SEN9120 - Advanced Agent Based Modeling written by Brennen Bouwmeester and Kevin Su

Compound events in the Hunter-gatherer age; an Agent Based approach

Resilience of humans in the Upper Paleolithic could provide insights in how to defend against today's environmental threats.

Understanding ancient behaviour through modeling. Illustration taken from [Pixabay]

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1. Introduction

Approximately 13,000 years ago, the Laacher See volcano located in present-day western Germany erupted cataclysmically. Archaeological evidence suggests that this is eruption – potentially against the background of a prolonged cold spell – led to considerable culture change, especially at some distance from the eruption (Riede, 2017). Spatially differentiated and ecologically mediated effects on contemporary social networks as well as social transmission effects mediated by demographic changes in the eruption's wake have been proposed as factors that together may have led to, in particular, the loss of complex technologies such as the bow-and-arrow (Riede, 2014a; Riede, 2009).

The eruption in the Laacher See can be classified as an extreme event, that together with a changing climate, could have contributed to the occurence of a *compound event* (Field et al., 2012):

1. two or more extreme events occurring simultaneously or successively
2. combinations of extreme events with underlying conditions that amplify the impact of the events.
3. combinations of events that are not themselves extremes but lead to an extreme event or impact when combined. The contributing events can be of similar (clustered multiple events) or different types.

As the existence of compound events is timeless, they are increasingly seen as part of a particular class of threat to society (Zscheischler et al, 2018; Leonard et al, 2014). At the same time, the use of historical cases as counterfactual templates for assessing the risk posed by such unlikely and inherently hard to predict events has been proposed (Woo, Maynard, Seria, 2017; Aspinall & Woo, 2019).

These processes have not, however, been investigated through agent-based modeling (ABM) before. Moreover, the bottom-up approach that is inherent to ABM aligns well with the definition of a compound event, as such an event arises only through emergence that is caused by multiple processes on a smaller scale. Therefore, it can be stated that taking an ABM point of view at the Laacher See approximately 13,000 years ago can support the thinking process and knowledge on building resilience for today's society (Leder et al., 2017; Riede, 2014b; Riede, 2017).

1.1 Problem formulation and relevance

Scientific relevance

The value that this research can have for science, is to aid in archaeological knowledge on the phenomenon of the Laacher See eruption, but also the interactions of small, mobile hunter-gatherer bands. By exploring different scenarios for the inhabitants of earth 13,000 years ago, several hypotheses for how life on earth was like back then can be tested and verified. It is important to note that models in general are not able to falsify hypotheses, as they are simplified versions of the real world. Their main purpose should be found in their ability to create insight in systems such as the world of the hunter-gatherers and showing emerging patterns under certain circumstances, rather than showing truths and facts about these systems. As the research will look into both shocks (volcano eruption), as well as stresses (climate change) that affect the system and how well the system can bounce back, it will be fitting to support research about resilience (Rutter, 1993).

Societal relevance

For society, the use of ABM for the Laacher See case can aid in understanding weaknesses of parts of society by looking at the failing or succeeding of our predecessors. By looking at the properties of flourishing bands and distinguishing these bands from failing bands, several hypotheses can arise for the best way to create a resilient society. The importance of resilient networks can be found, as well as the sharing of knowledge amongst each other. However, it is important to note that the model will not be able to create one-size-fits-all solutions to societal problems, which is due to the fact that the model is a simplified representation of reality. It can never be stated that findings in a model can be compared 1 on 1 to the real world. Still, the knowledge created by thinking about states and (inter)actions can be valuable for creating systems in the real world that are more resilient and robust.

Research question

This research will be aided by the following research question: *What is the impact of the interaction between climate change trajectory and an extreme event, such as the Laacher See eruption, on the generational development of hunter-gatherer bands?*

All steps taken and choices made within the research have been focused on fulfilling this research goal as good as possible, meaning it will be most valuable for that purpose, but lacking at fulfilling other purposes.

1.2 Research method

To answer the research question, an agent-based model will be developed using the software Netlogo. Agent-based models are a branch of computational models to simulate the actions and interactions of different entities to assess their effect on the system as a whole, in this case, the development and behaviour of hunter-gatherer bands and their interaction with existing compound events. Since the potential knowledge can be found within the interactions between small bands of hunter-gatherers, agent-based modeling allows one to capture the behaviour of these parties in their environment (Abar, Theodoropoulos, Lemarinier & O’Hare, 2017).

1.3 Structure

The document is structured to follow the steps from the Good Modelling Practice guide by (Nikolic et al., 2019). Chapter 2 explains the conceptual building blocks for the agent-based model and the assumptions being made. Chapter 3 shows how the different parties together with their interactions have been modelled. Chapter 4 shows the results from the model, its experiments and its validation. Chapter 5 discusses the policy suggestions, limitations of the model and the future research opportunities. The overview of the literature being used can be found after chapter 5.

1.4 Reading guide

This report holds a complete cycle of creating and interpreting an agent based model. The starting point of this cycle is a relatively vague concept of what should be investigated, which can be found in appendix 1. From that description, a model narrative has been produced, which has been implemented with its according assumptions, parameters, key performance indicators and visualization. These parameters were altered during the experimentation setup, for which the results were analyzed and concluded upon. This report should be read together with the agent based model that can be found in compound_events.nlogo and the python code which is used to analyze the experiments, which can be found on the following github: https://github.com/WKSu/compound-events

2. Conceptualization

This section conceptualizes the problem to find the relevant concepts and also provides the basis for the Netlogo model. The system identification clarifies the relevant concepts and the level of aggregation. The concept formalization will translate the concepts identified before into a structure which contributes to the programming.

2.1 The components of the Agent-Based Model

Before translating the states and (inter)actions of the hunter-gatherer bands to an agent based model, the concept of an agent should first be defined. Figure 1 shows the general framework for agent-based models, in which agents operate. There is no universally accepted definition of what an agent is. However, Jennings et al. (1998) provided a definition which emphasizes on two important properties of an agent:

“An agent is a computer system, situated in some environment, that is capable of flexible and autonomous action in order to meet its desired objective.”

An agent is therefore *autonomous*, has particular properties and actions, and has a *social ability* (Chen, 2015). Autonomy means that the agent can operate within a certain environment, and has control over its actions and internal state. The precise interactions and behaviour are governed by rules the agent refers to. Being social means that within the environment, the agent is able to interact with other agents as well. All these actions change the state of an agent. In the following paragraphs this framework will be applied to the problem context of the hunter-gatherer bands.

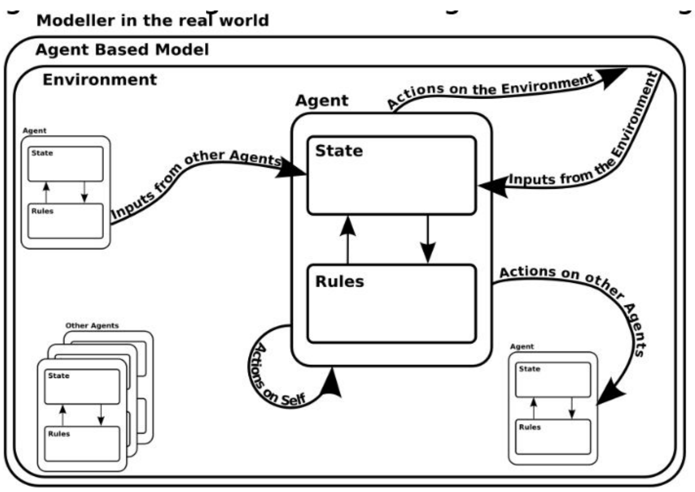

Figure 1: The general framework of an agent-based model (Nikolic, 2018a).

2.1.1 Static model representation

As the model will be mostly about the interactions between hunter-gatherer bands, their environment and climate change, only one real agent can be pointed out within the system: Hunter-gatherer bands. Therefore, these are the only agent that will be considered for the model. Figure 2 shows the agents, their states (variables) and actions, but also their interactions with their environment and the climate (Nikolic, 2018b).

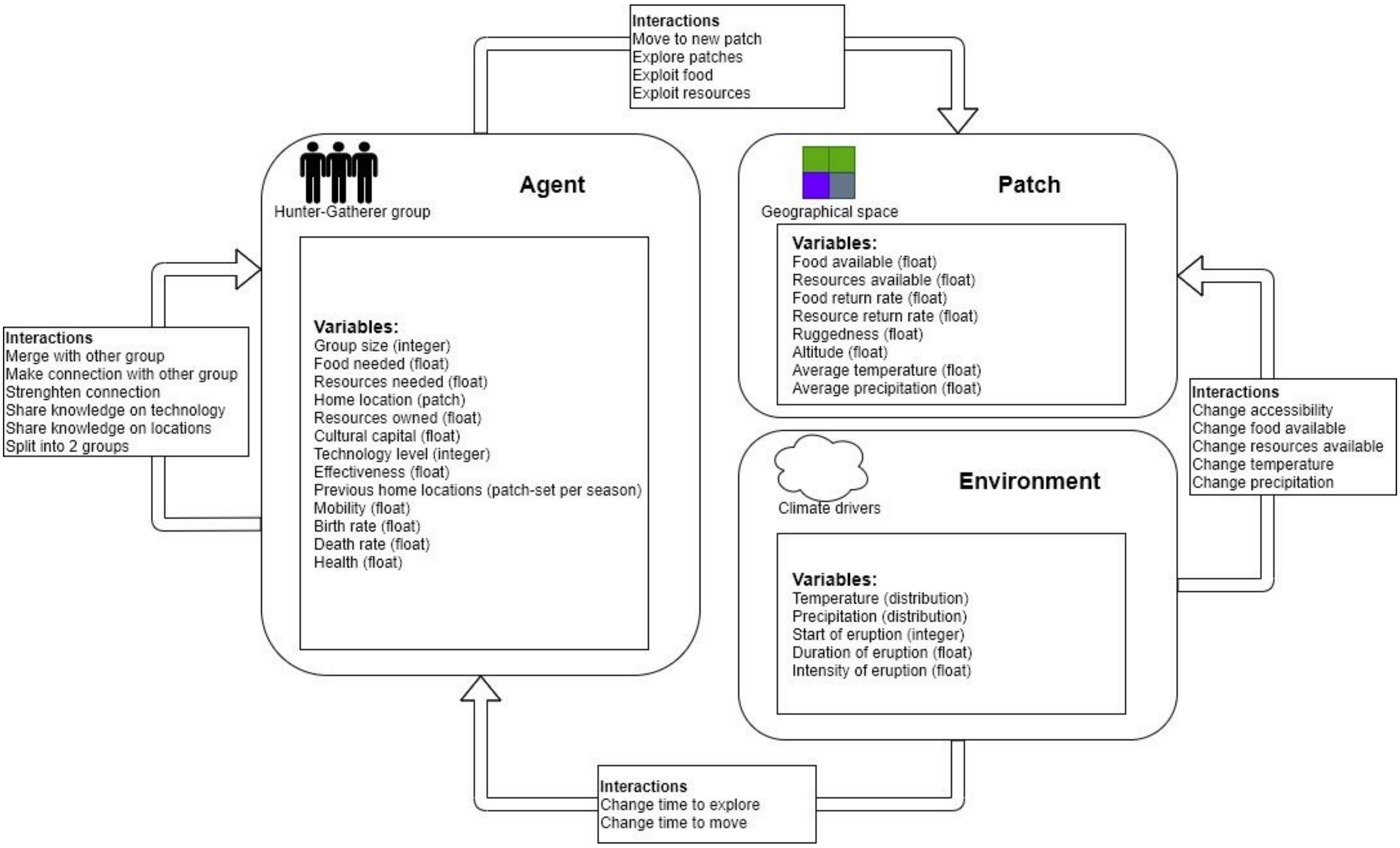

*Figure 2: the formal representation of the **static** concepts in the model.*

The interactions shown in Figure 2 emphasize the different parts of the research question. By making the environment (climate and extreme event) able to change the development of the hunter-gatherer bands and the ground on which the bands live, the model will be able to show the actual tipping points where the bands are boosted or slowed down by the environment they live in.

Important to note is the spatial boundary of the model for the population. As the research question focuses on the development of bands as a whole, it can be assumed that the properties of individual members of these bands do not add value to the model. That is why the lowest spatial scale at which the model operates can be seen at single bands of hunter-gatherers. This assumption entails that the change of for example group size of the band does not distinguish old and sick members from healthy and strong ones, which might cause an overestimation of the loss of productivity and an underestimation of the loss of knowledge when a certain group decreases in size (band members die).

2.1.2 Model flow representation

*Figure 3: the formal representation of the **flow** concepts in the model.*

Figure 3 shows the continuous internal logic of the model that was built. As can be seen the model has been divided into several blocks of actions. The colors indicate which of the parts of the model is holding the variable used. Green variables are part of the environment and climate in the model. Red variables are owned by the patches in the model and blue variables are owned by the bands themselves. Once per run (at the beginning), the model is setup, by adding amounts of food and resources to the patches. Also the average temperature and precipitation levels are added per patch, which will change during the model. After the model is set up, it can be run.

Every step, the first thing all bands will do is check whether they should split up or not. This happens when the band is too big to continue as one, and if the new groups will be of sufficient size after spitting up. After deciding to split, the presence of other bands is checked, with which bands can merge or share knowledge. These possible interactions are based on Gamble (1982). If links already exist with the present neighbours, these connections become stronger, and more knowledge will be shared between the bands.

