PaleoCOOP model

Authors: María Coto-Sarmiento, Abay Namen, Aris Varis, Radu Iovita

Model designed by: María Coto-Sarmiento

Protocol for the paper:

Coto-Sarmiento, M.; Namen, A.; Varis, A. and Iovita, R. (submitted 2023): The impact of cooperation under climate constraints: an Agent-Based Model for exploring Paleolithic behavioral adaptations in the Inner Asian Mountain Corridor.

Preprint:

Introduction and open data

PaleoCOOP Model was written on NetLogo software 6.2.2 [1] and the code, data and sources are available at Github archive is openly available here https://github.com/Mcotsar/PaleoCOOP.

As part of open science and transparency policies in archaeology, the agent-based model was performed according to practices following the ODD document protocol [2][3][4]. Supplementary information on the model can be also found here https://osf.io/jm3zy/.

Overview

Purpose and Patterns

PaleoCOOP is an Agent-Based Model that simulates human interactions with an evolutionary framework. This model primarily focuses on exploring the impact of behavioral adaptation on the survival of groups of individuals in extreme climate environments.

PaleoCOOP provides insights into cooperative behavior, resource competition, and the ability to thrive in challenging climatic conditions by analyzing the interplay between human decision-making and behavioral adaptation in extreme conditions:

a) human cooperation: the model tests the influence of extreme environments on human cooperation;
b) the mechanism for adaptation to understand how individuals learn from one another and adapt their behaviors to promote group survival;
c) competition for better resources: competition for access to better resources can shape individual behavior. This study allows us to interpret the relationship between resource availability, cooperation, and group competitiveness;
d) survival in extreme climate environments: the model explores how groups of individuals adapt and survive under different climatic conditions.

PaleoCOOP explores four different theoretical climate scenarios, each representing a climate environmental condition. These scenarios serve as theoretical settings to analyze and compare the adaptive strategies for human cooperation. By examining the effects of climate variation on cooperative behavior, the model enables a comprehensive exploration of the different factors that contribute to individuals adopting cooperation or defect in different climatic contexts.

Entities, state variables and scales

Environment

The model uses a GIS package on NetLogo and it requires an ASCII elevation raster map. The maps also use shapefiles with original sites and lakes and rivers. The map of the environment is represented by a grid of patches (534 x 328, see article for a better description). Water and mountains are represented with shapefile and ASCII elevator raster shapefile, respectively.

We created two environments for the model: Altai and Tian Shan, divided in patches into two geographical spaces, Altai and Tian Shan within the territory of modern-day Kazakhstan. Each patch on the map represents 1 km² of the geographical area.

Patches are characterized by three key elements: water, mountains, and unspecified resources. Water bodies, including lakes and rivers, represent the existence of water in the environment. Despite the inclusion of water as a component within the model, its substantive role or impact has not been explicitly incorporated or accounted for in fulfilling the objectives of the model. Mountains are defined by their elevation as indicated on the map.

Resources play an important role in the model. The aim here is to establish a theoretical scenario where certain patches have more abundant resources compared to others. This definition of attractiveness is given by the patches with higher resource availability, strategically located in random areas where archaeological places were found. This approach creates a geographical distribution environment similar to a potential real environment.

The factors of the environment are represented in **Table 1**.

Name	Overview description
basemap-dataset	Map used with QGIS extension NetLogo
attractors-dataset	shapefile that includes archaeological data
river-dataset	shapefile that includes rivers
lakes-dataset	shapefile that includes lakes
display-map	Display in the model rivers and lakes
display-attractors	Button. Display the archaeological places located in Tian Shan and Altai
clean-maps	Button. Clean all and reset the shapefiles
elevation	Convert the elevation of a DEM.asc map to the model
min-elevation	Minimum elevation of the DEM (m)
max-elevation	Maximum elevation of the DEM (m)
patches-region-tienshan	Patches are divided into two regions: Altai and Tian Shan. This corresponds to patches of the region Tian Shan
patches-region-altai	Patches are divided into two regions: Altai and Tian Shan. This corresponds to patches of the region Altai
climate-temperature	Patches are divided into two environments that include different climate temperatures in Tian Shan and Altai. The temperature also depends on the scenarios selected
resources	Resources on the patches. Consumption of resources will depend on the different scenarios. Default level: 50 (random area), 100 (attractive area)
noresources?	Boolean. True: resources are less than 20 % on the patch, and False: there are enough resources on the patch
resource-decrease-rate	Resources are decreasing in every time step. Default level: 0.1

`resource-recovery-rate`	Resources start to recover after they run out in every time step. Default level: 1
`attractors?`	Boolean. True: identify patches with potential attractor places, False: otherwise
`origin-tienshan?`	Boolean. True: patches from Tian Shan, false: patches from Altai
`origin-altai?`	Boolean. True: patches from Tian Shan, false: patches from Altai.
`scenario`	Chooser. Selection of scenarios.

