Social Cooperation and Resource Management DynamicsAmong Late Hunter-Fisher-Gatherer Societies in Tierra del Fuego (South America)

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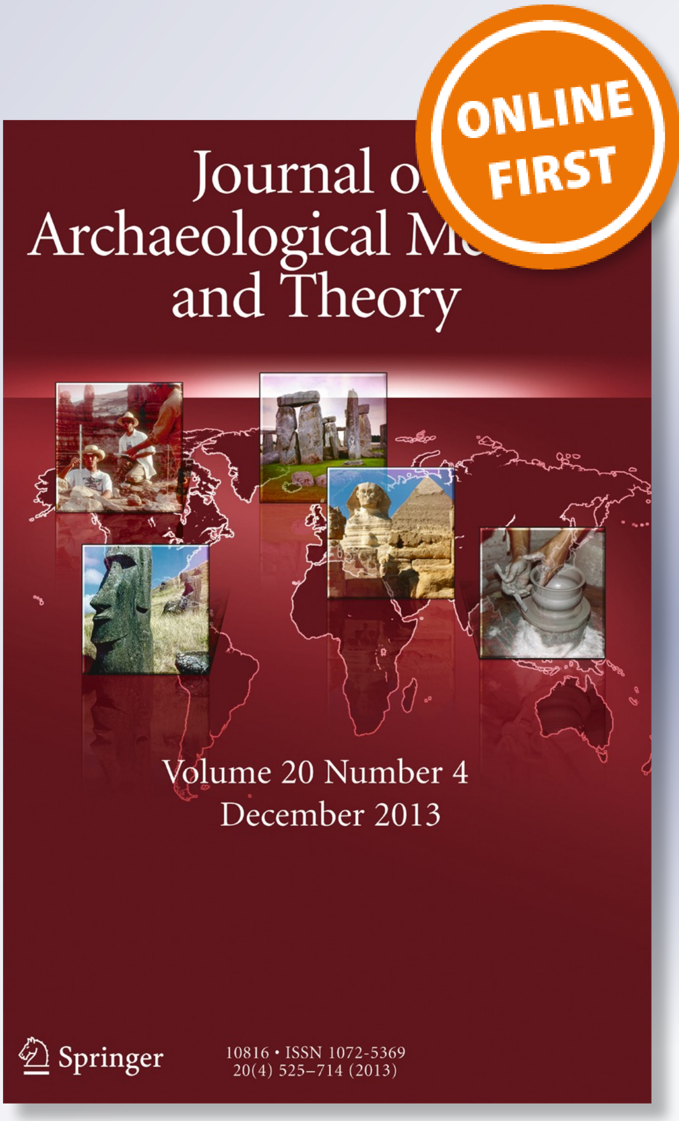

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Social Cooperation and Resource Management Dynamics Among Late Hunter-Fisher-Gatherer Societies in Tierra del Fuego (South America)

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Abstract This paper presents the theoretical basis and first results of an agent-based model (ABM) computer simulation that is being developed to explore cooperation in hunter–gatherer societies. Specifically, we focus here on Yamana, a hunter-fisher-gatherer society that inhabited the islands of the southernmost part of Tierra del Fuego (Argentina–Chile). Ethnographical and archaeological evidence suggests the existence of sporadic aggregation events, triggered by a public call through smoke signals of an extraordinary confluence of resources under unforeseeable circumstances in time and space (a beached whale or an exceptional accumulation of fish after a low tide, for example). During these aggregation events, the different social units involved used to develop and improve production, distribution and consumption processes in a collective way. This paper attempts to analyse the social dynamics that explain cooperative behaviour and resource-sharing during aggregation events using an agent-based model of indirect reciprocity. In brief, agents make their decisions based on the success of the public strategies of other agents. Fitness depends on the resource captured and the social capital exchanged in aggregation events, modified by the agent's reputation. Our computational results identify the relative importance of

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resources with respect to social benefits and the ease in detecting—and hence punishing—a defector as key factors to promote and sustain cooperative behaviour among population.

Keywords ABM · Cooperation · Computer simulation · Yamana · Ethnoarchaeology

Introduction

Western thought has a long intellectual tradition exploring why people cooperate, including nineteenth-century theorists such as Durkheim and Marx. Questions about why people cooperate and how cooperative behaviours are maintained are long-standing issues in the social sciences that have given rise to an array of perspectives, from those claiming that human beings are altruistic by nature to the idea that humans are naturally motivated by self-interest.

These questions provided the baselines to design an ethnoarchaeological research project aimed at exposing the dynamics embedded in aggregation and cooperation processes between hunter-fisher-gatherer societies that inhabited the coasts of the Beagle Channel at the southern extreme of South America (Briz *et al*. 2009). According to ethnographical documents, these groups, which called themselves Yamana or Yaghan, developed sporadic aggregation events when a whale or fish was found stranded on the beach (Gusinde 1937). In such occasions, individuals who discovered this exceptional accumulation of foodstuff made a public call with smoke signals in order to take advantage of windfall resources, bringing together several families that would be dispersed otherwise. Cooperative activities related to production, distribution and consumption processes were improved and social norms were reinforced.

The general aim of our project is to identify the mechanisms involved in aggregation practises in order to strengthen social ties and to assess the role of cooperation in historical change. The use of a simulation in this case study enhanced the opportunity to explore the evolution of cooperative behaviours to the extent that the social dilemma over whether to make the call or remain silent can be formalised in a computer model used to distil the role played by different factors (*e.g.* scarcity and variability of resources, visibility of social units, reputation, *etc.*) in promoting or hindering aggregation events in Yamana society.

Social Cooperation in Hunter-Fisher-Gatherer Societies

Cooperation is a crucial topic of study in the social sciences. Not only is it one of the most significant forms of social interaction, but it also constitutes a key factor in understanding the development of humankind as a species and in explaining its social and historical transformation (Alexander 2008; Bowles and Gintis 2003; Boyd and Richerson 2005; Carballo *et al*. 2012; Henrich and Henrich 2006; Ingold 1988; Marx and Engels 1977; West *et al*. 2011).