After interacting with each other, bands decide whether they should move to a new location (Mandryk, 1993), explore the area around them or stay in their current position and gather the food and resources available. When bands find out there is not enough food or resources on their current location, they will find a better place to live and move there. If bands are relatively efficient and have time left to spend after exploring, moving and gathering the needed food and resources, they will spent their remaining hours to gather additional resources, which can be used in the next time period, but also to increase the technology level of the band, which can be translated to creating additional or improved tools used for gathering and hunting. However, in order to be able to create these new technologies and actually use them, the cultural capital of the bands should be high enough (bigger than or equal to the technology level). When all bands are done exploring, moving and gathering, they will "use" their gathered products to be able to survive. If they did not manage to gather enough food and resources needed to survive, their health will drop, which means some band members will die. After updating the band properties, a new time period starts.

2.1.3 Time

To answer the research question, it is important to have a time length in which the effect of events are researched. Furthermore, the order in discrete models can have significant effect on the results of the model (Wilensky & Rand, 2007). It is also necessary to consider time in the agent-based modelling, precisely what can be accomplished in each discrete time step. These decisions will be reflected in this section.

The shortest time present in the model will be existing of a season. In this three month period, each and every action of the bands is performed, before the model moves on to the next season. As the model should show insight into generational change of the properties of bands, the model should also run for several generations. Next to that, a small warm-up period will be necessary in order to get the most out of the model. Although we have tried to implement as much knowledge into the model as possible within the setup, the bands will lack knowledge about locations when the model starts, and some bands will spawn at locations that do not support their full needs, meaning they will change in size drastically, or die completely. To make sure that the model can give useful insights, the largest time period presented by the model will be 60 years, which is equal to 240 seasons (ticks)

Also related to time, is the schedule that bands create at the beginning of a season. Figure 4 shows how much time is needed for each of the 4 possible actions that the bands can perform. Although these calculations will not be exactly the same as in the actual model, they show the relationships between the different variables well. If the group needs more food, more time will be spent gathering food. Likewise, the more effective the group is, and the bigger the group is, this gathering process will be faster. Different in resource gathering is the assumption that groups can hold on to resources across seasons, meaning that an overload in resources in one season can mean that a group needs less time to gather resources in the next season. This will create a positive feedback loop where bands that are flourishing will be able to flourish more and more.

When bands decide to move, the time and resources that are needed to perform this movement are calculated through the mobility of the group, which is based on their size and a random initial skill, and the accessibility of the patch that will be the bands' new home. This accessibility factor is based on the relative altitude of the new home compared to the altitude of the current home, but also the ruggedness index, which describes how hard it is to enter the patch. Next to these factors, also the distance to the current home will be taken into account. To be able to move to a new home, the total cost of moving can not exceed a chosen maximum of days. This will make sure that bands do not spend too move time traveling, meaning they will have time left to gather some resources and food to be able to survive.

Time scheduling
Time available = 100
Time needed for food gathering = $\frac{\text{Needed food}}{\text{Food effectivity X Group size}}$
Time needed for resource gathering = $\frac{\text{Needed resources - resources owned}}{\text{Resource effectivity X Group size}}$
Time needed to move (if moving) $\frac{\text{Number of patches moved X Accessibility}}{\text{Mobility}}$
Time needed to explore (if exploring) $\frac{\text{Number of patches explored}}{\text{Mobility}}$

*Figure 4: the formal representation of the **time** concepts in the model.*

2.2 Assumptions for rules in the model

When building a model, a representation of reality is created. This inherently means, that constantly choices have to be made considering what to take into account, and what to ignore. Therefore, it is important to keep track of every choice that is made during the building of the model. The assumptions that are the result of the choices we have made are displayed in this chapter. They should always be taken into account when the model is used to create conclusions.

2.2.1 Setup model

1. **Scale of model:** The smallest unit we will follow is a band of hunter-gatherers of group size 1 - infinite. The hunter-gatherers in a band move together as 1 and there is only knowledge about the state of the whole band. The patches cover all of Europe 13000 years ago, but only taking into account the altitude and ruggedness-index (Compiled by ZBSA after Andrén et al. 2011; Björck 1995; Brooks et al. 2011; Hughes et al. 2016; Lericolais 2017; Lunkka et al. 2012; Moscon et al. 2015; Patton et al. 2017; Seguinot et al. 2018; Stroeven et al. 2016; Subetto et al. 2017; Vassiljev/Saarse 2013; Weaver et al. 2003),
but also the precipitation and temperature (Fordham et al., 2017) of the corresponding area of a patch. Considering time, only seasonal change will be tracked as the model should show changes and patterns over different generations of bands.

2. **Warm up phase:** To make sure no warm up phase is needed, the initial population per patch is based on the initial resources and food on that patch. This leads to the assumption that the initial technology level is equal to the cultural capital, as bands have had access to enough resources before the model starts running. However, due to the lack of knowledge and possibility of bands having a low cultural capital level, some warm up phase is needed to get rid of the bands that are not able to survive under any circumstances and to get the networks and knowledge sharing going.

3. **Ireland:** As hunter-gatherers did not cross the sea from England to Ireland yet, only 1 band should spawn on Ireland (Bocquet-Appel et al., 2005).

4. **Cultural Capital**: Cultural Capital mutates randomly each season by pulling a number from a normal distribution with adjustable standard deviation and the mean equal to the cultural capital of the previous season. The initial value is determined randomly, using a normal, uniform or poisson distribution. Also, the mean and stdev can be changed by the user.

5. **Technology level:** Technology levels can never become higher than the cultural capital of a band, as we assume that bands would not know how to use their own technology when their cultural capital does not suffice.

6. **Initial Group Size:** Random normal set with a minimum of 10 and a maximum of 40, meaning a mean of 25 Hunter-Gatherers and a standard deviation of 10.

7. **Mobility:** The initial mobility of a band is generated randomly using a uniform distribution. This can vary from 1 - 10 and will make moving and exploring easier as the value is higher. The mobility will not be altered during any model runs. However, for actions this mobility value will only be a part of the calculations of how mobile a band actually is. This real mobility exists also of the group size, and the properties of the patches that need to be crossed.

33. **Population Spread**: The model tries to setup the population in the initialization of the model in such a way that most hunter-gatherer bands will end up on *livable* patches, this is achieved by finding the median of these patches and adding an absolute value of 200 to it to create a better spread.

2.2.2 Bands actions

8. **Needs of bands:** Bands need two different types of products, namely resources and food, which are not specified further. Also, it is ignored that both hunting and gathering can collect both food and resources. There is no real distinction between hunting and gathering. od is needed more, but will grow back faster on the patches. Resources are needed to survive (building homes and fires) but can also be used to (abstractly) create new tools for hunting and gathering, which increases the efficiency of the bands in hunting and gathering. Every season each member of a band needs 90 units of food (1 for each day) and 30 units of resources (1 for 3 days).

9. **Band decision logic:** At the beginning of any season, bands decide whether their current home can support their needs. If so, they stay and spend all time on gathering. If not, the look in their known location for the current season for a new home that can support their needs. They then choose the closest one patch and move there, to spend their remaining time of gathering. If no patch exists in their knowledge that has sufficient resources and food, the band explored the neighbouring patches of the current home location. After that, they will move to the patch that has the highest resources and food combined (weight of 0.5 and 0.5). Their remaining time goes into gathering. The biggest bands get to gather, move and explore first, as it is assumed they will be able to push smaller groups out of their territory.

10. **Band action order:** The order in which the bands choose to explore, move and gather will be random. This means that when two bands have their home on the same patch, one of them can gather their resources and food before the other, which might mean the second band has to move due to a lack of resources and/or food.

11. **Knowledge about patches:** Bands remember the amount of food and resources on a patch for a specific season. Therefore they will have 4 lists of known locations, including the timely presence of resources and food. For deciding what to do during a season, they will only use the knowledge for that particular season. The model will always start in the summer. During the runs, bands will randomly forget some of the knowledge that they have acquired, as it is assumed that bands are not able to remember the livability of all patches in Europe for all seasons.

12. **Explore:** If no known patch fulfills the requirements for needed food and resources, explore the patches around the current home, which takes 10 days (out of 90 total days) - mobility, meaning more mobile bands will be faster.

13. **Moving costs:** Moving to any patch will take time which is based on the relative altitude of the new home, the ruggedness index of the new home, the initial mobility of the bands and the size of the bands. In this formula, traveling through any 1 patch takes 1 day, where hard to reach patches will add time. In this cost, only the reachability of the new home will be taken into account, meaning the accessibility of the patches in between are ignored. This has been assumed to let go of any optimization calculations of the route to take to the new home location. This also leads to the assumption that the distance which is traveled is the shortest distance (direct). If the costs are too high, the band cannot travel to the destination they wish to go to.

14. **Moving resources**: If a band decides to move to a new location, take one unit of the owned resources per group member in a band to the new location. The other resources owned are dropped on the location and given back to the natural habitat (patch).

15. **Spending remaining time:** If a band has time left after exploring and moving, the remaining time will be used to gather. This gathering depends on both the cultural capital and the technology level of a band. The higher the product of these two properties of the bands, the faster they can hunt and gather. If there is still time left after the band has hunted and gathered enough food and resources, they will acquire additional resources until the patch is depleted or there is no time left.

16. **Health**: If the hunter-gatherers are able to have no shortages in food and resources, their health will become 100, independent of their current health. Otherwise, their health will drop

17. **Population Growth:** The death rate is dependent on the health of a hunter-gatherer band. A health level of 70 will mean that only 0.7 of the band will survive (round up to an integer). The population grows with a standard rate.

37. **Cultural Capital Mutation**: It is a random mutation drawn from a normal distribution of the previous cultural capital value with a parameterized standard deviation. This change occurs every season and can become positive as well as negative. The cultural capital will also be able to drop if the technology levels are low enough, meaning they are able to forget certain skills and tools.

2.2.3 Band interactions

18. **Splitting into two groups:** When a band has a size that is bigger than the maximum size of a group, they can decide to split into 2 seperate bands, the group size will be split equally, and both groups will keep the knowledge of their previous bigger group. The connections that the group had before splitting will also move on to both of the groups.

19. **Connecting with other bands:** When two bands come across each other (are on adjacent patches) they will create a connection which can be seen in the model. From that point on, every additional season that they spent adjacent to each other, the strength of this connection will increase by 1. If a band dies out, the connection disappears.

20. **Sharing location knowledge and merging:** When bands are connecting to each other, the number of seasons that they have been close to each other decides what information they share. The user decides the 1st threshold (which is a parameter in number of seasons in which the bands have been living close to each other, which can have intervals without any contact) the 2nd and 3rd are respectively twice and four times times as high as the first threshold. Also when the first threshold has been passed, the bands share knowledge about locations in spring and summer, which are seen as the easiest months. The number of locations shared per season cannot exceed 50. For the 2nd threshold they also share fall and winter, which means the bands must have a close relationship as sharing information about surviving in the hardest months is valuable information. Again, the number of locations shared per season cannot exceed 50. The 3rd threshold gives room for merging, if the combined group size does not exceed a maximum group size and there are enough resources on their current home to support their needs.

21. **Information priority:** When a band receives knowledge about a patch for which they already have the knowledge, they prioritize their own knowledge, even when the knowledge of the other band is newer. They cannot prioritize based on time, as this requires a time based memory, which is not present.

22. **Sharing technology knowledge:** When the 1st threshold for sharing location knowledge has been reached between two bands, each time they meet, their technology level will increase by 1. This assumes that all bands can teach each other something they do not know yet. However, as technology can only be used when the cultural capital allows for this, the increase that happens due to this interaction might be undone in a later stage in the season.

23. **Loss of connections:** If a band is on a patch which has been affected by a compound-event, this band loses all its existing connections to other bands as it is isolated. Also, connections will disappear over time, if bands live too far apart for several seasons in a row.

24. **Everlasting knowledge:** Bands will lose only parts of their location knowledge randomly. They will only update their knowledge about a patch if they decide to visit it again and find a different amount of food and resources than expected. This inherently means that some of the knowledge of bands can be generations old, which reminds of the existence of myths within communities about old paradises that can be falsified when the band decides to visit this “mythical” patch.

25. **Calculating cluster:** When the model calculates the number of existing clusters in the model, meaning bands that are connected in a cluster, the Louvain communities algorithm is used (De Meo et al., 2011).

2.2.4 Environment Data

26. **Climate data**: The climate data of 13,000BP in Europe is based on PaleoView[1] based on the Community Climate System Model 3 (CCSM3). As the scale of the model is so large, there are absolute differences between model predictions and present day observations that can be caused by internal errors, errors in the initial state of the model or errors in model forcing. To adjust for this, the creators of the data have applied a correction factor to the data which was used in the model.

27. **Landmass:** The EPHA Allerod map[2] is used to create the landmass of Europe between 13900-12700BP, which is a mix of multiple other maps.

28. **Altitude**: The altitude data is contemporary altitude received from the GEBCO database[3] . It is the same base source that the Allerod map also used, however, provided a better format for the model.

29. **Terrain Roughness:** Terrain Roughness Index is decided using the degree of irregularity of the surface, using the GDAL Roughness Function. This is a relative index of the patches and its surrounding cell based on the EPHA Allerod Map. This map was chosen because it represented the relative changes in land mass the most.

30. **Map Consistency:** Because of the multitude of data and different data sources used to create the environment in NetLogo it is not always guaranteed that they are consistent with each other. For example, the landmass in PaleoView is different than that of EPHA Allerod Map. These maps at the moment are chosen because they specialized in one aspect the best. If a map was inconsistent with another map, only data would be used of one map. In this case, EPHA Allerod Map also has elevation data, however, the GEBCO altitude map provided a higher and better absolute resolution of altitude.

31. **Volcano data:** For the location of the volcano and the spread of the ash-fallout, the findings of Bogaard & Schminke (1984) and Reinig et al., (2020) are used.

32. **Climate change data:** To simulate the climate as accurately as possible, the climate data from GISP2 is used, which has measured the level of CH4 in Greenland and Antarctica, which is used to estimate the change in temperature (Blunier & Brook, 2001). For this simulation, the weather trend has been fastened to be 100 times as fast to save computational time.