Table 1. Environment Factors. Includes also buttons.

Process Overview and Scheduling

We simulate four theoretical scenarios, with each time step representing one year (one tick = one year). The simulation spans 1200 time steps (months), the equivalent of 150 years. The initialization and the end of the simulation may differ based on the specific experiment being conducted.

The model develops stages during the simulation: learn, interact (cooperate or defect) and consume, and finally, move to another place. The stages of the model execution in time steps can be seen in **Fig. 1**.

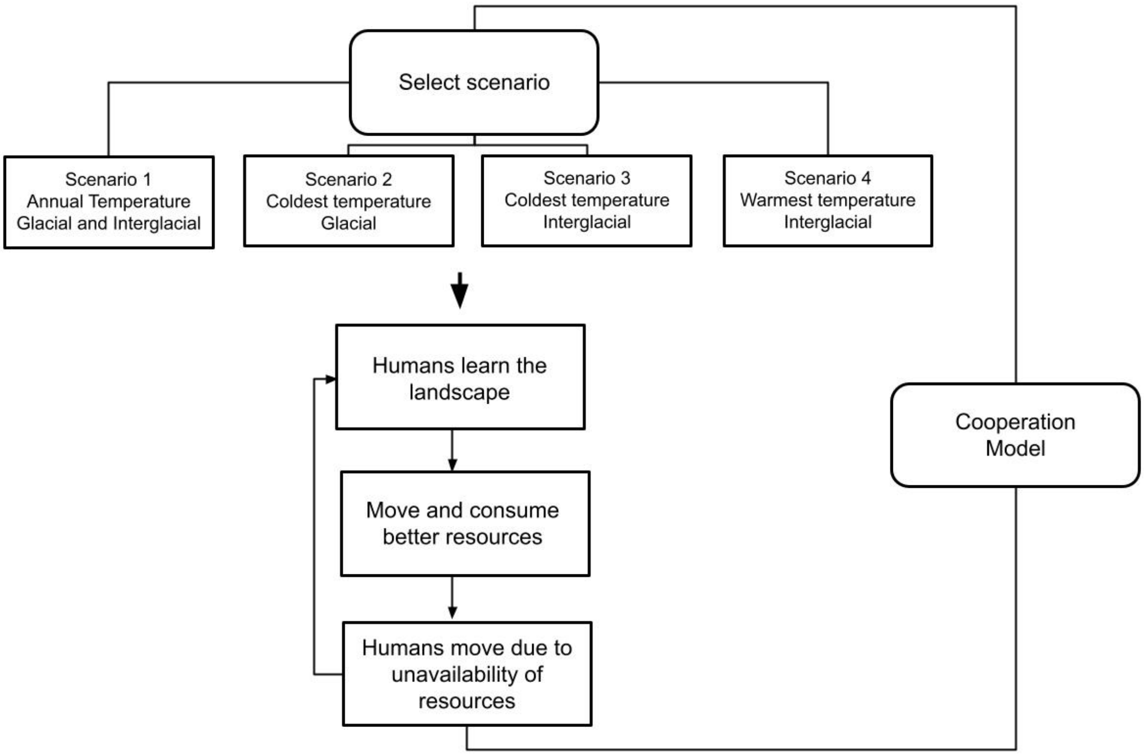

Fig 1. Diagram with the stages for the model.

The model incorporates three different entities (agents): groups of humans from Tian Shan and Altai and attractors places. The two groups of humans are initially located in different random locations within Tian Shan and Altai. The specific characteristics of humans from each area are outlined in **Table 2.** To ensure a more homogeneous model design, both groups of humans possess identical features at the beginning of the simulation.

The parameters for the agents (human agents and attractor places) are described in **Table 2**.

* **Note:** hominins and heminins have the same features in the model. Hominins correspond to human agents from Tian Shan and heminins represent human agents from Altai.

Name	Overview description
`places`	attractor place agents where humans go for resources and protection from cold temperatures. They have different colors: red from Tian Shan and blue from Altai.
`attractor-resources`	Extra resources from attractor places. Default level: 100
`hominins`	Human agents from Tian Shan.
`heminins`	Human agents from Altai.
`Nhominins`	Define the number of individuals (from Tian Shan and Altai) in the simulation.
`color`	Colors of the humans to distinguish their behavior on the model. Greens are cooperators and Reds are defectors in the model. Blacks are humans under 12 years old they have not decided yet.
`age`	age of the humans. Default level: 0-50
`maximum-age`	maximum age of humans. Average 50 years old.
`minimum-reproduction-age`	the minimum reproduction age of humans. The reproduction rate is 12 years old.
`learning-rate`	Defines the probability of learning the path to arrive someplace. It will depend on the specifics of the difficulty defined by the climate. Default level: 1 (20 % less in extreme scenarios)
`traits`	Define how hominins transmit and spread traits to others. Hominins get one trait when they are 12 years old. Default level: 1 is cooperation and 0 is not cooperation.
`energy`	Energy of humans. 0 = no energy 100 = entire energy.