Therefore, many debates about whether humankind is a cooperative species or a self-interested species have been raised in various disciplines (Huxley 1888; Kropotkin

1902; Wright 2011). Within formal disciplines (and especially in the life sciences), these debates are not limited to the study of human societies, as they recognise cooperation as an ethological-specific trait in some species such as primates (de Waal and Suchak 2010; Warneken *et al*. 2007), or in eusocial species (Thorne 1997; Wilson and Hölldobler 2005).

In human societies, cooperation may be achieved differently than from a simple synchronised action that implies mutual benefit, as appears in some eusocial cases (Tarpy *et al*. 2004). Human cooperative attitudes, which are set out for development on a grand scale, have been recorded in anthropological studies under the umbrella of reciprocity and directly linked to other concepts such as redistribution and exchange (Durkheim 1909, 1917; Malinowski 1961; Mauss 1931). Therefore, the fact that human cooperative dynamics far exceed kinship or reciprocity-based relationships (reciprocal altruism) limits the explanations of mainstream or traditional approaches such as classical evolutionary theory (Henrich and Boyd 2001). In recent times, different hypothesis linked to cultural evolutionary theory have been proposed regarding the evolution of human cooperation (see Boyd and Richerson 2005; Tomasello *et al*. 2012).

Human cooperation not only involves the development of a historical memory (based on learning as well as on the social transfer of knowledge), but it also entails long-term foresight of the social consequences of individual behaviour. Continuous investment is made in time and effort to develop and maintain cooperation through social norms and their institutionalisation (Axelrod 1986; Gumerman *et al*. 2003), the generation of social prestige mechanisms (Henrich and Boyd 2001; Henrich and Gil-White 2001; Ohtsuki and Iwasa 2004), the establishment of coercive and punitive mechanisms (Boyd *et al*. 2010; Sigmund 2007; Sugden 2012), inclusion in and exclusion from the group (Field 1998; Henrich 2004) and the cost of signalling in cooperation and group-beneficial behaviour (Bliege Bird and Smith 2005; Smith and Bliege Bird 2005).

There is a general consensus that there is a surplus in reciprocity that surpasses the material interests involved, which is described as "(…) the kernel of social cohesion in general" (Narotzky 2007, p. 406). Even though cooperation is based on individual attitudes and decisions, its *raison d'être* lies in its existence within a network of social relations, being a structural element for human societies (Melis and Seemann 2010; Nowak 2006).

Many studies conducted in the social sciences that compare cooperation with competition are based on game theory (Axelrod 1997; Elliott and Kiel 2002; Nowak and Sigmund 2000; Skyrms 2004). In them, a cooperator is defined as someone who pays a cost for another individual to receive a benefit (Nowak 2006). The extreme stylisation implied in this definition clashes with the concept of cooperation that appears in anthropological disciplines, where social variability and a critical reading of the ethnographical literature makes it difficult to arrive at single and simplistic definitions.

The study of hunter–gatherer societies has been of paramount importance for learning about "human cooperation" as it occurs in a social simulation (Mithen 1994). Apart from the fact that we were hunter–gatherers for most of our history and that this kind of society still exists (Henrich *et al*. 2001), a long evolutionary history of cooperative production in foraging societies is probably responsible for the universal human tendency to cooperate (Hill 2002). Despite existing debates over the suitability of using these groups as examples of how early humans could have behaved (Estévez and Vila 1996), studying them allows us to open our minds to the notion of human cooperation, as they best exemplify this trait (Apicella *et al*. 2012), as well as to understand how such tendencies evolved (Hill 2002).

We define cooperation as a social relationship that allows certain social and economic practises to take place in a particular way in which different social agents are involved; these agents develop production, distribution and consumption processes collectively so that the profits/returns/payoff for all participating individuals increase. These profits/returns/payoffs, which are not necessarily strictly material in nature, are neither immediate nor uniform (there is not necessarily a proportional relation between the investment made and the benefits received). Social benefits such as reputation, which may lead to future material benefits, may play an outstanding role here and may even be more important than immediate material benefits.

Ethnographical documentation about this society, combined with general anthropological background knowledge, gives us a clear idea about how cooperative practises would have taken place in our case study. It also allows us to enrich the range of payoffs, which focus on the reproduction of different aspects of social life that could have been derived from an aggregation event. On one hand, an increase in the workforce and "technological knowledge capital" may have led both to educating youth in particular manufacturing techniques (transfer of knowledge) and to a more general way to innovate. On the other hand, there are other payoffs regarding social organisation as follows: rites of passage or other "cultural reproduction" activities such as singing, explaining myths and tales or playing.

Making Hypotheses About Social Cooperation, Ethnoarchaeology and Computer Simulation: Bridging the Gap

Throughout the history of archaeological research, considerable effort has been devoted to theoretical and epistemological reflection about the relationship between the archaeological record and the dynamics of past societies. The need for methodological improvements to go beyond the fragmentary nature of material evidence and to reach a solid interpretation of social and historical processes (Lull 1988, 2005) has been a long-standing aim in archaeological inquiry. In this sense, new archaeology explicitly tackled this issue, engendering different interpretative tools such as the extensive use of models and the development of middle-range theory (Binford 1977).

It must be stated here that we consider ethnoarchaeology to be a methodological tool for developing new methods, techniques and hypotheses in archaeology (Agorsah 1990; Aldenfender 2001; Béyries 1997; Béyries and Pétrequin 2001; Carlson 2009; David and Kramer 2001; Estévez and Vila 1996; Gould 1980; Roux 2007). For us, ethnoarchaeology entails the critical use of ethnographical, ethnological and historical sources about recent past societies (Axtell 1979; Carlson 2009; Davidson 2006; De Rojas 2008) and ethnographic living societies (Politis 2007). Its general aim is to obtain analytical tools for answering social questions, improving our archaeological methods and/or hypotheses (Briz 2010; Zurro *et al.* 2010) through dialectical contrast between archaeological methods and results and ethnographical sources (Estévez and Vila 1996).

Computer simulation offers the opportunity to include theoretical foundations based on empirical observation of archaeological and historical records. On one hand, this helps us to find evidence and assumptions about a given historical/social process; on the other, it helps us to analyse its dynamics, its logical implications and, hence, the plausibility of a given hypothesis or interpretation. Likewise, computer simulations are powerful tools for assessing how a practise may evolve within a particular time frame. Thus, it allows us to experiment in archaeology and consequently to narrow the range of plausible paths for investigating past societies.