34. **Implementation of CH4 data from Blunier & Brook (2001)**: Min-max normalize the CH4 data to get a realistic temperature trend where the CH4 values are set in such a way that it represents the temperature in the model. Unfortunately, the calibration and therefore

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[1]https://onlinelibrary-wiley-com.tudelft.idm.oclc.org/doi/full/10.1111/ecog.03031
[2]http://www.zbsa.eu/zbsa/publikationen/open-access-datenmaterial/epha-european-prehistoric-and-historic-atlas/bollingallerod
[3] https://www.gebco.net/data_and_products/gridded_bathymetry_data/

the relation of CH4 to temperature is done in an absolute manner. The focus here was to replicate the behavior rather than the precise values in order to get the most out of the model.

35. **Seasonal Weather:** The weather changes every season by taking the previous year's data of the same season using a random normal distribution and a standard deviation based on the map's deviancy. This is the climate food and resources use to update their new variables. Day to day extremities are therefore not taken into account as in the model only the aggregate of the season is used.

36. **Updating Food and Resources:** Food return is based on the moving average of temperature and precipitation. It takes into account the harvesting of the hunter-gatherers on the patch by using a parameterized growback rate based on the optimal values.

38. **Volcano Impact Time**: The Laacher See Eruption most-likely started in late spring/early summer (Schweitzer, 1958). The bulk of the magma volume erupted in 10 hours, the ash fall lasted a few weeks but not more than a few months (Schmincke et al., 1999). This is why the compound event eruption is modelled into one season, however, the impact of the ash duration is set to six years (Kaiser, 1993).

3. Model design

Based on the conceptualisation and assumptions in chapter 2, a narrative can be formulated to translate the concepts and assumptions for the implementation in the Netlogo software. As mentioned in the assumption, the model will be constructed based on the actions which impact individual agents in the model. Although the model itself can show the actual coding decisions, this chapter will show insight in how the model can be changed by using the parameters, and how the model can be interpreted by looking at the “model world” and the present monitors.

3.1 Visualizing the model

The colors and shapes that NetLogo provides offers a valuable possibility for visualizing the state of the model. As can be seen, Europe of approximately 13.000 years ago is loaded into the “model world”, distinguishing water and land patches. Also, the location of the Laacher See volcano can be seen explicitly by using a self-made picture of a volcano. When the eruption takes place, the patches that are affected by the lava and ashes can be recognized by their changed color, being either red when affected by the lava or a scaled orange when affected by the ashes. The hunter-gatherer bands have their own appearance, and can be seen while they move across fertile patches in Europe. When two bands are connected to each other, a red link can be seen between them, which can visualize existing networks across multiple bands. When a band dies, it disappears from the screen, as well as all of its connections. An additional feature is the display of clusters within the model. When the color-clusters switch is turned on, the color of the links that are part of a certain cluster have the same color, which differs per cluster. Another interesting feature is the given that Ireland is only inhabited by one band of hunter-gatherers at the start of each run. Literature has shown the absence of crossing between Europe and Ireland at the time period that is being modelled (Bocquet-Appel et al., 2005)

In the following paragraphs, the models internal working will be explained making use of the XLRM framework, shown in Figure 5 (Kwakkel, 2017). Paragraph 3.2 will discuss the M in XLRM, namely the performance metrics (Key performance indicators). Paragraph 3.3 elaborates on the policy levers and the external factors, as they are both seen as input. The relationships in the system have already been explained in chapter 2, which are translated into all of the code in the Netlogo file.

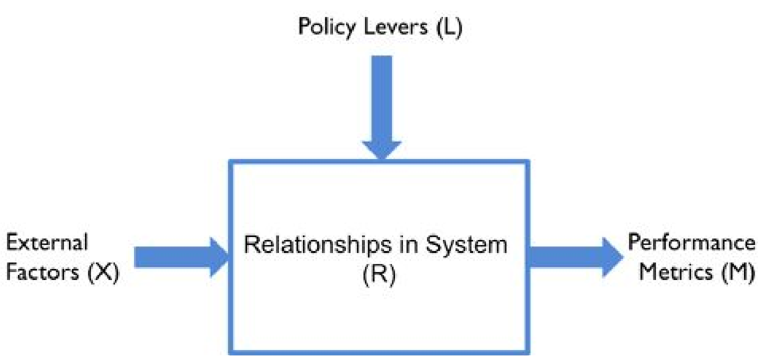


Figure 5: The XLRM framework (Kwakkel, 2017 p240).

3.2 Key performance indicators

In order to make sense of the model runs and behaviour, it is important to have certain Key Performance Indicators (KPIs) in place that can together be interpreted as the most important measurements of how “successful”, “typical” or “different” particular runs behaved compared to each other. As the goals of the model at hand is to understand hunter-gatherer band behaviour across several generations with the possible effects of compound events, it is useful to pick KPIs that show both the success of bands in surviving and flourishing and how this success is impacted by the compound events.

3.2.1 KPIs on hunter-gatherer population

The first KPIs that should be taken into account is the *number of existing bands*, which can be compared to the initial number of bands to see growth or decline in hunter-gatherer flourishment. Next to the number of groups, the *average group size* of the existing bands should be tracked to give meaning to the first stated KPI. If only a few groups exist, but they are very large groups, this does not mean a decline in number of hunter-gatherers. Together these KPIs can show to what extent the hunter-gatherers are able to survive in the corresponding environment (for that run). A third KPI that can give insight in the survivability of the bands is the *number of bands that vanished* completely. This number will show the harshness of the environment, and together with the other KPI’s on the number of hunter-gatherers, this number can indicate the fluctuations of the existing groups.

3.2.2 KPIs on hunter-gatherer characteristics

Next to the total population size of the hunter-gatherers, it is important to keep track of the skills of these existing groups and of their knowledge of the environment. The *average cultural capital level* will show how “efficient” the existing groups are at hunting and gathering.

The importance of this skill can then be compared to the knowledge of the bands across different runs. The knowledge of the environment can be monitored by looking at the *average number of known patches* across the different seasons. Looking at the impact of these two KPI’s will give an indication of the relative importance of knowledge versus skill. Because of the logic that connected bands are able to share knowledge amongst each other, unconnected bands will have a relative decline in intelligence over time, which can also be measured. This creates a KPI that can actually show the loss of knowledge about certain technologies, which has been stated in the introduction.

A third important characteristic of the bands is their ability to move around Europe. For this, the *total number of movements* and the *time spent on these movements* will be tracked during the runs. The two KPI’s together can show how “busy” bands are with travelling around, which might be able to show whether mobile bands have a lead over less mobile bands.

3.2.3 KPIs on hunter-gatherer connections

To extend the measurement of the importance of knowledge, the connectivity of the bands will also be measured during the experiments. The *average number of connections* that a band has and the *total number of clusters* will be monitored to give an insight in the connectedness of the hunter-gatherer bands across Europe. Again, the size of the total population can put the number of clusters in perspective which will be somewhere between 1 (all bands are connected) and the total number of bands (no bands are connected).

3.2.4 KPIs on the impact of compound events

The KPI’s stated in the paragraphs above give a relatively complete overview of the performance of hunter-gatherer bands under stable circumstances. They do not, however, look into the effect of climate change and/or the eruption of the Laacher See volcano. The effect could be seen indirectly in the number of bands that go extinct, while altering the climate and changing the duration before the volcano erupts. Hypothetically, the number of bands will decrease after the volcano erupts, and also while the climate becomes more extreme over time. Next to these indirect effects, the direct effects will also be measured during the run. As it is known which geographical parts of Europe were affected by the volcano, the bands who are living in these areas will be seen as affected by the effects of the volcano (including ashfall). With this logic in mind, the *number of affected bands* can be measured during runs.

3.2.5 Overview of KPIs

Table 1 gives an overview of all KPIs, on which has been elaborated in the previous subparagraphs of this paragraph. Note that some of the important KPIs have been merged into more aggregate ones, in order to keep a clear view on what to evaluate during the experimentation, which will take place in chapter 4.

Table 1. Overview of KPIs.

KPI	Representation in experiments
Hunter-gatherer population	
Number of existing bands	Total population
Average group size	
Number of bands that vanished	
Hunter-gatherer characteristics	
Average cultural capital level	Average difference between cultural capital and technology level
Average technology level	
Average number of known patches	Average number of known patches
Total number of movements and the *time spent on these movements*	Total movement per band per season
Hunter-gatherer connections	
Number of connections	Total number of clusters per band
Total number of clusters	
Impact of compound events	
Number of affected bands	Total effect of volcano (number of affected bands)

3.3 Model parameters

Next to the aforementioned KPIs that will be outputted from the model, the model also requires inputs, which will be used in the logic of the model. For these model parameters, we distinguish 3 types of parameters. All of these types will be elaborated upon in the following paragraphs. Note that these paragraphs will also serve as a guide through the parameters which users of the model will need to understand their meaning.

3.3.1 Visualization

Some levers and buttons in the model only change the visuals of the model, but do not have any influence on how the model runs. However, it is important to explain also these parameters for the user to be able to understand their changes to the parameters fully.
Show_volcano_impact: If this parameter is set to “On”, the model will show the ash fall and the level of intensity of this ash fall.

Show_links: This parameter decides whether the existing links between bands are shown by the model or not. When many bands exist the links could interfere with the clarity of the behaviour of the bands. However, when the option is set to “On”, the links can clearly show existing networks between bands.

Color_clusters: This parameter decides whether the model will give a colour to the different existing clusters in the model. When this is set to “On”, the model will create a rainbow effect to distinguish all clusters from each other.

3.3.2 Policy levers

Within the system, it is important to distinguish what can be adjusted by actors and what cannot be altered by actors. As the model at hand is about the situation of 13,000 years ago, there are no real policy levers. However, we have picked a set of parameters which are most likely properties that the bands could have adjusted during their lifespan. This set is also useful for current policies.
Max_effectiveness: This number indicates the maximum number of resources or food that 1 member of a band can hunt/gather in a single day. When the cultural capital of a band allows for it, the band can operate at this maximal effectiveness, meaning the band can gather 90 * group_size * max_effectiveness items per season.

Threshold_location_knowledge: This number shows how many seasons two bands have to be connected to each other before they will start sharing any knowledge. If a connection reaches this strength, the bands will start sharing location knowledge for summer and spring, which are assumed to be the 2 easiest season of the year to gather and hunt. Also, bands will share their technology knowledge, meaning connected bands will get more efficient over time. The threshold for bands to start sharing knowledge on the 2 hardest seasons of the year is always twice as high as the threshold for sharing knowledge for the 2 easiest seasons. Note that strongly connected bands can still stop sharing new knowledge if the bands have lived too far apart for too long.

Decrease_connection: This indicates the number of seasons that it takes before the connection between two bands decreases by 1. If the number is set to 1, this means that every season that two connected bands live too far apart, their connection strength will drop by 1. Note that the strength only decreases when bands are living too far apart.

Cooperation_radius: This number shows how far bands can maximally live apart, for them to still connect to each other, or strengthen their connection. The number is given in “distance” meaning a diagonally adjacent patch will be further away than an adjacent patch.

Mean_cultural_capital: This number shows the initial mean value of the cultural capital of the bands. This parameter is seen as a policy lever, as investing in teaching young member can be a good way of becoming a better hunter-gatherer band. Together with a type of distribution (uniform, normal or poisson) and a standard deviation, the initial cultural capital of each band is decided.

3.3.3 External factors

Next to the policy levers that can be influenced, there are also external factors, that cannot be influenced by the actors in the system. Each of the external factors in the model will be explained in this paragraph.

3.3.3.1 Volcano related parameters

Start_event: This parameter decides when the volcano eruption takes place, measured in seasons. If the number inputted here is larger than the model run, no eruption will take place.

Ash_fallout: This parameter decides the way in which ash is spread around the volcano. The option in-radius will cause all patches around the volcano within a given range to have ash fall. The wind-cone option will focus on historical data and can imitate the actual ash fall of the Laacher See, by creating ash fall in two cones that are based on the wind direction.

Ash_eruption_distribution: This parameter can either be skewed near, skewed far or normal. Each of these settings refers to the way in which ash fallout happens near the volcano. Logically, skewed near means that more ash falls closer to the volcano.

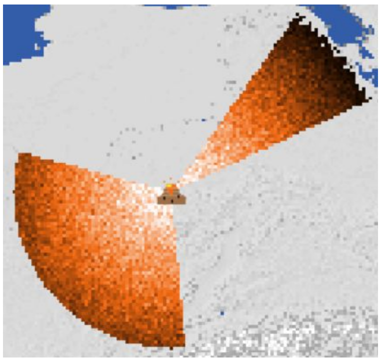
Volcano_eruption_distance: This distance shows how many patches around the volcano are affected by the “lava” of the volcano. This is considered to be very small, as the patch size is relatively big compared to the volcano. If any bands are present in the radius of this distance, they immediately die.

Random_ash_fall: When the ash spread happens with the wind-cone selection, next to the ash that falls within the cones around the volcano, there is also some random spread of ash on the other patches, which happens within a certain radius around the volcano. This parameter indicates the percentage of patches that receive this random ash fall. These affected patches are selected randomly.

Ash_wind_direction (1 and 2): When the ash spread happens with the wind-cone selection, these parameters will select two wind directions for the ash spread which can be set individually. We chose two cones as this imitates the available historic data best.

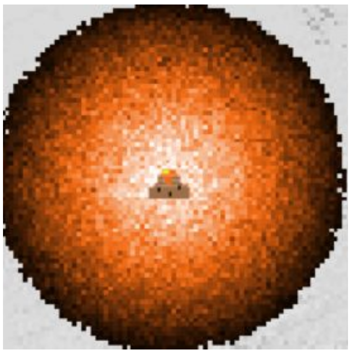
Ash_eruption_distance (1 and 2): These parameters decide how far the ash actually spreads from the center for each of the two cones. The parameter is measured in number of patches.