`max-energy`	Maximum energy that humans start the simulation.
`risk`	Risk of humans.
`human-risk`	Risk that human agents perceive. Risk is related to difficult situations in order to survive
`body-temperature`	Body temperature of human agents
`initial-body-temperature`	Initial body temperature of human agents. The initial body temperature is 37
`hominin-speed`	Speed of the human agents on the landscape. Default level: 0.75
`movements`	Chooser. Movements of the human agents: random walk and lévy walk. Default level: random walk. Lévy walk was not tested in the model.
`levy-alpha`	For Levy walk. Based on the paper [5]
`levy-min-step`	For Levy walk. Based on the paper [5]

Table 2. Agent factors (Human agents and attractor place agents)

The population size for each group is determined by the experiment that can be adjusted using the `nHumans` slider. Both Altai and Tian Shan have an equal number of humans at the beginning of the simulation. It is assumed that individuals from both areas share identical features to maintain consistency and standardization in the model.

We incorporate "attractors" places, which represent sites with greater resource availability. These attractors are randomly placed within the geographical environment where the high availability of resources is. The attractor's places are independent of patches with more resources and they possess their own set of resources. For the model, three static attractors are initially created for each area of Altai and Tian Shan. The number of "attractor" places can change over time in the simulation, either increasing when new places are founded or decreasing when all the resources in a place are spent.

To reproduce a more realistic model, individuals are randomly assigned varying ages, with an average mortality rate set at approximately 50 years [6]. The reproductive capability is enabled for individuals over the age of 12, with a 10% chance of reproduction rate. Across the different scenarios, the reproduction rate and average age remain consistent, ensuring uniformity in the model's parameters. By incorporating these age-related factors and reproductive considerations, the model captures essential aspects of human life cycles and population dynamics, contributing to a more accurate representation of ancient societies' behaviors and adaptations.

At the beginning of the simulation, humans can move through the landscape while simultaneously acquiring the knowledge required to identify areas with better resources. We use the `human-learning` factor to incorporate some complexity into how people can learn the proper path to arrive at the attractor locations. An additional level of difficulty of 20 % is added for more extreme scenarios (Scenarios 2 and 3). Once individuals learn the optimal path to reach a place, they move toward areas with better resources. We assume that better resources are concentrated in specific areas although they may still consume resources all over the land.

The consumption of resources varies in individuals depending on three factors: a) the social strategy that individuals choose b) the specific scenarios and c) the region. In the model, the selection of a cooperation strategy may always imply that individuals consume fewer resources than defectors, as well as in more extreme scenarios where resources are sparse. In addition, resource consumption can be affected by the regions where individuals are located, whereas in Altai the resources can be more limited. While cooperative behavior prioritizes group welfare and resource sharing, defective behavior prioritizes their own self-interest without considering the well-being of others [7]. The probability of cooperation of the population can be previously selected in the model: a percentage of 0 means no probability of cooperation, while 100% is a full probability of cooperators within the population. The role of cooperation for each individual can change based on the cooperation model during the simulation (see cooperation model).

All individuals begin with a maximum energy level of 100 %. The energy level can be adjusted using the `max-energy` slider, which describes the percentage of the energy of humans. The energy is spent differently and It will vary depending on the location and the scenarios. For example, we assume that individuals are constantly spending energy at each timestep, although the amount of energy spent varies given the perception of the risk and the climate conditions. While energy consumption can be slowed down, it cannot be restored unless they are near attractor places where humans can recover energy by consuming additional resources.

In addition, individuals may also consume extra energy obtained from attractor places. These places not only provide energy but also serve as shelter from extreme cold conditions for the population. In other words, the attractor places contribute to decreasing the body temperature and increasing the energy of humans. However, groups of only cooperative individuals under favorable conditions of resources are allowed to create new attractor places. It is assumed that individual defectors are unable to cooperate to help other individuals fund new sites unless a limited number of cooperators are present. In addition, attractors can be funded under two conditions: a) attractors must be at least in a radius of 5 km away from existing attractor locations and b) more than 50 % of available resources. If both conditions are not met, then attractors cannot be funded.

Nevertheless, defectors can still consume energy from existing attractor locations. However, excessive resource consumption by humans can lead to the attractor disappearing due to resource depletion and cannot be replaced.