Agent-based modelling (ABM) is characterised by the way that the abstraction of the target system is constructed. In ABM, there is a direct correspondence between the entities observed in the real system (and the interactions among them) and the agents that represent those entities individually and explicitly in the computational model (Edmonds 2001). ABM makes abstraction of the target system easier, providing the opportunity to implement idiosyncratic characteristics of past social human dynamics (*e.g*. heterogeneity, autonomy, explicit space, local interactions or bounded rationality) (Epstein 1999), but requiring adherence to the logical consistency of formal models at the same time.

Even though there are some complicated ABM models in archaeology that attempt to reproduce or emulate real empirical archaeological data and high-level patterns, in the present case, we adopted an experimental or exploratory approach to build simple and heuristic models focused on controlled experimentation, theory building and hypothesis generation (Premo 2010). See examples of this type of research in Kohler and van der Leeuw (2007) and Kohler *et al*. (2012). This approach allows us to explore different conditions and variables involved in the emergence, development and resilience of a given social phenomenon or process. By systematically varying these variables and conditions of experimental parameters, we can study the range of plausible conditions that affect the phenomenon under study, as well as to what extent (Premo 2010).

Consequently, computer simulation is used here as a tool to build a model focused on the evolution of social cooperation in a hunter-fisher-gatherer society in Tierra del Fuego. The ethnographical sources and ethnoarchaeological results provide the basic social rules and variables followed by the agents of the simulation.

Late Hunter-Fisher-Gatherer Societies of Fuegian Channels, Case Study: The Yamana Society

The Yamana or Yaghan society was a hunter-fisher-gatherer society that inhabited the southernmost tip of South America in the nineteenth and twentieth centuries (Gusinde 1937). For over 7,000 years, the societies established in this region developed a long-lasting social organisation based on fishing, hunting and gathering strategies as well as on the development of nautical technology (Orquera *et al*. 2011). These marine-coastal economies persisted until the arrival of Europeans in the seventeenth century and collapsed three centuries later, following the same colonisation trend as occurred in the rest of the Americas (Fig. 1).

According to archaeological and ethnohistorical information, this society developed a hunter–gatherer and fishing economy specialised in the management and exploitation

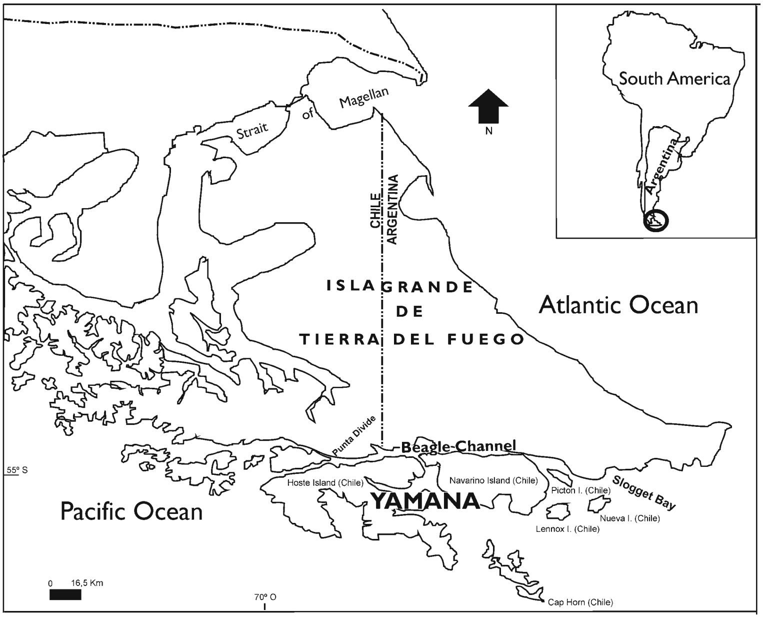

Fig. 1 Map of Tierra del Fuego

of maritime resources by hunting pinnipeds, seabirds and guanacos, gathering shellfish and fishing (Orquera and Piana 1999, 2009). In order to avoid resource depletion, a high level of mobility on small groups of canoes (or even a single canoe) was the most common behaviour. Nevertheless, cooperation seems to have been an equally important in daily practise, involving both relatives and non-relatives.

The evidence for cooperative activities is clearly documented in historical written sources and most of them are related to food procurement: hunting guanacos (Bridges, MS: 08-14-1872, 06-15-1877), hunting seabirds (Bridges, MS: 03-28-1870; Hyades

Fig. 2 Landscape of the Beagle channel

and Deniker 1891, pp. 359–360; Gusinde 1937, p. 509), fishing (Bridges MS: 11-20-1871, 01-02-1872, 07-17-1877; Gusinde 1937, p. 531), gathering mussels and mushrooms (Bridges, MS: 10-26-1870, 06-14-1872, 06-15-1877; Gusinde 1937, p. 523) and acquiring bark to make canoes (Gusinde 1937, p. 424; Hyades and Deniker 1891, p. 350) (Fig. 2).

However, historical documents provide an interesting case in which communal participation, reciprocity, social reputation and norms were enhanced and codified more explicitly. This dynamic occurred when a cetacean or massive fish was found stranded on the coast (Bridges, MS: 05-05-1872; 01-15-1872, 03-19-1872; Lothrop 1928; Gusinde 1937, pp. 355, 375 and 532–533, among others).

According to the sources, when a person discovered a whale drifted ashore, he/she lit a fire in order to notify nearby families of the finding through smoke signals (Gusinde 1937, p. 990; Martial 1888, p. 181). If the signal was seen, an aggregation event could take place, bringing together a large number of people to share in the feast; this scenario also provided the opportunity to celebrate youth initiation ceremonies and perform communal tasks (Gusinde 1937, p. 789–790). The steps to take after discovering a beached animal were precise; the person who discovered the animal was considered the one "responsible" for ensuring fair and tidy distribution. Frequently, mature and reputable men would agree with this person about who would process the whale, since not everyone had the experience and skills to accomplish the task (Gusinde 1937, p. 578). This specialist, called *wálaputës* in the Yamana language, selected the assistants to accomplish the activity (Gusinde 1937, p. 558).

It is important to remark here that a beached whale was an unpredictable event and people had not developed the technology to hunt these mammals in the open sea. However, when a wounded whale occasionally swam near the coast, the Yamana would get close enough to the prey with their canoes to kill it with harpoons and spears (Gusinde 1937, p. 460; Lothrop 1928, p. 33).