Ash_eruption_angle (1 and 2): The ash eruption angles are the last parameters that create the ash fall-out cones if wind-cone is selected. They decide how many angles the cone will be in which ash spreads. If both cones have an angle of 180 degrees, and the difference in their heading equals 180 degrees, the ash fall-out will be exactly the same as the fall-out with an in-radius setting.



Cone_impact (1 and 2): As one of the wind directions was much more present during the volcano eruption, the strength of the selected cones can differ, meaning more ash will fall in one of the cones. The strength decides how much the patches within the cone are actually affected by the ash fall-out.

Ash_eruption_radius: If the option in-radius is selected for the ash-fallout, this parameter can decide how many patches far the ash reaches. This parameter is measured in the number of patches.



Mean_ash_intensity: Independent of the way ash fall-out is modelled, this parameter selects the mean of the intensity of the fallen ash. This parameter is used in the normally distributed, skewed-near distribution or skewed-far distribution to decide how much impact the ash has on each of the patches. The parameter can vary between 0 (no impact) and 100 (nothing livable is possible on the patch)

Stdv_ash_intensity: In addition to the mean impact of the ash-fallout, also the standard deviation of this ash-fallout can be chosen, which will only impact the values of impact when the fall-out happens in normally distributed fashion.

Decay_type: After ash has fallen down on several patches, the user can decide in what way this ash impact decays over time. There is a “gradual” option, which creates a linear decay of ash and an exponential decay which creates a situation where the biggest part of ash decays in a short time, but the last parts of ash take a long time to decay. Note that when exponential decay is chosen, the ash impact will become 0 as soon as the impact drops below 1. This has been implemented because the ash impact would never reach 0 on its own.

Volcano_duration_effect: If the type of decay is selected to be gradual, the user can select a time period after which every single patch should be clean from any ash. This means that only patches with a ash impact equal to 100 will require this much time to become clean. All other patches will become clean earlier.

Decay_exponent: If the type of decay is selected to be exponential, the decay exponent can be selected, which decides the shape of the decay distribution. A low value will create a situation where it takes a long time for the ash to decay and a high value will make the ash fade away relatively fast.

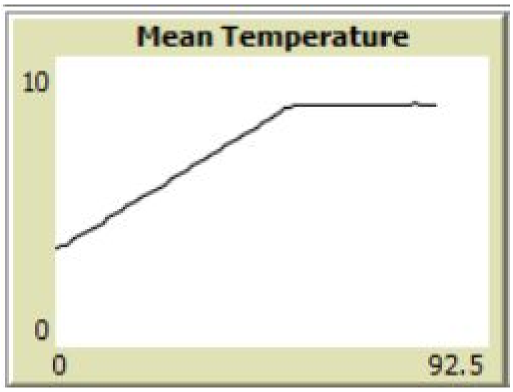
Percentage_ash: Independent of the type of ash-fallout, this parameter decides how many of the patches within the cones or radius actually get affected by the ash at all. If the value is set to 1.00, all patches are affected. This value does not change the intensity of the effect of the ash-fallout.

Impact_ash_on_livability: This parameter decides how much the patches are impacted by the ash-fallout. If the value is set to 1, this means that the percentage of ash impact (out of 100) will be the decrease in growth of resources and food. The lower this value, the higher the impact of ash on livability, as more food and resources will disappear.

3.3.3.2 Climate change related parameters

Max_temp_change / Max_prec_change: If the user chooses to implement climate change into the model, these parameters decide how much the temperature / precipitation will have increased or decreased at the end of the change period.

Environment_delay: If the user chooses to implement climate change into the model, this parameter decides how long the linear increase/decrease of temperature/precipitation takes until it reaches the maximum temperature/precipitation. Together with the max change of the temperature/precipitation, this value decides how intense the climate change will be. The example below shows an increase in temperature of 5 degrees over 50 seasons.



Increase_temp_variation / Increase_prec_variation: Next to the linear change to the height of temperature/precipitation, there is also the option to make the weather more extreme as effect of climate change. These parameters decide how much the standard deviation for the normal distribution of temperature/precipitation will increase. A higher value will cause the temperature/precipitation to become more extreme (both in higher and lower values). The two ways of simulating climate change can be combined.

Variation_delay: As with the linear change, also the increase in variation will happen in a linear fashion. This parameter determines how long it will take before the distribution of the weather has changed to the maximum variation.

GISP2_trend: Next to the manually set climate change, the GISP2 trend will simulate a climate change based on historical data, which will induce a small ice age halfway during the model. If the parameter is turned on, this trend will take place, otherwise the temperature will stay constant. Note that this trend only influences the temperature in the model.

3.3.3.3 Band related parameters

Average_group_size: This parameter decides the mean of the distribution that decides the group size for each of the existing bands. The standard value is 25.

Stdv_group_size: Together with the average_group_size, this parameter shapes the distribution that decides the initial group sizes for the existing bands. The standard value is 5.

Number_of_bands: Although the spawn location for the bands is decided by the amount of existing food and resources on the patches, this parameter decides how many bands will spawn. The number of bands will change the population density, meaning that the impact of connections will change if this number is altered.

Merge_max_size: This value decides when two well connected groups will merge to become one band. The sum of the group size of the two separate band must be lower than or equal to this parameter in order for the two bands to be able to merge.

Split_min_size: This parameter decides when groups that have a large group size are able to split up and become two separate bands. The value shows the minimal group size of the two new bands. As it is assumed that the bands split into two equally sized groups, for bands to be able to split, their group size should not be smaller than twice this parameter.

Standard_birth_rate: In contrast with the death rate of bands, the growth of the bands is standardized. This parameter will be multiplied by the group size at the end of a season to decide the growth. As there is no such thing as 0.6 members, the number is rounded up to an integer.

Maximum_days_moving: As it is assumed that bands need time to hunt/gather, it is important to give them a threshold for the maximum time they are allowed to spend on traveling. This parameter shows how many days a band can spend on traveling within a season, before they have to start hunting/gathering. A higher value will show more mobile behaviour by the bands.

Mobility_size_factor: This parameter decides the influence of group size on the mobility of bands. It is assumed that bigger bands have a harder time to move around, for which this value decides the strength of the influence. A higher value will create a simulation where small bands are much more mobile than big bands, and where bands are more mobile in general.

Resources_tool: This parameter shows how many resources a band needs per band member in order to increase their technology_level by 1 unit. It can be interpreted as the number of sticks needed to create a speer or a bow for one of the members. Note that these resources will only be used if the band has resources left after using the needed resources to be able to survive.

Max_shared_locations: This parameter decides how many of the known locations bands can actually share with connected bands. As it is not likely that bands are able to share their full knowledge on Europe with each other, this value will limit the memory and ability to share information. A higher value will create a simulation where bands are able to share more information.

Stdv_cultural_capital: This value decides the spread of initial cultural capital values. Together with the mean cultural capital, it designs the distribution that decides the actual initial cultural capital values. A higher value will create a simulation where the cultural capital is greatly different across the existing bands.

Cultural_capital_distribution: This parameter decides the distribution that is used to create the initial cultural capital. It can be normally distributed, for which it will use the standard deviation of cultural capital, poisson or uniform, for which it only uses the mean cultural capital.

Cultural_capital_mutation: This parameter decides how much the cultural capital of bands will change over time. For each season, the new cultural capital of a band is pulled from a normal distribution, which has a mean equal to its previous value and a standard deviation equal to this parameter. Higher values will create more extreme changes of cultural capital over time.

3.3.3.4 Environmental parameters

Optimal_temperature / Optimal_precipitation: These parameters show the optimal circumstances for food and resources to grow in Europe. When a certain patch has both the optimal temperature as well as the optimal level of precipitation, it will grow the most food and resources possible. For the food and resource growth calculation, both temperature and precipitation are weighted equally. The further away the temperature and/or precipitation is from the optimal values, the less livable the patch will be.

Max_food_patch / Max_resource_patch: If a patch has both the optimal temperature as well as the optimal precipitation level, the patch will have available food/resources equal to these parameters. There is a linear decrease in availability when the circumstances are worse than optimal, in each direction (lower than optimal or higher than optimal). These parameters also decide the barrier for food and resources that grow back over time. The available food/resources can never exceed these parameters.

Max_deviation_temp / Max_deviation_prec: These parameters decide how far away the temperature/precipitation can be from the optimal temperature/precipitation to still have some growth of food and resources. The higher the value, the larger the geographical area where growth can take place. If either the temperature or the precipitation is further away from the optimal value than the max deviation, no growth will take place at all.

Max_altitude_food_available: As circumstance can get more extreme at high altitudes, this parameter can give a maximum value at which food/resources can still grow. Every patch that has a higher altitude will have no food or resources whatsoever.

Growback_rate: This parameter decides how much food and resources are added to the patches at the beginning of a season. The **lower** this value, the faster a patch can return to its optimal state. The growback rate parameter is the denominator that makes sure only a part of the food and resources returns to the patches. The numerator is the amount of food/resources that would have existed on the patch during the setup (look at Max_food_patch/Max_resource_patch and Optimal_temperature/ Optimal_precipitation).

3.4 Model verification

For the verification, the states of the agents are assessed. Adjustments were made to each of these states to be able to view their influences on the system. If an unexpected result occurs to the system due to the state change, that part of the model is reconsidered and changed are made when needed. Note that these verification steps were taken at what was assumed to be the final model. During the building of the model, many more mistakes were made and corrected. These can often be seen as comments in the Netlogo code or in commits in github, which adds trust in the code to be able to reach its goal.

3.4.1 Setup

- Correct implementation and reading of the GIS data by NetLogo. **False**. The problem is that some datasets use widely different coordination systems. This is fixed by creating consistency between the different datasets. **Correct.**
- The agents should only spawn in locations where food is available: If the optimal temperature is set to a lower value, the agents should spawn more to the north of Europe. **Correct.**
- Ireland held only 1 band of hunter-gatherers as there was no traffic from the mainland yet: Visual inspection. **Correct.**
- The food available on patches should never exceed the maximum food available: ask max-one-of patches [food_available]. **Correct.**
- No bands should spawn in the ocean: Visual inspection. **Correct.**
- Bands should have knowledge about their spawn location in summer: Visual inspection: **Correct.**
- Bands need 90 food units per member per season: print food_needed = 90 * group_size. **False.** Problem: the food_needed is only updated at the beginning of a tick, meaning the reported value can be wrong if the group_size changed last season. Solution: Changed the location for updating variables to be sure: **Correct.**

3.4.2 Agent characteristics and interactions

- Technology level should never exceed cultural capital: run several times and halt if this would be the case. **Correct.**
- Bands with an effectiveness level lower than 1 should decrease in group size after a season. Visual inspection: **Correct.**
- Unlinked bands should be their own community. Visual inspection: **Correct.**
- Bands can own resources after a season but not food: Visual inspection: **Correct.**
- When bands split, both the mother and child have the same properties, including links: **Correct.**
- Bands share information when their connection is strong enough: **False.** Problem: when large networks arise, some bands will have knowledge on all of Europe. It is not logical that a band can remember food and resource distributions for 4 seasons for all of Europe. Solution: Bands can share only up to 50 locations and will only remember location up to their cultural capital level. **Correct.**
- Ensure that hunter-gatherer bands are not able to spend more time than they are allocated. **False**. The move function still allowed them to get out even when they should not have the time to so. Fixed it by catching this in an if-else statement so it does not happen. **Correct**.
- Make sure that agents follow a clear and logical movement pattern based on food and resource availability. **False.** There was old code used for testing purposes which had a random walk. This has now been removed. **Correct.**
- Hunter-gatherer bands are not able to go over water. **Partially correct**. When the water body area to the next land patch is small, hunter-gatherer bands are still able to ‘skip’ over water. This is kept in the model because small distances are in theory possible.

3.4.3 Impact of environment

- Patches that have a lower ash impact should return to their stable state sooner: Visual inspection: **False.** Problem: Ash depletion happens based on percentages, meaning all patches will slowly converge to the same depletion rate. Solution: change ash decay into either gradual depletion or exponential: **Correct.**
- After all effects of the volcano and its ashes have depleted, no more bands should get impacted by the volcano. **False.** Problem: Impacted bands can still split after getting impacted which increases the number of affected bands. Solution: Set to the number of impacted bands after all impact of ashes is completely gone, meaning the value will be constant from that point onwards.
- Bands should slowly move back to the patches that were once impacted by the volcano. **False.** Problem: the food and resources do not raise back up to their regular state but remain as low as during the ash-fallout. Solution: reset the food and resources availability when all ash has faded away. **Correct.**
- In case the in-cone option has been chosen, random ash should fall within the distance of these cones. **False.** Problem: Some patches are indeed affected, but before the ash fall can have an effect on the patch that it is on, the ash disappears. Solution: change the order in which impacted patches receive the corresponding effect and when ash disappears. **Correct.**
- If GISP2 is turned on, there should be an ice age starting around 120 ticks. **Correct**
- If temperature were to rise by 5 degrees, bands would die after a while more than normal. **Correct.**
- The patches that are affected by the ash the most, should return to their normal state after approximately 24 seasons. **Correct.**

3.5 Model validation

For the validation, the correspondence between the model outcomes and real-world phenomena are assessed. This will be done by considering two perspectives related to validation (Wilensky & Rand, 2015).

1. Different levels of aggregation of the validation process
   This includes microvalidation and macrovalidation. Microvalidation is analysing whether the behaviors and mechanisms of encoded in the agents are similar to real-world behaviours. Macrovalidation is ensuring that aggregate, emergent properties of the model correspond to those in the real world.