Energy in individuals is intrinsically linked to extreme scenarios and the perceived risk by individuals in their environment. In extreme scenarios, individuals need to spend more energy compared to scenarios with a less extreme climate.

The rate of energy is also influenced by the level of perceived risk and the distance of the attractor places. In the model, in areas with more resources or attractor places, individuals assume a lower risk due to a better strategy of distribution of resources among the population. When individuals do not perceive a significant risk, the energy decreases at a much slower rate. Conversely, when individuals are located in a place with limited resources, the perceived human risk tends to increase. The energy decreases at a faster rate compared to situations with a lower perceived risk. When this perception of the risk exceeds 80%, the energy decreases even further. It is significant to notice that Individuals can perish if they deplete all their energy and the energy level drops to 0. Thus, individuals located in attractor places are expected to expend less energy compared to those in non-attractor places, as we assume that attractor locations provide a sense of safety and security. This difference in energy expenditure between attractor and non-attractor places is a crucial aspect of the model, as it reflects the adaptive behaviors of individuals seeking out favorable environments for resource acquisition and protection (See **Table 3** for further information).

Tian Shan					
Factors		**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
`energy`	safe place	0.01	0.02	0.02	0.01
	no safe place	0.1	0.2	0.2	0.11
`risk` (increase or decrease)	safe place	- 0.1	- 0.2	- 0.2	- 0.1
	no safe place	+ 0.1	+ 0.4	+ 0.4	+ 0.1
Altai					
`energy`	safe place	0.015	0.025	0.025	0.01
	no safe place	0.15	0.3	0.3	0.11
`risk` (increase or decrease)	safe place	- 0.15	- 0.3	- 0.3	- 0.1
	no safe place	+ 0.15	+ 0.5	+ 0.5	+ 0.1

Table 3. The distribution of energy spent per time step and risk varies across scenarios in different areas. The location of human agents is crucial in determining the energy expenditure and level of risk, depending on whether the area is safe or unsafe.

The model includes the analysis of mobility strategy patterns and resource availability [5] [8]. We previously defined a place of origin where hominins initially arrive and a second place where humans migrate. Humans have the ability to migrate from their place of origin to other locations over long distances if resources are scarce, with the aim of finding new available resources. Migration occurs when individuals in patches with no resources fail to find available resources within a period of time, forcing them to seek new resources by moving to other areas with more available resources. Moreover, humans leave their place of origin and move to other areas when the resources of the patches are below 20 %. This threshold indicates that resources are scarce, prompting individuals to conserve their remaining resources. Thus, some individuals are compelled to migrate to alternative areas with better resource availability, leaving their previous place behind.

Upon migrating to a new location, the first stage of the model starts again in the new place, continuing until resources become again limited within that area. At such a point, individuals are once again compelled to move, either back to their original place of origin or to alternative locations in proximity.

Here, the dynamics of the model are designed to explore the effect of dispersal dynamics on the population, specifically examining the role of a) resource scarcity, b) cooperation behavior, and c) climate scenarios. It is worth mentioning that this dynamic illustrates a significant mobility pattern observed in humans when searching and competing for resources distributed in specific locations.

Design Concepts

Basic principles

PaleoCOOP uses an evolutionary agent-based model to test four theoretical climate scenarios under cooperation dilemmas. The model addressed significant questions, such as how humans survive under harsh conditions, the role of social strategies under different climate temperatures, and whether these strategies enhance human adaptability in extreme conditions.

The fundamental principles for the PaleoCOOP model are a) climate change can influence human cooperation, b) population size can be influenced by the pressure of the group to deal with cooperation dilemmas and c) the selection of one strategy (cooperation or defectors) is contingent upon the percentage of cooperation observed in the model.

We provided insight into our model by testing four different theoretical climate scenarios in order to analyze how the survival of humans can be influenced by the selection of a specific strategy.

Adaptation

The model indirectly reflects adaptation by simulating diverse climate scenarios, requiring human agents to adjust and acclimatize to their respective climate environments (for more information, refer to the “Learning and Cooperation” subsection).

Objectives

This model simulates groups of individuals aiming to enhance their behavior by learning and adapting to their environment. Their goal is to discover superior resources while engaging in competitive interactions. Additionally, they endeavor to optimize foraging by identifying attractive resting spots to replenish energy and regulate body temperature

Learning and Cooperation

The PaleoCOOP model includes learning by allowing agents to acquire knowledge about the path to find optimal resource acquisition. The decision rules in the model can evolve over time during the simulation, particularly within the cooperation model.

At the beginning of the simulation, humans engage in a learning process and individuals must learn how to identify attractors and find them, which correspond to locations abundant in resources. However, the learning process varies across scenarios, with higher complexity observed in extreme environments.