The paramount value of whales in Yamana social life is supported by different lines of evidence. First, references about beached whales are frequent and detailed in historical accounts; there were specific terms for naming the parts of a whale (Bridges 1933). Likewise, all sources agree that a beached whale was a festive social occasion and describe atmospheres of profuse happiness and enthusiasm provoked by the event (Chapman 2010; Gusinde 1937, p. 375). Second, the historical record indicates that whale blubber and mushrooms were the only edible resources that people habitually stored using preservation techniques. While mushrooms were kept dehydrated, whale blubber was preserved in peat bogs (Gusinde 1937; Orquera and Piana 1999, pp. 197–198). As a result, the accumulation of portions of whale in peat bog areas was a real option, despite the social rule of shared consumption with other members of society. Third, the importance of whales in the Yamana way of life is demonstrated in the fact that they are embedded in the mythology and narratives of this group, which had songs to bring them to the coast (Gusinde 1937; Fig. 3). Finally, social norms punished people that did not notify the community of the presence of a beached whale (Bridges 1876, p. 57, cited in Orquera and Piana 1999). A quarrel would take place if these individuals were caught and they were excluded from future episodes of food sharing. Thus, cooperation was strengthened as a social positive value even though there was a food surplus.

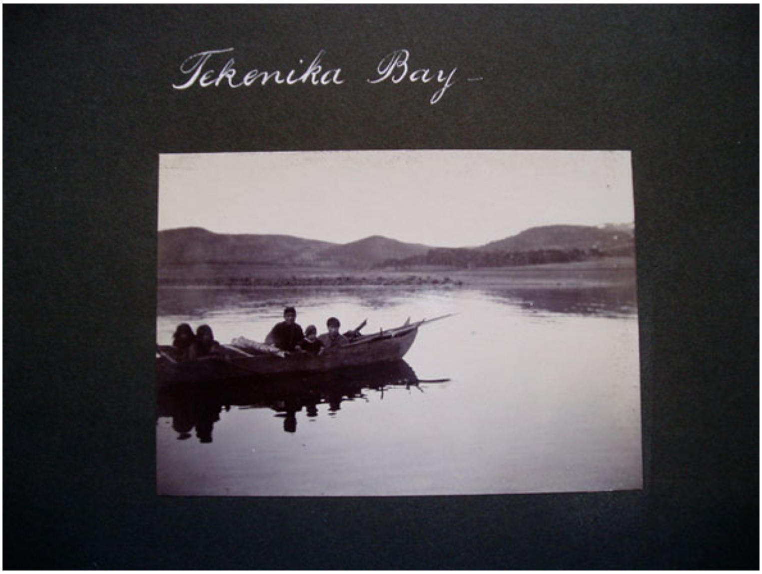

Fig. 3 Yámana canoe in the Tekenika mission (courtesy of South American Missionary Society)

This study aims to quantify the incidence and interaction of each variable involved in this specific dynamic of social cooperation in order to clarify the importance of reputation and imitation strategies for achieving a particular social behaviour.

Description of the WWHW Model: Purpose and Basic Assumptions

Wave when hale whale (WWHW) is an agent-based model developed to explore the emergence, resilience and evolution of cooperation in hunter-fisher-gatherer societies like that of the Yamana, in which individuals face the social dilemma of whether or not to call and share a highly profitable but unpredictable resource. The model abstracts the main factors that, in our opinion, might condition the evolution of cooperation as follows:

- A social mechanism of indirect reciprocity that promotes cooperation
- The stochasticity of the natural events that generate cooperation opportunities
- The characteristics of these events that determine their visibility (*i.e.* people' ease in finding them) and the chances of someone being caught if they do not cooperate (defect)
- The relative benefit of the social activities that people develop when they gather together in aggregations

Another important assumption of the model is the evolutionary mechanism in the imitation process of strategies. The complete description of the model implemented in Netlogo 5.0 (Wilensky 1999) and the source code can be downloaded at the following website: http://ingor.ubu.es/models/wwhw.

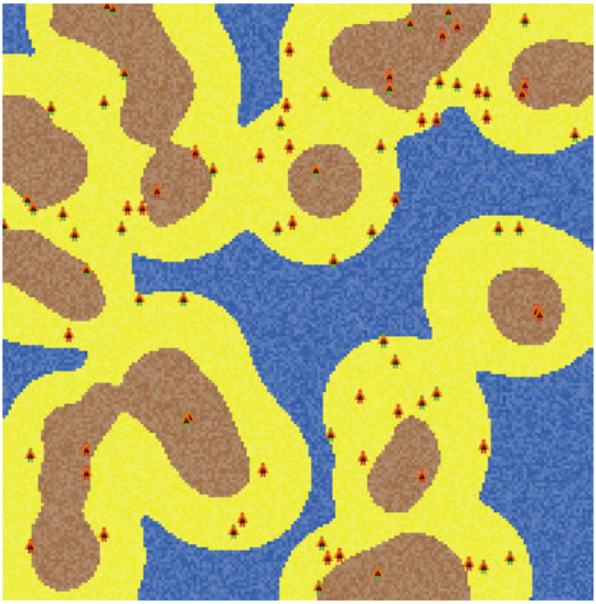

Fig. 4 Two-dimensional representation of an environment, consisting of 201×201 patches (*blue* for water patches, *yellow* for beach patches and *brown* for land patches)

Entities, State Variables and Scales

The spatial environment is represented as a two-dimensional plane regularly divided into $M \times M$ equal-size spatial units, called Patches, which represent water, beach and land spatial cells (Fig. 4). The relevant parameter of the spatial distribution of patches is the *beach-density* that determines the number of beach patches where whales can get stranded.

There are two types of agents: people and whales. People agents represent households/canoes; they move looking for beached whales and make decisions about whether or not to call other people when a beached whale is found. The number of people remains constant over the course of a simulation run. On the other hand, whales are non-mobile agents and represent a scarce but important source of meat that appears from time to time on one of the beach patches, providing perishable food.

The WWHW model is characterised by a set of variables of different nature; the study parameters (Table 1) are the exogenous variables established by the user that define a computational experiment under analysis (a given scenario) and remain constant in each run; the entities' variables define the state of each individual entity (agent), namely people (Table 2) and whales (Table 3) at each period of time; and a set of global variables that determine some accessory features of the entities and the model.