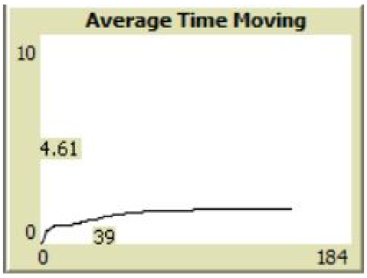
2. Different level of detail of the validation process
   Here, face validation and empirical validation are relevant. Face validation checks whether mechanisms and properties of the model look at real world mechanisms and properties. Empirical validation checks whether model outcomes resemble real-world data.

It is important to note that there can never be full validation in the models of complex systems such as the hunter-gatherer model. All models are wrong to some extent, as they are simplifications of reality. Still, it is important to have at least a minimum level of validation for the model, to make sure that the users of the model and the readers of the results can relate well enough. The biggest part of validation during this project happened during the meetings and check-offs with Professor Felix Riede. The notes that were created during these meetings can be found in appendix 2.

3.5.1 Microvalidation and Macrovalidation

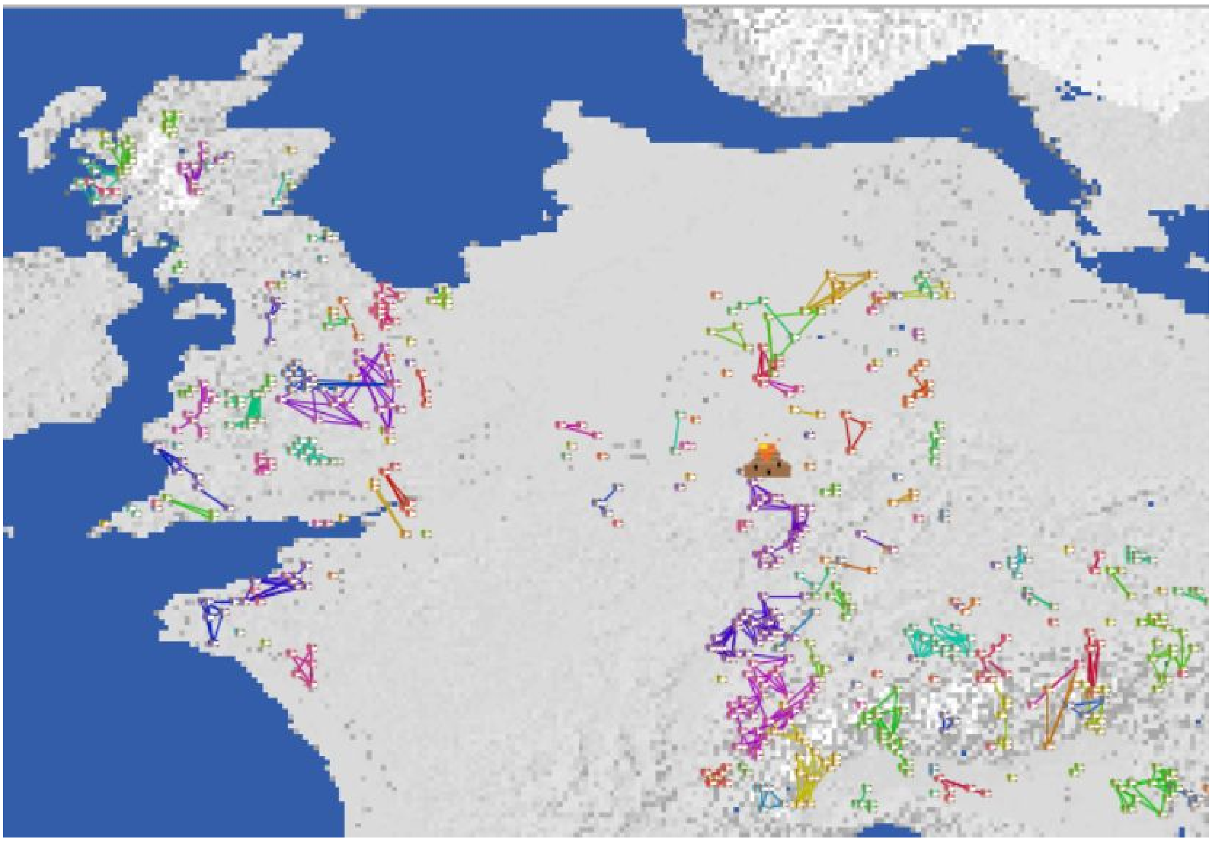
As it is very unclear how hunter-gatherer actually behaved 13,000 years ago, it is hard to perform a clean validation, however, the behaviour has been related to underlying assumptions to see whether the model represents what is thought to be realistic behaviour.
For the model as a whole, the locations and interrelations between bands will be inspected. Also, the opinion of Professor Riede has been taken into account for this type of validation.

When looking at a single hunter-gatherer band, it would make sense that the band will move to another location more often than not. As the growback rate of food and resources will eventually be slower than the growth of the bands, there will be a point in time where the band needs to move elsewhere to find their needs. The movement has been tracked to show this property of the hunter-gatherer bands. What can be seen in the figure below is a constant moving behaviour of the bands, which increases slightly over time. This happens because the number of bands also increases, meaning the bands have to compete for the available food and resources, which makes movement necessary. When climate change is active, the movement will take an even bigger part of the bands' activities as more and more patches will lose their livability.



As hunter-gatherer groups will survive only in the most flourishing areas of Europe, their home locations should be focussed around livable areas, meaning areas with a relatively low altitude, a temperature close to the optimal one, as well as a precipitation level close to the optimal level. Moreover, bands should not be able to stay connected to other bands that have moved far away from them, but shape clusters with the bands close to them. Also, the flourishing locations in Europe will create opportunity for the bands to keep on growing and splitting. This is why some locations are densely populated and others seem to be completely empty.

Around the time of eruption of the volcano, the population density in the affected areas drops as band either die or move away from the affected patches. As the ash disappears. the groups slowly return to the livable patches that were once covered in ash. This shows what is assumed to be real behaviour by the bands.



3.5.2 Face Validation and Empirical Validation

As there is not much data available on the behaviour of the hunter-gatherer bands 13,000 years ago, again the validation relies mostly on the expert opinion of Professor Riede and the comparison between assumptions of the behaviour and how the model behaves. Something that can be empirically validated, is the location of the Laacher See volcano, which has been found in Bogaard & Schminke (1984). is the ash-fallout patterns that can be compared to the evidence found at archeological sites as has been aggregated in Reinig et al., (2020). In Figure 6, the ash-fallout from this paper can be compared to the modelled ash-fallout. Also, the weather pattern around the time of the eruption has been based on the methane concentration data, which is empirically validated. A third characteristic that can be empirically validated, is the temperature across Europe, where the northern parts are colder on average. Besides the mentioned characteristics that can be empirically validated, the level of reality of the model relies on micro and macro face validation. These characteristics include population densities, group sizes, ash effects, connected clusters and actual effects of the volcano eruption and climate change.

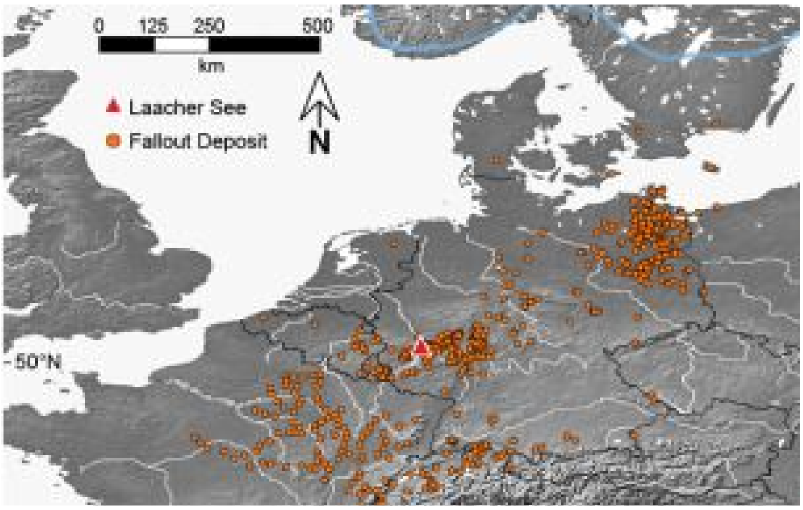
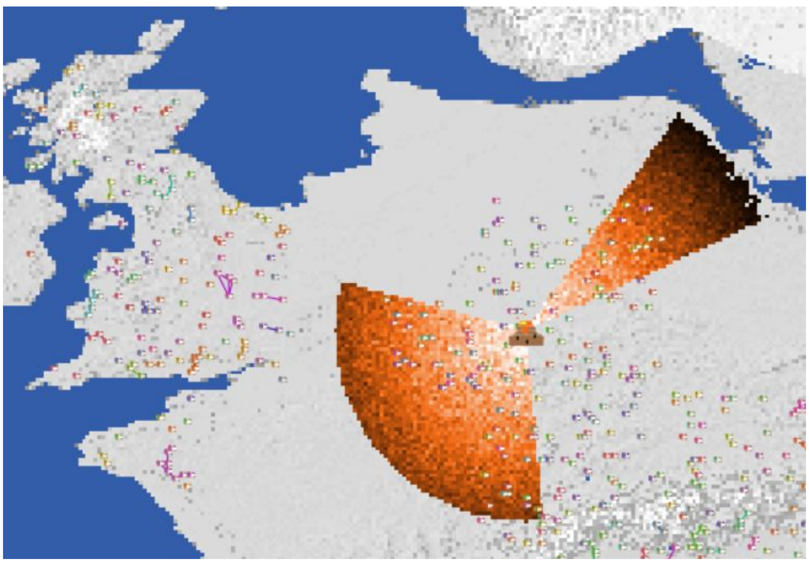


Figure 6: The spread of the Laacher See eruption ash-fall (Reinig et al., 2020 p2).



4. Results

The results section explores the model using experiments under different circumstances. First, the parameter spaces will be defined to get an overview of the experiment recipe. The results of these experiments will be also analyzed, generating an answer to the research question.

4.1 Setting base parameters

As it is not viable to change every single parameter that the model relies on, it is important to have a well considered base value for each of the parameters. If this base value is over- or underestimated too much, this can change the model in such a way that the altered parameters will not show any impact on the model, as the extreme value of one of the parameters is too large/small. An example could be the maximum food available on a patch. If this number were to be set to 0, no life is possible at all, meaning all runs would end into a bandless world, independent of the other parameter settings. This paragraph will explain the base values created for the parameters that will not be changed during the experiments.

Population size

As the optimal temperature and precipitation will decide the spawn location of bands, only livable patches will sprout bands. By visual validation, the spawn locations have been altered to match the findings of Bocquet-Appel et al. (2005), which can be seen in Figure 7. This is a way around to find exact relationships between food production and livability. By altering the optimal circumstances, to match the spawn locations, we have calibrated the optimal temperature backwards.

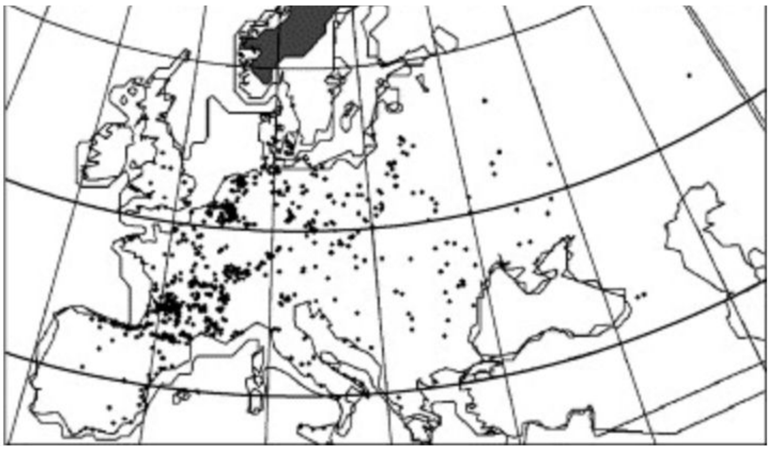
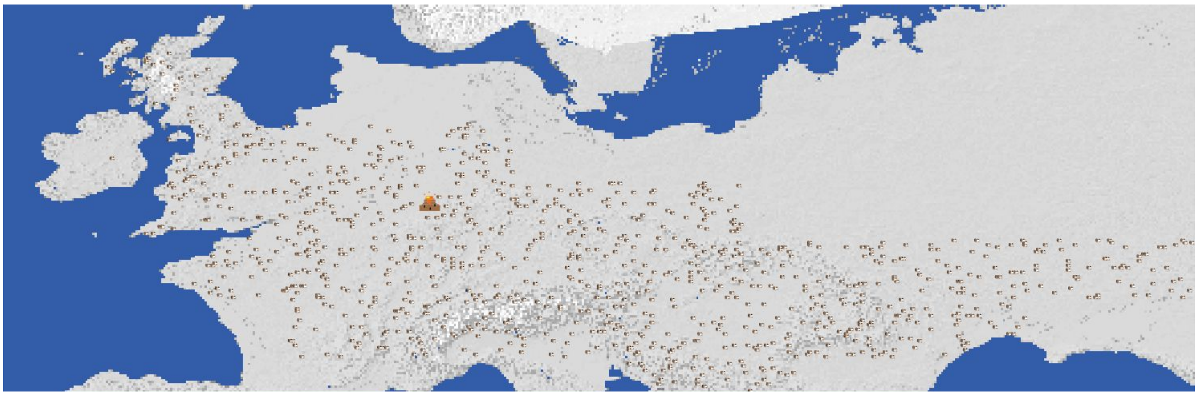


Figure 7: The spread of hunter-gatherer bands (Bocquet-Appel et al. 2005 p1657).