The cooperation strategy plays a significant importance in this model as humans have the ability to select a social strategy between cooperation and defection over time (refer to the “cooperation” submodel subsection). The strategy can be modified during the simulation based on various factors, such as a) cooperation model, b) social pressure, and c) competition for limited resources that implements the competition among individuals to pursue better alternatives.

Mobility patterns

The model includes the analysis of mobility strategy patterns and resource availability [5] [8]. We previously defined a place of origin where hominins initially arrive and a second place where humans migrate (for further information, refer to the article).

Sensing

At the beginning of the simulation, all agents are initially unaware of their environment. Thus, they must learn how to become familiar with their environment and identify the best leading to high resources. Once the path is learned, individuals become capable of detecting better resources within the set radius of perception and directly heading toward them. The better resources are located in attractor locations with potential refuges for humans. Here we introduce the concept of perceptual learning, whereby agents actively explore and perceive their surroundings to optimize their movements seeking resources while dealing with climate. Upon moving once more, human agents need to relearn the new environment.

Interaction

Interaction occurs through the cooperation model. The adoption of a strategy (cooperation or defection) will depend on the interaction of the human agents with others (see “cooperation” subsection for more details).

Stochasticity

Although this model is not stochastic *per se*, stochasticity is used in various aspects concerning the human agents and environments within the model.
Firstly, during the initialization, the distribution of patch values is influenced by the dataset of observed places. Based on these data, the environment is reconstructed in

a way that locates patches with higher resource abundance closer to these archaeological places of interest. For the remaining environments, the distribution of resource values is stochastic in nature.

Secondly, the initial positions of the human agents in Altai and Tian Shan, as well as their initial movements, incorporate a level of randomness used in the `learning-rate`. However, once agents locate resources with higher value, they proceed directly toward these resources, while subsequent movements remain random. In addition, patterns of a random movement in the model was included for the humans.

Thirdly, human agents possess the capability to create new attractor places. The new attractor places are randomly distributed in the environment.

This introduces additional stochasticity to the model, allowing for exploration and variability in the placement of attractor locations.

Collectives

Social structure is not specifically included in the model, a group of individuals is moving but each agent represents one individual with one social behavior. On the other hand, collectives are included in the cooperation model through social pressure by using a `radius-for-strategy` in the model (see “cooperation model” section).

Observation

The observation outputs of the model included can be seen in the **Table 4.**

Factor	Overview description
`population (count hominins/heminins)`	Count the total number of human agents
`cooperate? = true`	Count the total number of human agents

	that cooperate
`cooperate? = false`	Count the total number of human agents that do not cooperate
`found-newplaces-tienshan` `found-newplaces-altai`	Count the total of the attractor places created in Tian Shan or Altai
`payoff-tienshan` `payoff-altai`	Calculate the payoff. See “cooperation model” section
`delta-tienshan` `delta-altai`	Calculate the delta. See cooperation model section
`death-hypothermia`	Total number of human agents who died from hypothermia. Not included in the model results
`death-old`	Cumulative death toll attributed to natural causes or old age. Not included in the model results
`death-starvation`	Total number of human agents who died from starvation. Not included in the model results

Table 4. Observation output factors

Initialization

Enviromment initialization (map): the model consists of a theoretical model environment divided by 534 x 328 patches. Each cell represents the model 0.5 km. We use a map for the model generated using the Geographical Information System (GIS) package on NetLogo. We added to the model shapefiles of rivers, lakes and archaeological data. In the model, we use a shapefile of points of the dataset of potential archaeological places of interest detected in Altai and Tian Shan.

The model initializes with the attractor places randomly located in both areas: Altai (three attractor places) and Tian Shan (x 3).

Environment initialization (scenarios): The model performs four distinct theoretical climate scenarios, which can be selected using the chooser in the model interface. In addition to the climate temperature, the scenarios differ in the behavioral patterns of humans, specifically in terms of energy expenditure, body temperature, and resource consumption. However, the cooperation model remains without any changes in all the scenarios.

Agents initialization (humans): Two groups of human agents are initially located in the regions of Altai and Tian Shan. Human agents start with random ages. The population size can be preconfigured using the `nHominins` slider. Human `movements` can be chosen between random walks and lévy walks. By using the `prob-cooperation` parameter to determine the percentage of cooperation, humans have the ability to choose an initial strategy to adopt at the beginning of the simulation, with the flexibility to change strategies during the course of the simulation depending on different factors (see "Cooperation Model" section).

Agents initialization (attractor place): attractor places represent places where individuals can seek refuge and protection from the cold. These locations are scattered throughout Altai and Tian Shan. To aid visual differentiation, each area has attractors assigned with a unique color.