Process Overview and Scheduling

The scheduling of the set of events that take place in discrete time-steps (or "ticks") is represented in Fig. 5.

Table 1 Study parameters

Parameter name	Brief description
Prob-beached-whale	Probability that a whale beaches at each time period. Whales appear at one of the beach patches (the beached whale process is fully described in the process section).
Social-capital-vs-meat-sensitivity	Parameter in the range (0, 1) that modulates the relative importance of the *social-capital versus meat* in the fitness function—the higher value, the more relative weight of *social-capital*.
Vision	Maximum distance (measured in number of patches) within which people can see beached whales.
Signal-range	Maximum distance (measured in number of patches) of the signal (*e.g.* smoke) created by cooperative people at the location of a beached whale to help others to find the resource.
Distance-walked-per-tick	Number of patches that a people agent can move at each time period.
Prob-mutation	Probability of an error or an exploratory strategy in the imitation process of people's strategies.
Rounds-per-generation	People can imitate other strategies (selection process) every *rounds-per-generation* periods of time.
Beach-density	Fraction of beach patches. The rest of patches, corresponding to the (1-*beach-density*) of the total of patches, are equally divided into land and water patches.
People-density	Density of people in the 2-D space (measured as the total number of people divided by the total number of patches).

According to the probability expressed by *prob-beached-whale*, a whale appears at a randomly chosen beach patch (*beach-a-whale* procedure). A beached whale is detected (*be-seen* procedure) by any people agent without target and at a distance of *my-range*, or closer, from the whale. When a people agent detects a whale, she moves

Table 2 People's state variables

Variable name	Brief description
Prob-cooperation	Probability of a people agent cooperates. We suppose there are only two strategies of cooperation: always cooperate (*prob-cooperation*=1) and always defect (*prob-cooperation*=0).
Last-public-prob-cooperation	The last public *prob-cooperation*. Whenever a people agent makes a public call and someone comes, or defects and someone observes her defection, this variable is updated with the current *prob-cooperation*.
Meat	Stock of whale meat held by a people agent.
Social-capital	Stock of social capital acquired by a People agent.
Fitness	Value of a people agent's success, determined by the variables *meat* and *social-capital*, used in the imitation process.
Reputation	Variable in the range (0, 1) that represents the reputation of a people agent.
{n-calls-history, n-been-caught-history }	Vectors that contain respectively the times a people agent called others and an aggregation happened, and the times she defected and was caught by someone, in the *last history-size* of generations.

Table 3 Whales' state variables

Variable name	Brief description
My-range	Radius (measured in number of patches) within which the whale is visible by people. This range is equal to the vision of the people if the whale has not been made public (*i.e.* if no agent has made a signal for this whale), or the signal-range, if a people agent has already made the whale public (by creating a signal).
Caller	If the whale is public, this variable stores the people agent who made it public by creating the signal; otherwise the variable has a "nobody" value.
Public?	Boolean variable which is "true" when the whale is public (*i.e.* a people agent created a signal indicating the location of the whale), and "false" otherwise.
Life	The number of time periods that a whale will stay in the environment before disappearing. It is decreased in one unit after each period.

(*walk* procedure) towards it until she arrives at the same Patch; if not, the agent moves randomly. In all cases, the distance travelled corresponds to the parameter *distance-walked-per-tick*.

When a people agent reaches a whale and nobody has publicly announced its presence yet (the state of the whale is private) she makes a decision—specifically, she creates a signal with probability *prob-cooperation* changing the state of the whale to public (*call-others* procedure). The limit distance *my-range* depends on the state of the whale (*i.e.* is it *public* or not?). If the whale is not public, the variable *my-range* is equal to the parameter *vision*, which represents the natural distance at which a people agent can see the food source. However, if the whale is public (*i.e.* a people agent has already called everybody else by creating a public signal), *my-range* gets the value of the parameter *signal-range*.

The reputation of a people agent depends on her public history of past actions, stored in two vectors as follows: *n-calls-history* and *n-been-caught-history*. If a people agent decides to call everyone else and there is a witness to her action, she adds a unit in the current generation period of the vector *n-calls-history* (*be-rewarded* procedure). On the other hand, if the agent decides not to call others and there are witnesses to that defection, she adds a unit in the current generation period of the other vector, *n-been-caught-history*.

Afterwards, each people agent updates her reputation (procedure *update-reputation*). The reputation *Ri* of the people agent *i* is computed as the division between two moving averages according to the following equation:

$$R_i = \frac{\sum_{j=1}^{h} \left(\#Cooperate_j\right)\delta^j}{\sum_{j=1}^{h} \left(\#Cooperate_j \cup \#BeSeenDefecting_j\right)\delta^j} \in [0,1] \tag{1}$$

The term $\delta \in [0,1]$ corresponds to the discount factor parameter *history-past-discount*. This parameter takes into account how important the *shadow* of the past is in terms of reputation. Values close to one mean that events in the past and the present are equally important for the population, yet values close to zero give much more weight to recent events than decisions taken in the past. The term $\#Cooperate_j$ corresponds to the j element of the vector *n-calls-history*, and the term $\#BeSeenDefecting_j$ correlates to the j

