecosystems removing  
459. one element might create a cascade effect that impinges on the entire trophic system (Chapin III et  
460. al. 2000). Normally, the higher the biodiversity the more resilient the system. Generally,  
461. environmental effects are better understood or hypothesized than the diverse outcomes from changing  
462. subsistence responses of humans as economies change and social behaviors shift, making systemic  
463. resilience measures problematic. This concept has been explored in the study of livelihood  
464. strategies and it is mostly accepted that HGs, who consume a wide spectrum of food products and  
465. share and divide their foodstuff to minimize vulnerability, are more resilient than many  
466. agricultural adaptations (Bender 1978, Winterhalder 1990, Diamond 2002).

**467. Relevance of this model to the study of the transition to agriculture**

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

481. The proposed approach also removes the linearity of simply expecting most systems to lead to  
482. agricultural adaptations and provides the possibility of formalizing the model and using it for  
483. simulations. This potentially offers improved understanding of circumstances where HGs changed their  
484. strategy to include some aspects of cultivation that may or may not have led to a greater reliance  
485. on agriculture. Such instances would represent changes in the 'shape' or 'size' (figure 1b and 1c)  
486. of the resilient area of the system, without the three domains separating (figure 1d). These cases

487. are important to gain a better understanding of transitions from foraging to horticultural and  
488. agricultural reliance where the archaeological evidence indicates that significant periods of time  
489. separate initial appearances of cultivation and the move to reliance on those foods (Allaby et al.  
490. 2008, Piperno and Pearsall 1998, Richerson et al. 2001, Smith 2001). This also means that most  
491. transitions to agriculture occur from 'mixed' economies, not directly from hunting and gathering.

**492. ABM as a tool to explore resilience of livelihood strategies**

493. The resilience of livelihood strategies as the consequence of the dynamics between complex social,  
494. economic and social domains is influenced by emergent properties of societies that follow non-linear  
495. pathways and is based on a 'bottom-up' approach to uncertainty and change (Wilson 2012 and  
496. references therein). In this perspective, Agent Based Models (ABM) and Simulations (ABS) represent  
497. some of the most useful tools to investigate these wider processes, and specifically in small-scale  
498. societies (see Rubio-Campillo et al., this issue). Traditionally, modeling and simulation approaches  
499. are split between two different perspectives: a) ecologically influenced or b) oriented to  
500. artificial societies (for a synthesis on this subject, see Epstein and Axtell 1996). The first  
501. perspective is primarily interested in environmental constraints and resource exploitation and  
502. management, often neglecting the importance of human behavior. The second perspective makes use of  
503. simplified virtual societies to investigate theoretical questions, thus removing what should be a  
504. basic component of the model: the environment where human interactions take place. ABM and  
505. simulation, provides the opportunity to integrate ecological and social aspects in realistic,  
506. heterogeneous scenarios (Rubio-Campillo et al. 2012 and references therein). In addition, ABMS is  
507. able to deal with a wide range of assumptions (Balbo et al. 2014, Lake and Crema 2012) as well as  
508. with agent's decision-making processes (Francès et al. 2015), opening the possibility to  
509. investigate subsistence shifts from both a theoretical and the empirical perspective. We consider  
510. that this model incorporates a number of useful interactions to evaluate the potential for the  
511. concept of resilience to improve alternative explanatory implications behind potentially complex  
512. pathways from hunting and gathering to agricultural lifeways.

**513. Conclusions**

514. The model we described in this paper constitutes a first conceptualization to be used as the basis  
515. for the implementation of formal ABM and ABMS. We stress that our work on the application of these  
516. ideas is at an early stage, and present this framework in the hope that it will be useful to future  
517. research on the question of OA and, more generally, of the resilience of social-ecological systems.  
518. The variables selected to explain the model can be easily converted into numerical values to be  
519. introduced in a computational model and adapted to any specific case study. The next step of the  
520. research will be the implementation of the proposed model to explore the mechanisms behind the

521. transition to agriculture in a set of worldwide case studies. We believe that our approach can  
522. positively contribute to the challenge of understanding how this transition took place and the  
523. adaptive mechanisms that were put in place in order to maintain the resilience of livelihood  
524. strategies (both HG and AP).
- 525.

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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.

Parameter	Variable	Measure <sup>a</sup>	<i>Palaeoproxies</i>
Environmental resources	Ecosystem productivity	NPP/NSP	Micro and macro-botanical remains Micro and macro-zoological remains Chemical and trace elements/nutrients Temperature and moisture proxies
	Variability of system productivity	Temperature Moisture/rainfall Seasonality Nutrient status	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)
Economic resources	Diet	Caloric intake	Archaeobotany (macro- and microremains) Archaeozoology Stable isotopes Residue analysis Chemical analysis on human bones
	Technology	Production/extraction / preservation efficiency	Geoarchaeology Archaeobotany (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)

**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).