For the model, each step of the simulation is equivalent to a period of 1 year. The duration of the simulation is limited to 1500 years. `Seed` is set up in the model with a default level of 1000.

Submodels

Climate scenarios

The model explores theoretical climate scenarios for each region, based on the average temperature observed during annual, glacial and interglacial periods.

We use the climate estimation proposed by Glantz et al. for the Glacial and Interglacial periods in both Tian Shan and Altai areas (refer to Table 2 from Glantz et al., 2018). Data and temperatures were collected by selecting the Community Climate System Model (CCSM4) for the Last Glacial Maximum (MIS 2 ca. 22,000 years ago), and the last interglacial (MIS 5e ca. 125,000 years ago) [11].

The model performs four distinct climate scenarios, which can be selected using the chooser in the model interface (See **Table 5**). In addition to the climate temperature, the scenarios differ in the behavioral patterns of humans, specifically in terms of energy expenditure, body temperature, and resource consumption. However, the cooperation model remains without any changes in all the scenarios.

The scenarios have been specifically designed to explore the potential behavioral response of humans in an environment with variable climate temperatures. Due to the divergence in the climate temperature in the two areas, Altai and Tian Shan are represented differently. Altai area presents higher extreme climate conditions than Tian Shan. In that sense, we understand here that human behavior may differ when faced with extreme environmental conditions, leading to different actions and responses.

Scenarios	BioClim variables
Scenario 1	Annual Mean Temperature (glacial and interglacial)
Scenario 2	Mean temperature of coldest quarter (glacial)
Scenario 3	Mean temperature of coldest quarter (interglacial)

Scenario 4	Mean temperature of warmest (Interglacial)

Table 5. Scenarios with the mean temperatures based on BioClim variables.

Cooperation

The model uses an evolutionary model proposed by Henrich et al. [14], [15] to explore cooperation dilemmas in diverse climate scenarios. For the authors, the mechanism of conformist transmission allows cooperation to be maintained without the need for extensive punishment. In other words, the cost of cooperation does not require a high punishment rate to stabilize the population when the population adopts common behavior (Henrich and Boyd, 2001: 81).

The equation can be described as follows [15]:

$$\Delta p_0 = p_0(1 - p_0)[(1 - \alpha)\, \beta\, (b_c - b_d) + \alpha\, (2p_0 - 1)]$$

Where the variable Δp_0 represents the frequency of cooperators in the population; the parameter α is the strength of the conformist transmission; $(b_c - b_d)$ are the payoff of cooperators and defectors.

$b_c - b_d$ is given by the following equation:

$$b_c = (1 - e)\,(p_0\, B\, (1 - e) - C + e\,(p_0 B - N p_1\, \rho)),$$

$$b_d = (1 - e)(p_0 B - N p_1\, \rho)\,,$$

$$\Delta b_0 = b_c - b_d = (1 - e)(N p_1\, (1 - e)\rho - C).$$

Where N is the number of individuals; b_c is the payoff of cooperation while b_d is the payoff of defectors; e is the probability of failing in cooperation; C is the cost that cooperators assume to contribute; B is the benefit divided for all groups.

The model incorporates the cooperation strategy based on three key premises: a) the evolutionary framework proposed by the evolutionary model, b) the probability of individuals cooperating or defecting and b) the distribution and consumption of resources between cooperators and defectors. A detailed list of factors for the cooperation model can be listed in **Table 6**.

Factors	**Overview description**
`cooperate?`	Defines if individuals are cooperators or defectors. True if humans cooperate. False if humans do not cooperate. Cooperation is distinguished by colors: Humans with green color are cooperators and red color are defectors. It is defined as a boolean (true or false).
`cooperative?`	Count humans with cooperation true. It is defined as a boolean (true or false)
`no cooperative?`	Count humans with cooperation false. It is defined as a boolean (true or false)
`prob-cooperation`	Defines the probability of cooperation for humans at the beginning of the simulation. Default level: 0.20.
`cost-cooperation`	Defines the cost of each cooperator that reverberates similarly among the group. No cooperators do not pay the cost but they benefit equally. Default level: 10.
`punishment-cooperation`	Defines punishment of cooperation in defectors. Default level: 7.

`prob-nocoop`	Defines the probability of no cooperation for humans. It should be a small number. Default level: 0.001.
`alpha`	Strength of conformist transmission. Range from 0 to 1. Default level: 0.20.
`pay-off tienshan`	Pay-off of the population in Tian Shan
`pay-off altai`	Pay-off of the population in Altai
`delta-p`	Rate of change of cooperative population
`radius-for-strategy`	radius of the strategy of cooperation that will depend on how many cooperators are around the agent. Default level: 3.