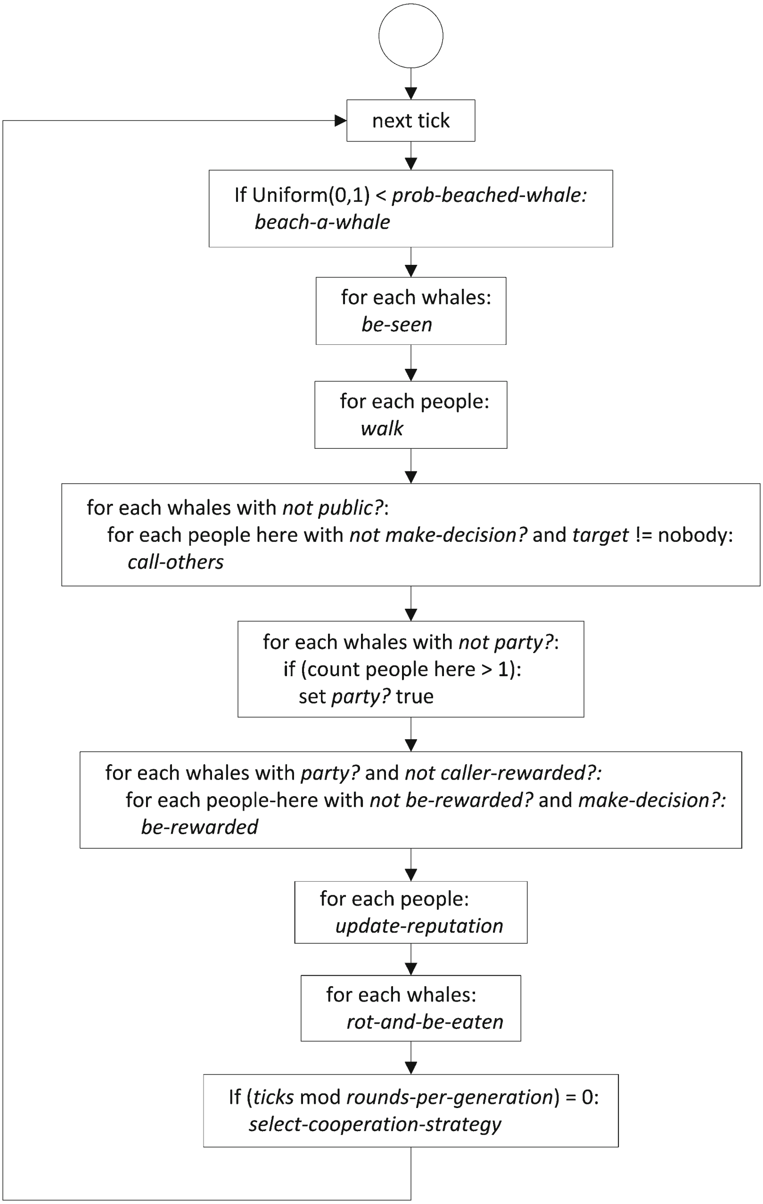

Fig. 5 Flow diagram of the schedule of execution. The order in which agents are chosen in "for each" statements is always random to avoid bias in agent selection

element of the vector *n-been-caught-history*. Both vectors always collect the last *history-size* (*h* index) registers of the agent's generations.

Note that the reputation of a people agent may only change when she takes an action (cooperate or defect) that is observed by someone else. If she defects but is not caught, her reputation does not change. Similarly, if she cooperates but nobody answers the call, her reputation does not change either. This feature matches the hypothesis that reputation is a kind of social tag that someone always receives from others and cannot be changed by her owner.

Afterwards (*rot-and-be-eaten* procedure), people exploit the whale, storing *meat*, and participate in social activities, storing *social-capital*. We simplify the process of storing *meat* and *social-capital* assuming that (1) the number of ticks that a whale stays in the model is fixed, and (2) the gain per tick of these stock variables (marginal gain) for any people agent depends only on the number of people sharing the whale at each moment and her reputation. Following these assumptions, the marginal *meat* per tick $\Delta M_i(t)$ that a people agent i get in an aggregation of size N (she consequently has to share the meat with N-1 individuals) is formalised by a bell-shaped function as follows:

$$\Delta M_i(t) = e^{-\alpha((N(t)-1)-\mu)^2} \textit{with } \Delta M_i(t) \geq 0 \tag{2}$$

The terms α and μ regulate the width and the peak location of the function. Depending on the value of μ, the function shows increasing and decreasing returns in different ranges of N. Although it is possible that the real exploitation of a whale by households initially showed increasing returns with the size of the aggregation, we set μ=0, focusing our analysis on the range of decreasing returns that depicts a more critical scenario for the evolution of cooperation.

On the other hand, the marginal *social-capital* per tick $\Delta SC_i(t)$ that a people agent i obtains in an aggregation of size N is computed by the following function:

$$\Delta SC_i(t) = R_i\left(1 - e^{-\alpha(N(t)-1)^2}\right) \textit{with } \Delta SC_i(t) \geq 0 \tag{3}$$

In this case, the function monotonically increases with the size of the aggregation N and has a higher asymptote at the reputation of the agent Ri. We suppose that a people agent's reputation conditions her capacity to gain social capital from others (*i.e.* if someone has a bad reputation, it is more likely that nobody wants to join her in social activities). All these assumptions fit with the hypothesis that social capital always grows with the number of people participating in social activities, although as this number increases, the marginal contributions of new participants decrease because they are probably redundant, limiting the gain of *social-capital*.

The fitness function quantifies the success of a people agent and takes the last two stock variables into account as follows:

$$\begin{gathered} F_i(t) = \theta SC_i(t) + (1-\theta)M_i(t) \textit{with } \theta \in [0,1] \\ \textit{where} \\ SC_i(t) = SC_i(t-1) + \Delta SC_i(t) \\ M_i(t) = M_i(t-1) + \Delta M_i(t) \end{gathered} \tag{4}$$

The term θ regulates the relative importance of each factor and corresponds to the model parameter *social-capital-versus-meat-sensitivity*; the higher the value of θ, the more important the *social-capital*.

Finally, when a period of *rounds-per-generation* ticks is reached, a process of imitation occurs (*select-cooperation-strategy* procedure). The selection process is implemented as a random tournament; each agent randomly chooses another from the population with probability directly proportionate to fitness; if the picker has less fitness, she copies the strategy of her choice or explores a new randomly-chosen strategy between the strategy space with probability *prob-mutation*. It is important to note that the value copied in the variable *prob-cooperation* is the variable *last-public-prob-cooperation*. The hypothesis is that a people agent only can imitate observable values, meaning that the strategy of a people agent is observable whenever there is a witness to her behaviour, cooperation or defection. After the imitation process, people agents initialise their *meat*, *social-capital* and *fitness* variables to zero, but do not change their reputation and their vectors of past history.