The initial size of the hunter-gatherer groups is based around an average of 25, with a standard deviation of 10, which is based on Wobst (1976) and Hassan (1975). These numbers will remain stable during experiments, as they will change and stabilize during the run, which means small tweaks to the initial number will not have much impact. Also, if large bands would like to split, the minimum size of the two new bands should be equal to or higher than 25, meaning only bands of size 50 and above are able to split.

Considering the size of the population, the findings of Bocquet-Appel et al. were also used. According to these findings, the total population in Europe ranges between 11,300 and 72,600 in the Late Glacial, with an average set on 28,736. Because of the average group size of 25 members, with a standard deviation of 10, to match these findings, the following number of bands is needed:

- 500 hunter-gatherer bands is on average ~12500 members
- 1000 hunter-gather bands is on average ~28000 members
- 2900 hunter-gatherer bands is on average ~72000 members

Considering these numbers, the number of bands should vary between 500 and 2900. However, due to limitations in computational power, the number of bands will be limited in the experiment setup.

Population growth of hunter-gatherer bands were rumored to be between 0.001 percent and 2.7 percent (Hassan, 1975). While most of the range could be explored, it is more interesting for the model to create a stable population growth in order to see the effects of the compound events. It is set on 2.5 percent.

Population characteristics and needs

The number of resources needed to survive, needed for an upgrade in technology level and the number of resources available and that grows back, are only relative to each other. This is also the case for food. That is why their exact values do not matter, but only their relative values. As has been stated in the assumptions, the best available patch will have enough food to support an average band for a year, which is a value of 9000 (25 members * 4 seasons * 90 units per season). For the resources, the best available patch will be able to support an average band for 1.5 years (25 members * 6 seasons * 30 units per season). Considering the growback rate of both food and resources, the base value is based on one where the food and resources are stable in normal circumstances (without climate change and the volcano eruption). This means that every season approximately 12.5% of the food and resources will grow back until a maximum value has been reached. This value also depends on the environment. For a technology upgrade, bands will require 45 units of resources per band member. This value is half the needed food per season, and requires bands to have spare time after exploring, moving and hunting/gathering.

The cultural capital distribution will be set to a normal distribution with a mean value of 50 (out of 100) and a standard deviation of 25. The bands with a low value might die out early in the model because of this base value, which will only show the importance of cultural capital under different scenarios or policy interventions.

The mobility of bands, or the ability of them to move around easily, is based on many factors according to literature (Mandryk, 1993), such as the size of the band, but also environmental factors such as temperature, precipitation and the livability (in terms of available food and resources). In the model, this mobility is based on size, ruggedness of the area, and relative altitude of the area. Next to these values, a small personal mobility skill is added to represent differences in mobility between different bands. The impact of differences in livability on mobility are represented indirectly by the ruggedness index, the altitude and the mobility skills of bands.

Environment
The maximum altitude at which food and resources can still grow is set to 2500m, which is based on the maximum altitude where people are living nowadays, which is 2480m (https://www.wikiwand.com/en/List_of_highest_towns_by_country). Although resource exploitation might still be possible at high altitudes such as mining (West, 2002), the model would require bands to live in such areas, which is unlikely.

The effect of the volcano eruption will be present 6 years (24 seasons) after the eruption at most, which is based on Kaiser (1993). Note that this is the maximum duration, and that the ash effects of many of the patches will have faded away before this time.

The way in which this ash fades away (decays) will be exponential in the base case. Based on the findings of Pyle (2016), the model biggest part of the ash will decay the fastest, while the last remaining bits of ash will take a long time to decay.

The ash fall will be most intense near the volcano, and will drop to lower impact the further it falls down from the volcano itself. This skewed near distribution is based on Scheidegger and Potter (1968).

As has been stated in the validation chapter as well, the volcano location and ash-fallout have been based on Bogaard & Schminke (1984) and Reinig et al., (2020) respectively. As the ash-fallout cone facing to the north-east was much stronger, the impact of the ash-fallout in that direction is set to 1.4 times the strength of the cone facing towards the south-west.

4.2 The story to be told

While altering parameters to see their impact on the different characteristics of the model, it is important to have a clear view on which parameters are most important for the behaviour of the model. This story should be based on the model narrative. The hunter-gatherers have 3 different strategies of surviving. The first one is to have great skill at hunting and gathering. By being able to harvest more units per band member per day, the band requires less time to harvest their needs and have more time to explore, move and prepare for future seasons. The second strategy is to cooperate with other bands and gain as much knowledge as possible. This would mean being able to move to locally optimal patches, but also improve the skill of hunting and gathering by learning from other bands. The third option is based around mobility and will create a simulation where bands travel a lot, without losing much time. During the experiments, it is important that these 3 strategies are all tested to find out the relative importance of each of them. Although there are many more parameters that can influence the survivability of the bands, the three aforementioned strategies are the minimal set of parameters that should be tested to find useful results.

On the environmental side of the system, the presence and timeliness of both climate change and the volcano eruption are of importance to create useful results. Although there are many parameters that can change the effects of both climate change and the eruption, the minimal parameters to be altered are the presence of the two environmental impacts.

4.3 Experimentation

The experiments are run through the BehaviorSpace of NetLogo. BehaviorSpace allows a parameter sweep using the conditions set. The parameters in Table 2 will be altered during experimentation along with their respective values. The bold values are the standard values that can create a base case scenario. In the last column, the reason for adding the parameter is given to the experimentation space. As can be noticed from the table, not all parameters are policy levers that were discussed in chapter 1. The other parameters will be interesting to establish the influence of external factors on the system and will show how the system reacts in different scenarios. Also, a lot of parameters are missing from the experiment setup, which is the result of fastly growing computational time when more factors are added to the scheme. In a later stage, more parameters should be added to the experimentation, to find the most valuable results. This first experiment setup will give a first insight in the relative importance of the strategies used by the bands, in different climate scenarios. Note that the start_event parameter can be interpreted as either including a volcano or not.

Table 2. Parameters used in experimentation

Parameter	Values	Explanation
max_effectiveness (policy lever)	[2 - **6** - 10]	If bands were to have invested in their efficiency to hunt and gather, this could

		create a higher survivability. This parameter will show the relative importance of skill.
cooperation_radius (policy_lever)	[1 - **3** - 5]	This parameter focuses on the cooperation and sharing of knowledge between bands. It will show the relative importance of working together and acquiring knowledge.
maximum_days_moving (policy lever)	[10 - **30** - 50]	This parameter will show the relative importance of the ability to move around easily.
start_event	[**120** - 240] (On or Off)	Altering the starting time of the volcano eruption will show how important it is for bands to be fully prepared for such a shock. Also, the situation where no volcano erupted at all will be analysed.
GISP2_trend	[**On** - Off]	Turning the existence of climate change on or off will show the impact of the stress of low temperature on the survivability of the bands. Together with the volcano eruption, this will create 4 possible situations: stable model, only climate change, only eruption, compound event.

In order to minimize the presence of chance in the analysis. For every parameter setting, multiple replications are completed and only the mean value over these replications is reported. For this experiment setup, every set of parameters will be ran for 10 replications. The more optimal setup would require more replications per set, as the model is influenced by many randomized variables and path dependencies. The graphs show what happens to each of the KPI's because of a change in one or more of the parameters. To make sure that the results stay clear, not all of the aforementioned KPIs will be analyzed, but only a subset. This subset exists of KPIs that give the most insight in the model. Table 3 gives an overview of the analyzed KPIs and the reason for taking it into account.

Table 3. KPIs examined in experimentation

Key Performance Indicator (KPI)	**Explanation**
Total population	The total population is the product of the band sizes and the number of bands which gives a clear indication of how well the hunter-gatherer bands are doing in terms of survivability.
Average difference between cultural capital and technology level	The technology level indicates both how well the bands are handling their resources as well as the level of cultural capital amongst the bands. It could be an indicator of the loss of technology for impacted bands.
Average number of known patches	This indicator shows how well the bands are working together with each other by looking at the knowledge of the bands. A higher value would mean a better cooperation. It also shows the amount of exploration by the bands, which would increase their knowledge.
Total movement per band per season	This indicator shows how much bands are moving around the area. This can either show that the existing bands are very mobile, or that they have no choice but to travel in order to survive.
Total number of clusters per band	Next to the knowledge about locations, also the number of clusters can indicate the cooperation between bands across Europe. A high number of clusters would mean that the bands are rarely connected.
Total effect of volcano	This adds the number of deaths by the volcano to the number of deaths due to a decrease in livability of the affected patches. It will show the effect of the volcano on the bands directly, but also indirectly via a halt in technology level that causes the effectiveness to be too low for affected bands, and thus unable to survive.

4.4 Data analysis

In this section each of the parameters named in table 2 of section 4.1, will be investigated and the results of the adjustments to these parameters will be discussed. For every parameter, the KPI's named in table 3 of section 4.1, are shown in a graph so the influence of that particular parameter on the different parts of the system becomes clear.

4.4.1 Optimal hunter-gatherer band strategy in different scenarios

As has been mentioned before, hunter-gatherer bands can take on three different strategies to survive. This subparagraph looks at which of these three is most optimal for survival and growth. Investment in “knowledge and connectivity”, “skill and efficiency”, and “mobility and movement” will be linked to the total population size and the extent to which bands are able to reach their potential in terms of cultural capital. It is also important what the effect of environmental factors is on the effect of the different strategies. In this subparagraph, each of the strategies will be tested in different environmental scenarios. Table 4 shows the different scenarios that are used in the analysis:

Scenario name	**Model settings**
Base case (BC)	No eruption, no climate change (0 0)
Volcano eruption (VE)	Eruption, no climate change (1 0)
Climate change (CG)	No eruption, climate change (0 1)
Compound event (CE)	Eruption, climate change (1 1)

Table 4. Scenarios and model settings

To cover the effect of different scenarios, violin plots have been created that show the final value for the total population of the corresponding runs. Also the varying total population during the run has been plotted. Together they give an insight into how well the bands are flourishing while using different strategies. In the following plots, the legend will remain as follows:

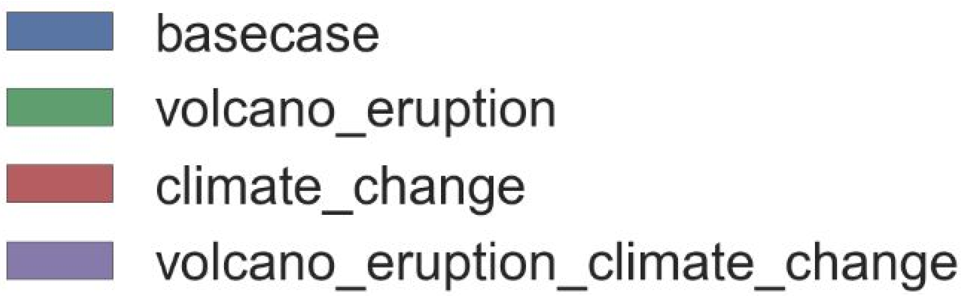


Figure 8: Total population varying over time (1 tick = 1 season)

Figure 8 shows the total population of Europe over time, for the 4 different scenarios. The figure shows both the average population over all runs that and also the standard deviation around this average. Note that each line in Figure 8 represents 270 different runs. The overlap of both mean values as well as standard deviations show that the model is relatively consistent in terms of behaviour. Only when extreme events happen, the behaviour changes drastically.

Both the impact of the volcano eruption (green and purple charts) as well as the impact of climate change (red and purple charts) can clearly be seen. As the volcano erupts on tick 120 (blue vertical line), the impact of the volcano can also be seen from this point on. The “ice age” also happened approximately during that period, which confirms the decrease in population around 120 ticks when climate change is simulated. The significance of the extreme events can be seen in Figure 11 and 12, which show the significance of the difference of the runs without the eruption, and runs with the eruption. Noticeable is the return of the eruption scenarios to the regular scenarios after approximately 25 ticks, which is the actual duration of the eruption effects. The hunter-gatherer bands are able to return to their stable state immediately after the volcano effects have been depleted completely.

Note that the total population in general is higher when climate change is turned on. This can be explained by the under calibration of the base case model. As can be seen in Figure 9, the inclusion of climate change will create a raise in food availability, which leads to an increase in population. This increase points out that the GISP2 trend differs from the temperature distribution that is loaded from the GIS file. Still, the behaviour shows that both the volcano as well as climate change have a negative impact on the total population. However, the graphs also indicate an increased growth rate of the population after the effects of the volcano and climate change have disappeared. This shows adaptive behaviour by the bands, which could be explained by the necessary movement for the bands, in combination with the survival of only the “strongest” bands, for which offspring will also be “stronger”. Another interesting behaviour which can be seen in Figure 9 is the shifting of food availability over seasons. The constantly oscillating values represent the seasons.

Both the difference in model settings for GISP2 and GIS, and the adaptive behaviour can be concluded from Figure 10, which shows the significance of difference in values over the two different scenarios. However, at the end of the run, the significant difference returns. This can be linked to the growth-rate of the population that outgrows the growth-rate of the population in the base case. The GISP2 temperature data seems to be more closely related to what we deemed perfect circumstances for food and resource growth. The lack of significant difference during the ice age can be explained by the lack of ice age in the base case. As the generally higher population is affected by the ice age, it drops to the level of the base case, which suggests that the two runs are the same from that point in ticks. However, this lack of significant difference is a coincidence, as the behaviour of the runs does differ.