Table 6. Factors for cooperation model. All the factors are defined by Henrich and Boyd, 2001

To enhance visibility and distinguish the roles of each individual in the model, cooperators are represented by the color green, while defectors are listed by the color red. New individuals below the age of 12 are visually represented in black, and once they reach 12, the color changes to indicate whether they become cooperators or defectors. This age-dependent color transition reflects the idea that the possibility of choosing a different strategy role is also influenced by age. Thus, newborn humans can decide their strategy role until they are over the age of 12. Although several studies have detected cooperation strategies in children from a very early age [16], the selection of a higher age corresponds to the possible absence of full development of cognitive and strategic abilities in selecting cooperative or non-cooperative decisions [17]. In the model, the selection of one strategy is primarily focused mostly on the pressure of the group, instead of being conditioned by their own experience since they are able to make decisions.

At the beginning of the simulation, humans may assume one role randomly depending on the probability of cooperation that it can set up previously. Within the model, humans interact with others in order to adopt one of two different social strategies: cooperation and non-cooperation. When humans choose to cooperate, they assume trait 1, whereas non-cooperators assume trait 0.

The assumption of one strategy is linked to the way of consuming resources in the model. By choosing to cooperate, they may adopt strategies such as resource conservation, equitable distribution, or sustainable resource management. These actions lead to more efficient utilization of resources, reducing wastage or overconsumption. In contrast, defectors prioritize their own self-interest and may engage in competitive behaviors, seeking to maximize their personal gains without considering the well-being of others. Consequently, defectors may exhibit higher rates of resource consumption as they prioritize their immediate needs or personal accumulation without regard for long-term sustainability or equitable distribution. Therefore, in the model, the selection of a cooperative strategy leads to individuals consuming fewer resources as they prioritize sustainable resource use and equitable sharing, contributing to better resource management and conservation within the population [18].

Individuals have the capacity to make decisions regarding cooperation, considering both the evolutionary equation and the social pressure of the group. Social pressure works similarly to real-life scenarios: if there is a high number of individuals around who are inclined to cooperate, an individual is more likely to choose cooperation as well. This selection is influenced by the presence of cooperative and non-cooperative individuals around [19]. We supposed here that the behavior of the majority can conditioner others to adopt cooperation or non-cooperative options, thereby increasing the likelihood of individuals choosing the same strategy as those around them.

However, the evolutionary model barely contemplated that individuals can decide to not cooperate at certain moments. Therefore, we have implemented this aspect into the model to address this limitation by incorporating additional factors that increase the possibility of non-cooperation decisions. In fact, humans in the simulation have the option to not cooperate based on three key assumptions: social pressure, the probability of non-cooperation (indicating a lack of interest or willingness to cooperate), and limited resources that implement competition between individuals. These factors influence the decision-making process and allow for variations in cooperative behavior throughout the simulation.

Corporal temperature

Human agents start with a corporal temperature of 37 ºC [20]. In extreme scenarios, we add the possibility of humans dying of hypothermia if they are not in a safe place for an extended period of time. When they are able to find a place, the corporal temperature increases with each step. Consequently, they must locate attractor places within a 30 km radius, providing shelter from the cold for individuals.

We also calculate the loss of corporal temperature:

$$\Delta T_b = (T_b - T_c) \cdot CR$$

Where ΔT_b is the result of the difference of the previous body temperature and the body temperature for each time-step; T_b is the body temperature at a given time-step; T_c is the climate temperature for each scenario in Altai or TianShan; and is CR the cooling-rate. The `cooling-rate` defines how fast a body loses temperature and is defined differently between scenarios. For more extreme scenarios, `Cooling-rate` the loss of temperature is faster than for non-extreme scenarios. In that sense, an individual can die of hypothermia when the body temperature is below 30 degrees.

The individual's normal body temperature can resume once they return to a safe location.

References

[1] U. Wilensky and W. Rand, *An introduction to agent-based modeling: modeling natural, social, and engineered complex systems with NetLogo*. Mit Press, 2015.

[2] D. P. J. Gary Polhill, "Using the ODD Protocol for Describing Three Agent-Based Social Simulation Models of Land-Use Change." Accessed: Oct. 07, 2022. [Online]. Available: https://www.jasss.org/11/2/3.html

[3] V. Grimm, U. Berger, D. L. DeAngelis, J. G. Polhill, J. Giske, and S. F. Railsback, "The ODD protocol: A review and first update," *Ecological Modelling*, vol. 221, no. 23, pp. 2760–2768, Nov. 2010, doi: 10.1016/j.ecolmodel.2010.08.019.