Analysis and Results: Experiment Design

The WWHW model has been designed as a "tool to think with". It is not meant to provide precise quantitative predictions, but to assist researchers in understanding the mechanisms and conditions in which people might cooperate and call each other when they find a beached whale. The inferences we want to get are of the kind "the *vision* does or does not favour cooperation in society" or "the frequency of beached whales does or does not favour cooperation in society". In order to obtain this, our analysis is focused on the asymptotic behaviour (the long run) of the system. In this model, when people can explore (random mutation) rather than imitating strategies, the system becomes ergodic and consequently the asymptotic behaviour is independent of the initial conditions (Izquierdo *et al.* 2009). We let each simulation run for a long enough time to guarantee that the effects of the initial conditions have disappeared, and we

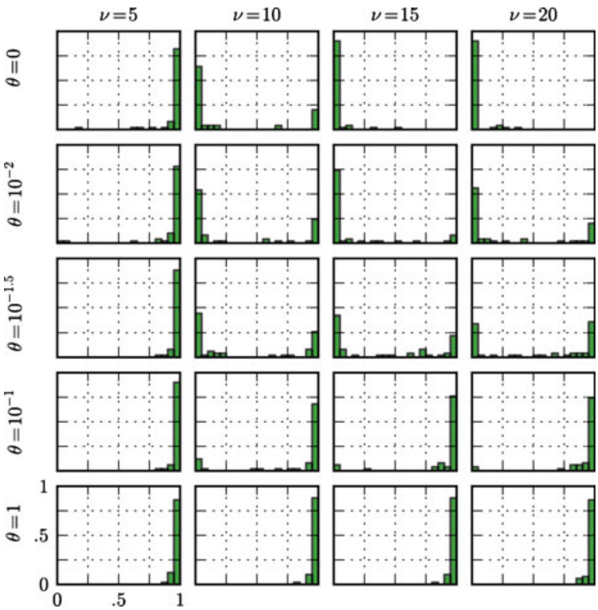

Fig. 6 Array of histograms of the stationary cooperation for a combination of the parameters *social-capital-versus-meat-sensitivity* θ and *vision* (υ), when the probability P_{bw} is 0.05. Results show that the stationary behaviour of the model concentrates in the region of all cooperation (percentage of cooperators close to one) or the region of all defection (percentage of cooperators close to zero). Simulations in between these extreme cases are unlikely

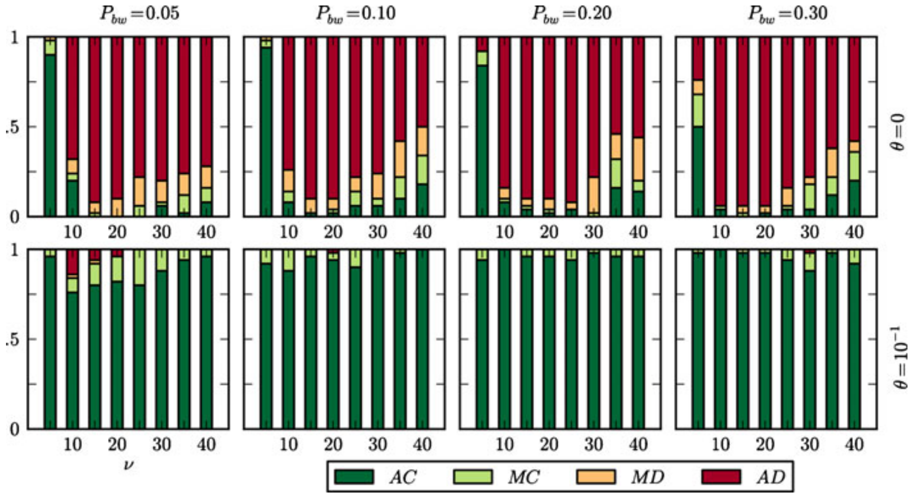

Fig. 7 Above, the *bar* plots of the frequencies of the stationary regimes for the case without indirect reciprocity θ=0, when the parameter *vision* varies and the P_{bw} is fixed. Below, the same plots for the case with indirect reciprocity (θ=0.1)

replicate several random and independent samples for each parameterisation to get statistics accurately enough[1]. The state of the system is represented by the average cooperation of the population (denoted by the term cooperation *C* hereinafter), and it is computed and recorded for each tick.

Stationary Regimes

Figure 6 shows the histograms of the stationary regimes for different combinations of the parameters *social-capital-versus-meat-sensitivity* (θ) and *vision* (υ), when the *prob-beached-whale* (P_{bw}) is 0.05 (similar results are obtained for other probabilities). An initial inference from these results allows us to make a simple characterisation of the stationary behaviour. The system mostly reaches one of the two stationary regimes that we have defined as "All Cooperation" (AC), whenever $C \geq 0.9$, and "All Defection" (AD), whenever $C \leq 0.1$. The rest of the regimes are almost negligible, and they are gathered in the "Majority Cooperation" regime, whenever $0.5 \leq C < 0.9$, and "Majority Defection" (DF) regime, whenever $0.1 < C < 0.5$.

Interpreting these computational results is rather intuitive. When θ=0, that is, there is no indirect reciprocity in the society and agents' fitness is driven only by the consumption of *meat*, the AD regime is reached in almost all cases, with the exception of low values of vision (υ), which we will explain afterwards. However, when the value of *social-capital* grows (in terms of fitness) and the social reputation mechanism has

[1] The initial state for all simulations corresponds to a population of 50 cooperators and 50 defectors randomly distributed in the space. The core parameters {*vision*, *social-capital-versus-meat-sensitivity*, *prob-beached-whale*} are explored by setting the rest of the parameterisation: {*people-density*=0.002 (82 *agents*); *beach-density*=0.5; *prob-random-move*=1; *distance-walked-per-tick*=4; *signal-range*=50; *rounds-per-generation*=50; *prob-mutation*=0.025; *history-size*=10; *history-past-discount*=0.8; *tournament-size*=5}. The time limit for a simulation is 10^5 ticks and 50 replications have been run for each experiment.