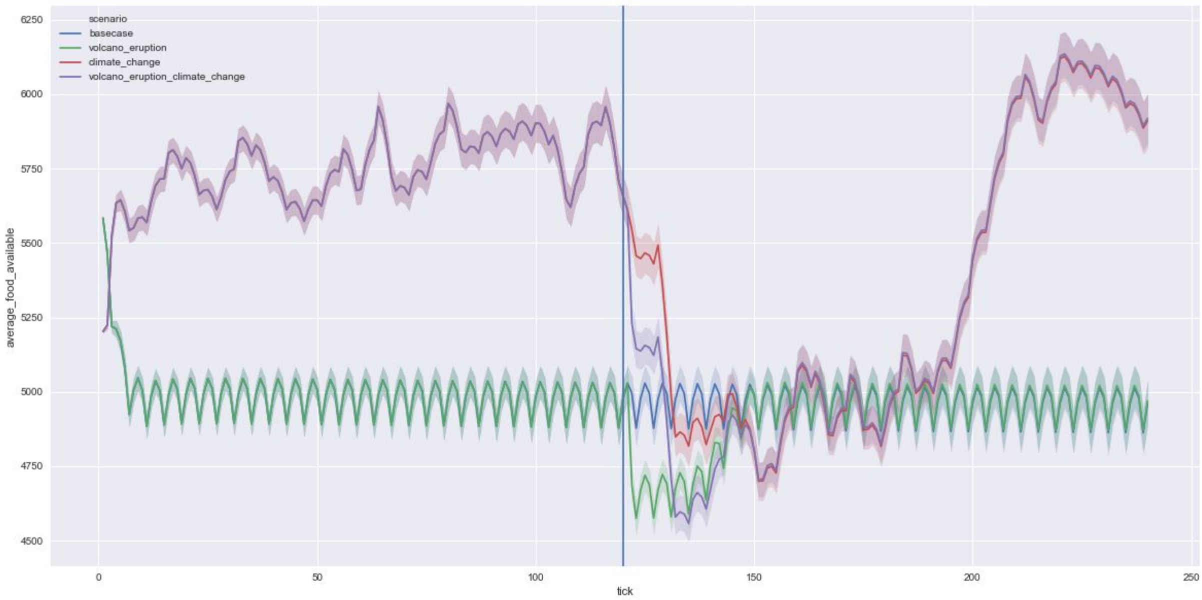


Figure 9: Average food available varying over time (1 tick = 1 season)

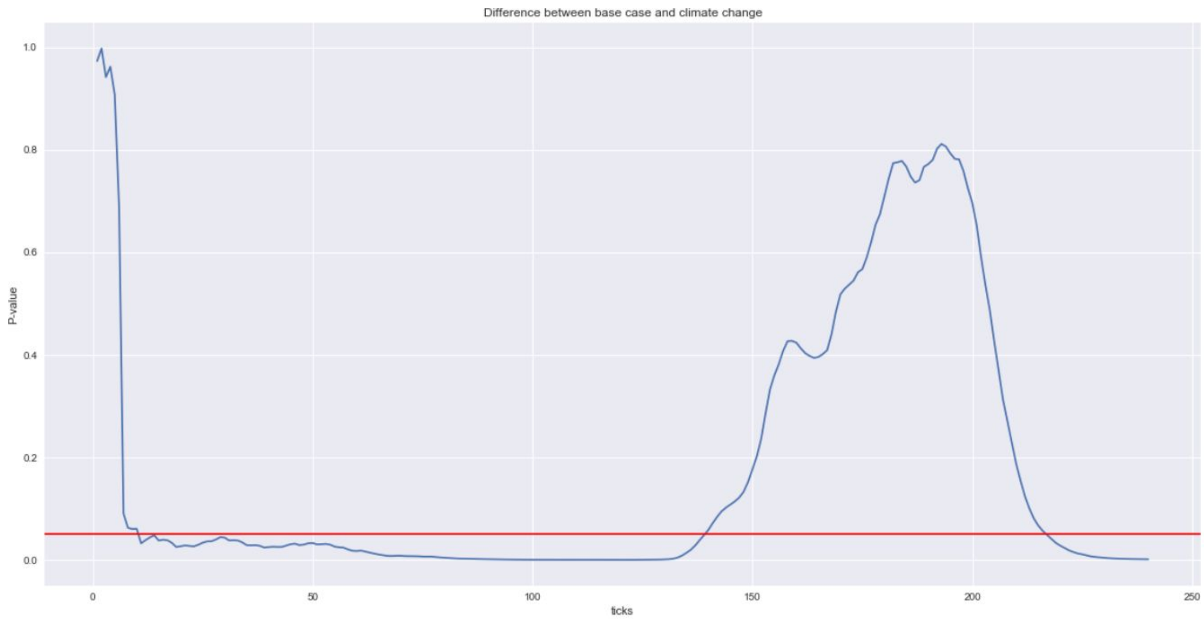


Figure 10: Significance of difference between base case and climate change scenario over time (1 tick = 1 season)

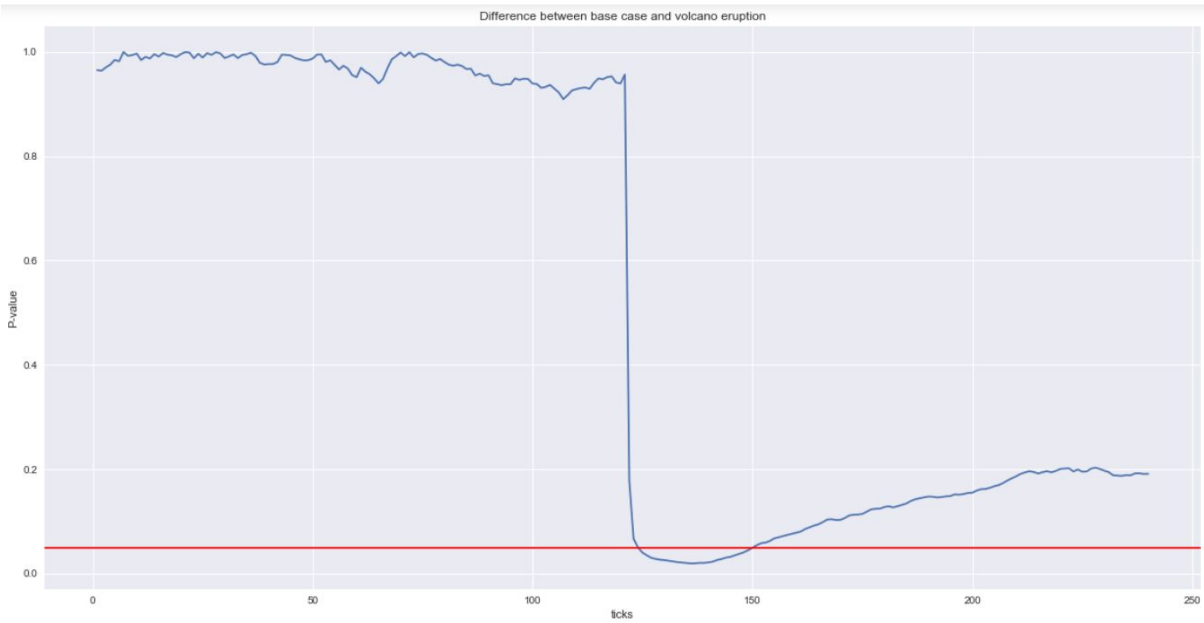


Figure 11: Significance of difference between base case and volcano eruption scenario over time (1 tick = 1 season)

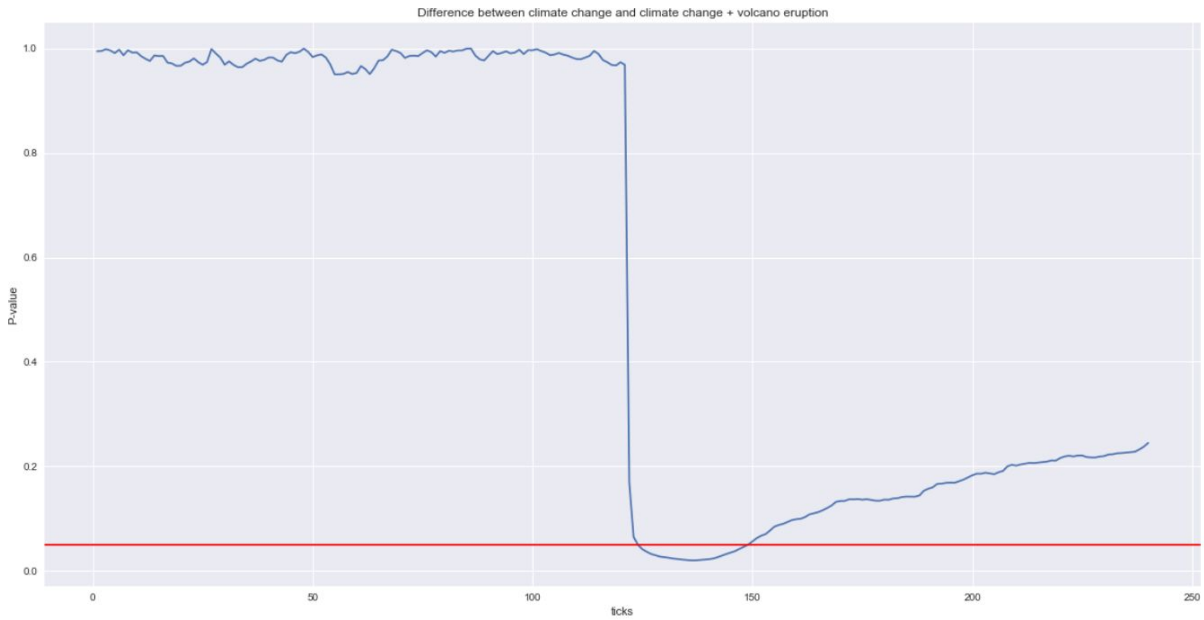
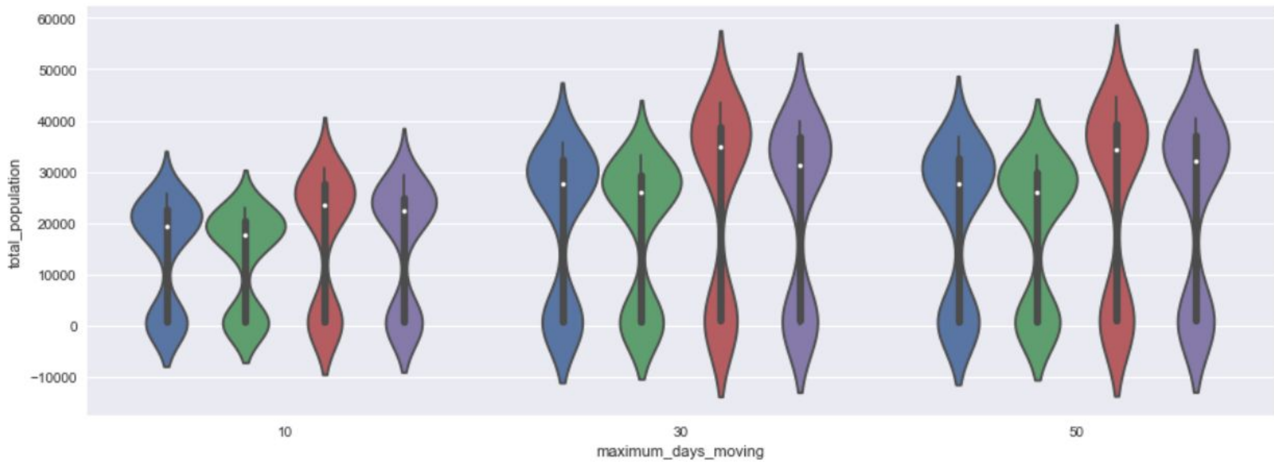
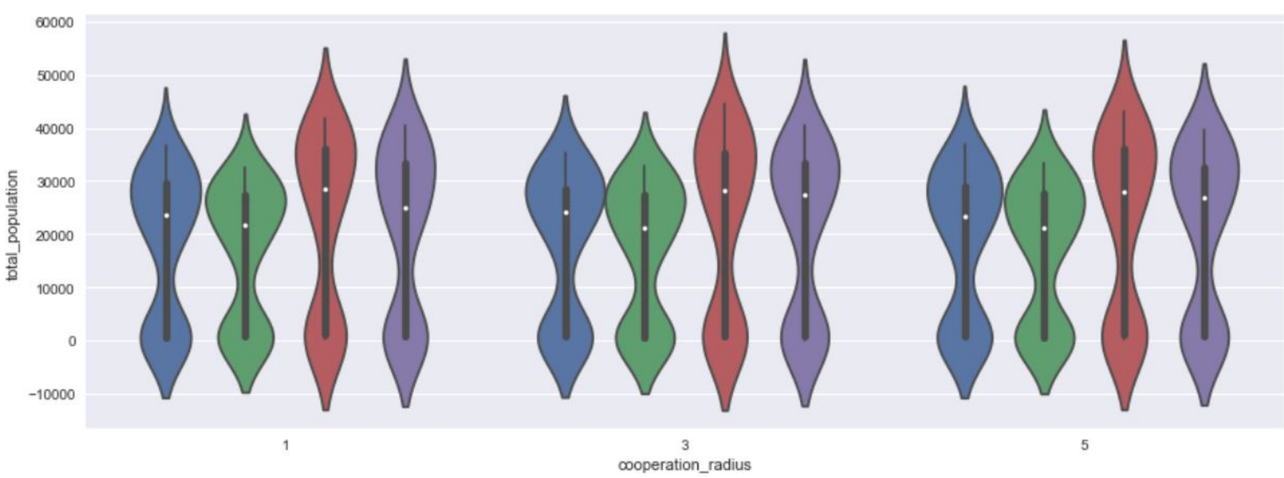


Figure 12: Significance of difference between climate change and compound events scenario over time (1 tick = 1 season)