[4] B. Müller *et al.*, "Describing human decisions in agent-based models – ODD + D, an extension of the ODD protocol," *Environmental Modelling & Software*, vol. 48, pp. 37–48, Oct. 2013, doi: 10.1016/j.envsoft.2013.06.003.

[5] J. I. Santos *et al.*, "Effect of Resource Spatial Correlation and Hunter-Fisher-Gatherer Mobility on Social Cooperation in Tierra del Fuego," *PLOS ONE*, vol. 10, no. 4, p. e0121888, Apr. 2015, doi: 10.1371/journal.pone.0121888.

[6] E. Trinkaus, "Late Pleistocene adult mortality patterns and modern human establishment," *Proceedings of the National Academy of Sciences*, vol. 108, no. 4, pp. 1267–1271, Jan. 2011, doi: 10.1073/pnas.1018700108.

[7] D. M. Carballo, *Cooperation and collective action: archaeological perspectives*. University Press of Colorado, 2012.

[8] Wren and Costopoulos, "Does Environmental Knowledge Inhibit Hominin Dispersal?," *Human Biology*, vol. 87, no. 3, p. 205, 2015, doi: 10.13110/humanbiology.87.3.0205.

[9] K. E. Fitzsimmons *et al.*, "Loess accumulation in the Tian Shan piedmont: Implications for palaeoenvironmental change in arid Central Asia," *Quaternary International*, no. 469, pp. 30–43, 2018, doi: 10.1016/j.quaint.2016.07.041.

[10] M. M. Glantz, A. Van Arsdale, S. Temirbekov, and T. Beeton, "How to survive the glacial apocalypse: Hominin mobility strategies in late Pleistocene Central Asia," *Quaternary International*, vol. 466, pp. 82–92, Feb. 2018, doi: 10.1016/j.quaint.2016.06.037.

[11] B. L. Otto-Bliesner, S. J. Marshall, J. T. Overpeck, G. H. Miller, A. Hu, and CAPE LAST INTERGLACIAL PROJECT MEMBERS, "Simulating Arctic Climate Warmth and Icefield Retreat in the Last Interglaciation," *Science*, vol. 311, no. 5768, pp. 1751–1753, Mar. 2006, doi: 10.1126/science.1120808.

[12] S. E. Fick and R. J. Hijmans, "WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas," *International Journal of Climatology*, vol. 37, no. 12, pp. 4302–4315, 2017, doi: 10.1002/joc.5086.

[13] R. J. Hijmans, S. E. Cameron, J. L. Parra, P. G. Jones, and A. Jarvis, "Very high resolution interpolated climate surfaces for global land areas," *International Journal of Climatology*, vol. 25, no. 15, pp. 1965–1978, 2005, doi: 10.1002/joc.1276.

[14] J. Henrich, "Cultural transmission and the diffusion of innovations: Adoption dynamics indicate that biased cultural transmission is the predominate force in behavioral change," *American Anthropologist*, vol. 103, no. 4, pp. 992–1013, 2001.

[15] J. Henrich and R. Boyd, "Why People Punish Defectors: Weak Conformist Transmission can Stabilize Costly Enforcement of Norms in Cooperative Dilemmas," *Journal of Theoretical Biology*, vol. 208, no. 1, pp. 79–89, Enero 2001, doi: 10.1006/jtbi.2000.2202.

[16] K. E. Slocombe and A. M. Seed, "Cooperation in children," *Current Biology*, vol. 29, no.

11, pp. R470–R473, Jun. 2019, doi: 10.1016/j.cub.2019.01.066.
[17] M. Gutiérrez-Roig, C. Gracia-Lázaro, J. Perelló, Y. Moreno, and A. Sánchez, “Transition from reciprocal cooperation to persistent behaviour in social dilemmas at the end of adolescence,” *Nat Commun*, vol. 5, no. 1, Art. no. 1, Jul. 2014, doi: 10.1038/ncomms5362.
[18] A. Angourakis, J. I. Santos, J. M. Galán, and A. L. Balbo, “Food for all: An agent-based model to explore the emergence and implications of cooperation for food storage,” *Environmental Archaeology*, vol. 20, no. 4, pp. 349–363, Nov. 2015, doi: 10.1179/1749631414Y.0000000041.
[19] C. Hilbe, K. Chatterjee, and M. A. Nowak, “Partners and rivals in direct reciprocity,” *Nat Hum Behav*, vol. 2, no. 7, Art. no. 7, Jul. 2018, doi: 10.1038/s41562-018-0320-9.
[20] P. Petrone, J. A. Asensio, and C. P. Marini, “Management of accidental hypothermia and cold injury,” *Current Problems in Surgery*, vol. 51, no. 10, pp. 417–431, Oct. 2014, doi: 10.1067/j.cpsurg.2014.07.004.