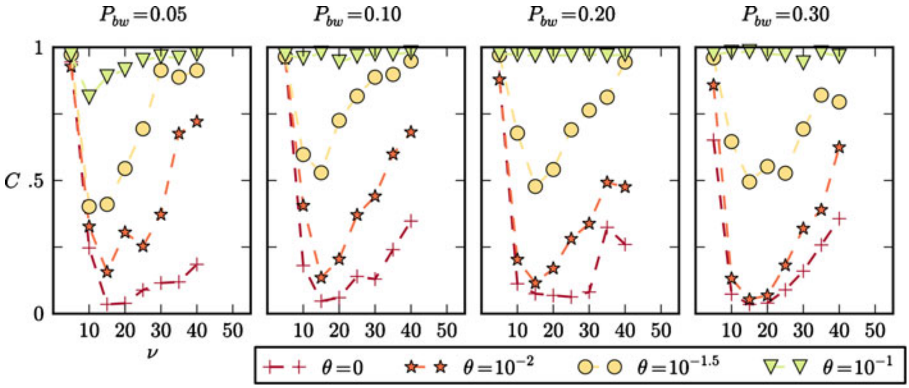

Fig. 8 Each graph shows the average cooperation at the end of simulations for different values of θ when the parameter vision varies, and the probability P_{bw} is fixed to a particular value

effects on the imitation process as a result, the AC regime becomes the most important, even for very low values of θ.

For the sake of clarity, the results are shown in a different way in Fig. 7. Here, the frequencies of the stationary regimes in two different cases, with and without indirect reciprocity, are shown for several probabilities of beached whale.

The Effect of Vision

In order to understand the effect of *vision*, in Fig. 8, we show the average degree of cooperation when the probability of beached whale remains constant and *vision* and θ vary. In the range of θ, in which both AC and AD regimes are possible, we see that *vision* pushes the levels of cooperation up for all frequencies of beached whale (*i.e.* the higher the values of *vision*, the higher the values of cooperation). The explanation is quite intuitive too, since vision increases the visibility of scarce resources as well as the chance of detecting defectors. When there is no indirect reciprocity (θ=0), the first feature reduces the difference in terms of the fitness of cooperators and defectors because the probability of finding meat grows for everybody regardless of their strategy. When the indirect reciprocity mechanism works (θ>0), the second feature clearly reduces the advantage of any selfish behaviour because defectors tend to have low reputations.

There is a particular and interesting result when vision is significantly low (υ=5). In this case, the system always reaches cooperation, even for θ=0 when defection should be the expected outcome. To explain this counter-intuitive result, we must refer to one of the assumptions of the model: the imitation of public strategies. The hypothesis of the model is that a people agent only can imitate observable values. Under this assumption, an individual's strategy only becomes public when she makes a public call and someone comes, or when she defects and someone observes her defection. When vision is low, a defection is rarely detected, so when someone imitates a defector, she is really imitating the last public behaviour of the defector, which probably corresponds to a past cooperative strategy since cooperation involves making the strategy public. Therefore, the imitation mechanism positively reinforces cooperative behaviour, and this effect dominates the system behaviour for low values of *vision*.

Conclusions

It is well known that humans have a universal tendency to cooperate. As such, the purpose of this research goes far beyond this notion. We aim to understand the conditions and mechanisms through which cooperation occurs in order to analyse how social ties (which are part of human nature) work.

Though Yamana society is just one example, this case study provides the opportunity to analyse cooperation in terms of a very specific and time-constrained dilemma. In this particular case, we already know on the basis of ethnographical sources that people promote cooperative attitudes and penalise those that do not cooperate. Social norms act as a way to regulate individual behaviour (in this case of the agents, which are understood as a social unit or household/canoe) in relation to what we can consider a promoted social standard.

This paper shows the state-of-the-art of the case study and first results obtained through the experimentation process. The model shows that polarised behaviours are stable. The system reaches a regime where a cooperative norm is established or a regime where selfish defection is generalised; intermediate results are very unlikely. Our analysis shows that two key parameters influence the chances that the population coordinates in one state or another. If the resource is the element that completely determines the population's fitness for survival, general defection is the most probable outcome. However, if social life regulated by reputation becomes important in the society, even for low values, then the benefits of aggregation are salient. Thus, a strategy that capitalises on social reputation proves to be more successful and the cooperative norm is promoted as a result. The other relevant cause is the effect of vision—how easy it is to find the resource and hence to detect a possible defector. In general, when social capital matters, vision enhances cooperative behaviour. These computational results formally support the hypothesis of the influence of variables that appear to be of paramount importance, such as the role of reputation and imitating strategies in promoting or hindering cooperation, the fact that individual behaviour becomes social when decisions (to cooperate or defect) are made public and opportunities for cheating and social punishment, among others.

Likewise, these results show that a stranded whale not only afforded food and raw materials but also provided the conditions to enhance social capital in Yamana society and to reinforce a network of relationships crucial for social reproduction (such as providing a scenario for holding youth initiation ceremonies). In other words, the exceptional accumulation of food mainly offered the possibility to perform practises and to materialise norms that created and recreated the *habitus* (Bourdieu 1977) of social life. Consequently, the value of the whale cannot be reduced either to its nutritional content or to its ability to bring together otherwise disperse people, as it produces a context for displaying social prestige and for a public demonstration of generosity (which could be used to obtain mates, to reinforce social networks to cope with stress conditions, *etc*.). This situation could explain the apparent low incidence of storage of whale blubber at the individual/household level.

It is worth mentioning here that evidence attained from this case study provides experimental and empirical support for signalling theory (Bliege Bird and Smith 2005) to the extent that it highlights the paramount importance of symbolic capital for obtaining benefits with material consequences. At the same time and in relation to hunter–gatherer research, these results show the value of reputation in a society with relative low levels of social heterogeneity or inequality among households.

The combination of ABM models and ethnographical sources in an ethnoarchaeological approach offers a heuristic and valuable tool for exposing the mechanisms embedded in cooperation practises; it has proven to be useful for formulating new hypotheses and for noting the strength of social ties and the effort invested in maintaining them. As a particular type of social behaviour, cooperation may occur in contexts where other social dimensions are enhanced; in our case study, ceremonies and many other activities were carried out during aggregation events in which cooperation was an essential factor.

This research is part of a broad project to explore cooperation in hunter–gatherer societies and to develop archaeological methods and theory in hunter–gatherer inquiry, such as identifying the materiality of cooperation in the context of aggregation events (Briz *et al*. 2009; Zurro *et al*. 2010). To accomplish this general goal, the dynamic of cooperative behaviours must be disentangled. Thus, future work will entail building a solid corpus of hypotheses based on historical reports and simulation results in order to elucidate what kind of archaeological variability is considered relevant in social aggregation/cooperation episodes. In our view, accurate identification of the variables implied in these social phenomena will lead to the recognition of unambiguous anthropic markers of social cooperation that may be extended to different case studies.

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