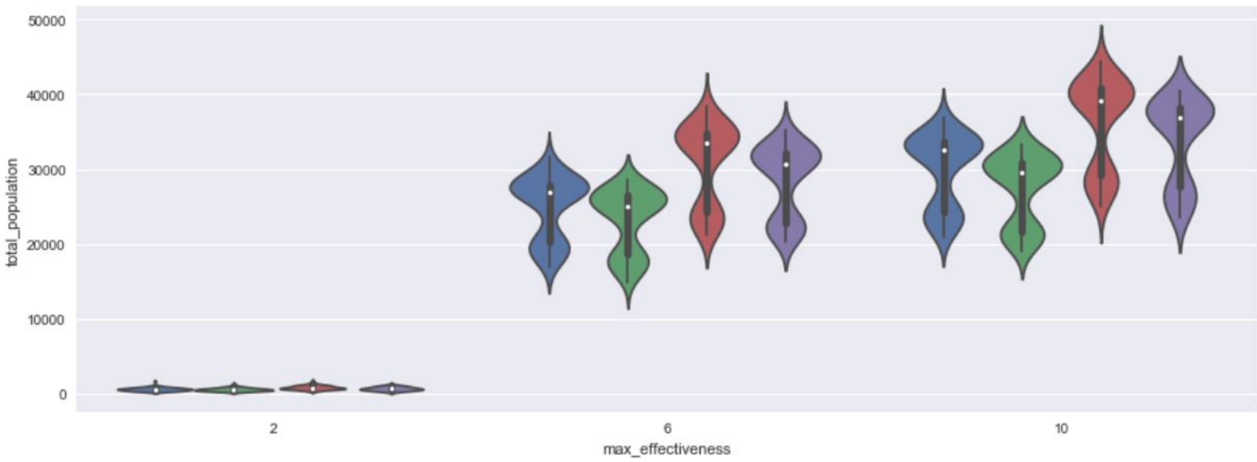


Figure 13 a, b and c: Effect of different strategies on the population growth (violin plots)

The violin graphs in Figure 13 show the mean values of the total population at tick 240 (end of the run), across the different scenarios of table 4, for different values of the policy levers: “maximum_moving_days”, “cooperation_radius” and “max_effectiveness”. The graphs show little difference in population size when the bands’ ability to cooperate is altered and also when the bands’ maximum time to move is altered. Only an increase in maximum effectiveness shows an impact on the total population, which is not able to survive when the maximum effectiveness is equal to 2. The plots suggest that investing in skill and efficiency is the way to go for hunter-gatherers and they could ignore cooperation with other bands and also mobility. This finding can be generalized across all researched scenarios. However, it is important to keep in mind that the maximum effectiveness value is relative to the available food and resources on the patches, as well as the needed food and resources to survive. The significance of investing in effectiveness can be caused by the overestimation of the effectiveness in general. Still, the absence of a significant impact of the other two strategies remains the same, meaning that the bands will find a way to survive on their own, without having to move far away from their current home.

Note that although the graphs show a possibility of a negative population size, this is only due to the way the violin plots are printed, as no negative value is present in the raw data.

The violin graphs also indicate that there is no significant difference for the success of a certain strategy in each of the scenarios. As the population is always higher in the climate change scenarios, this can not be linked to the strategies used to survive. It can be concluded that only skill can make a difference in survival for each of the scenarios, and that both cooperation and knowledge investments as well as mobility and movement investments do not change success whatsoever.

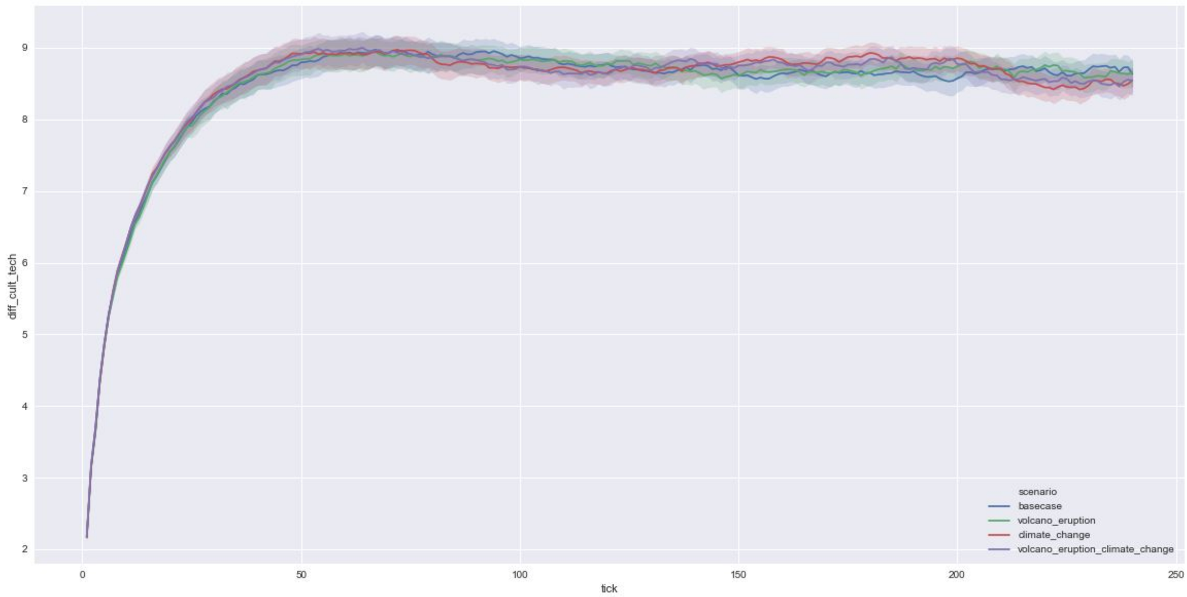


Figure 14: Potential effectiveness and achieved effectiveness

Next to the total existing population, it is also important to look into the extent to which hunter-gatherer bands were able to reach their potential effectiveness. Figure 14 shows the extent to which bands are able to reach and remain their potential effectiveness. It also shows the impact of climate change and the volcano eruption to this extent. It can be stated that the impact of both climate change as well as the volcano eruption have no effect on the extent to which bands reach their potential effectiveness. In each of the scenarios, the bands operate on approximately 10% lower than their potential, which is caused by the mutation in cultural capital and the lack of resources for the bands to be able to craft additional and more effective tools. In terms of lost technologies caused by the extreme events, no loss can be identified.

4.4.2 Smooth movement across Europe

Next to the survival and growth of the population and the extent to which bands are able to reach their potential cultural capital, it is important to look at the movement and knowledge of the hunter-gatherer bands. As the relations in the model are complex it can not be assumed that investing in movement will create more movement. Therefore, plots have been created that show the increase in knowledge and movement for investments in cooperation or mobility. Both Figure 15 and 16 distinguish the 3 aforementioned strategies of the hunter-gatherer bands and show how the use of these strategies changes the behaviour of the bands. For each scenario, independent of the other parameters, only the runs with the max value of each of the strategies is taken into account. For example, to check the importance of cooperation, we take only runs where bands can connect to other bands of maximum 6 patches away.

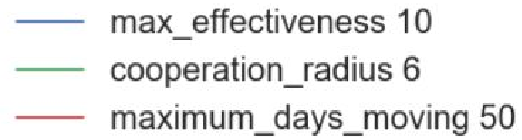


Figure 15 shows that bands will have a larger set of known locations when they are allowed to move further or when they can cooperate with bands that are further away from them. Although this knowledge can not be used as much as the skill strategy in order to survive, this figure does show the importance of mobility and cooperation for the knowledge of the bands. If the model would be altered to nerve the importance of skill, this behaviour might be more present. Figure 16 shows when bands are allowed to move around for a longer time period, they will do so. This shows that cases exist where bands can survive if they are allowed to move further away within a season. Again, if max effectiveness would be calibrated to be less impactful, these figures show that the model does create value for both mobility and cooperation. Moreover, both climate change and the eruption can be seen in the movement of the bands. RIght after the impact of the volcano (and the start of the ice age), the bands have a sudden increase in movement, which represents their fleeing from patches that are impacted by ash. The loss of knowledge due to the extreme events can not be seen.

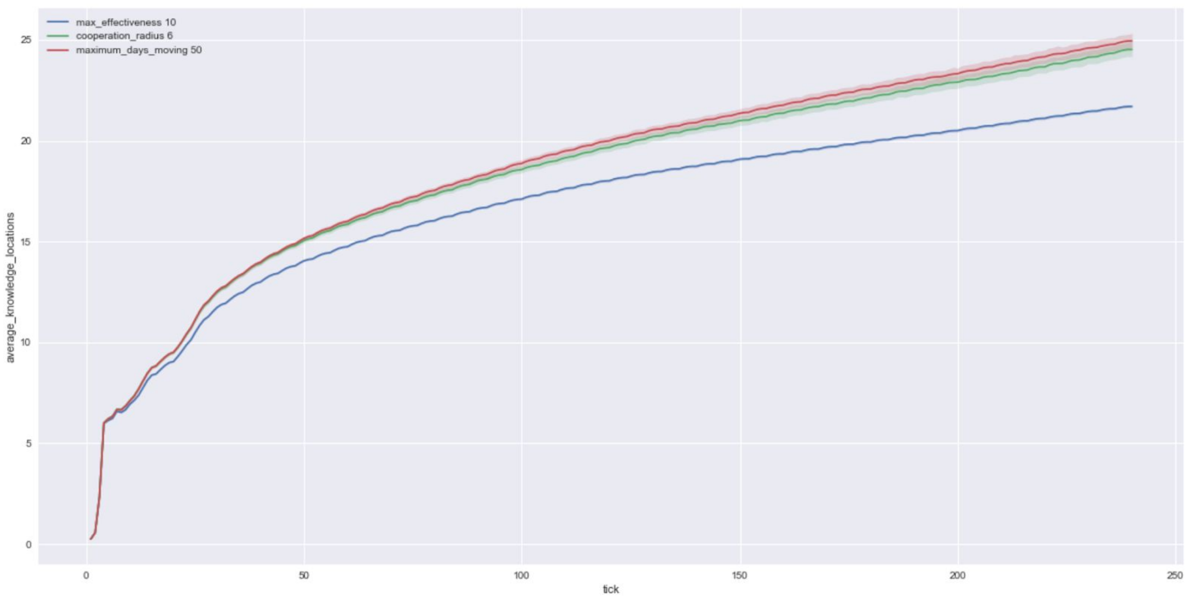


Figure 15: Average knowledge about locations for different survival strategies

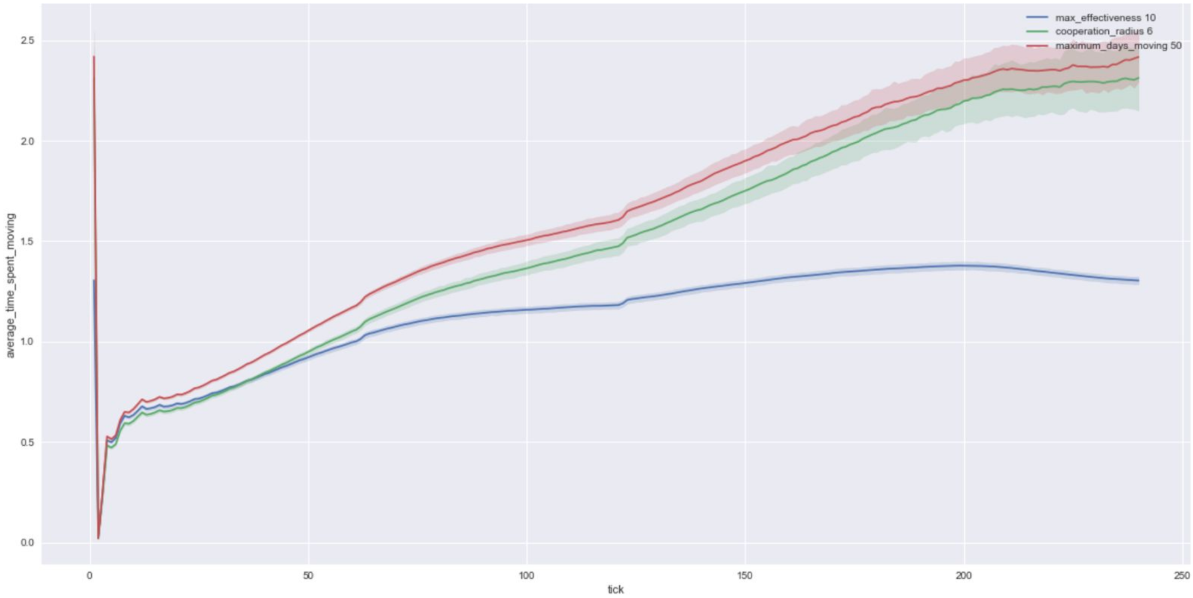


Figure 16: Average movement per tick for different survival strategies

4.4.3 Separation by environment

The number of existing clusters give an indication of how much the existing bands are separated from each other. This subparagraph looks into the effect of extreme events on this level of separation. Figure 17 shows the effect of different scenarios on the number of existing clusters per band. A high value in this kpi shows that the bands are relatively unconnected, as each solo band is also a community. Figure 17 shows a regular decrease in connectivity amongst the bands with means from 0.12 to 0.16 communities per band, meaning that for every band, 0.12 to 0.16 communities exist, or the average community exists of 8 to 6 bands. Note the sudden increase in connectivity when the volcano eruption takes place (120 ticks). It is counterintuitive that the bands are more connected after an eruption, however, it may be that the bands that are affected by the eruption were relatively unconnected, meaning their extinction increased the overall connectivity. This would support the importance of cooperation amongst hunter-gatherer bands to be able to survive. Another explanation is that affected bands are forced to move out of the scope of the volcano, which means the livable area is smaller, which causes a higher population density and a higher overall connectivity.

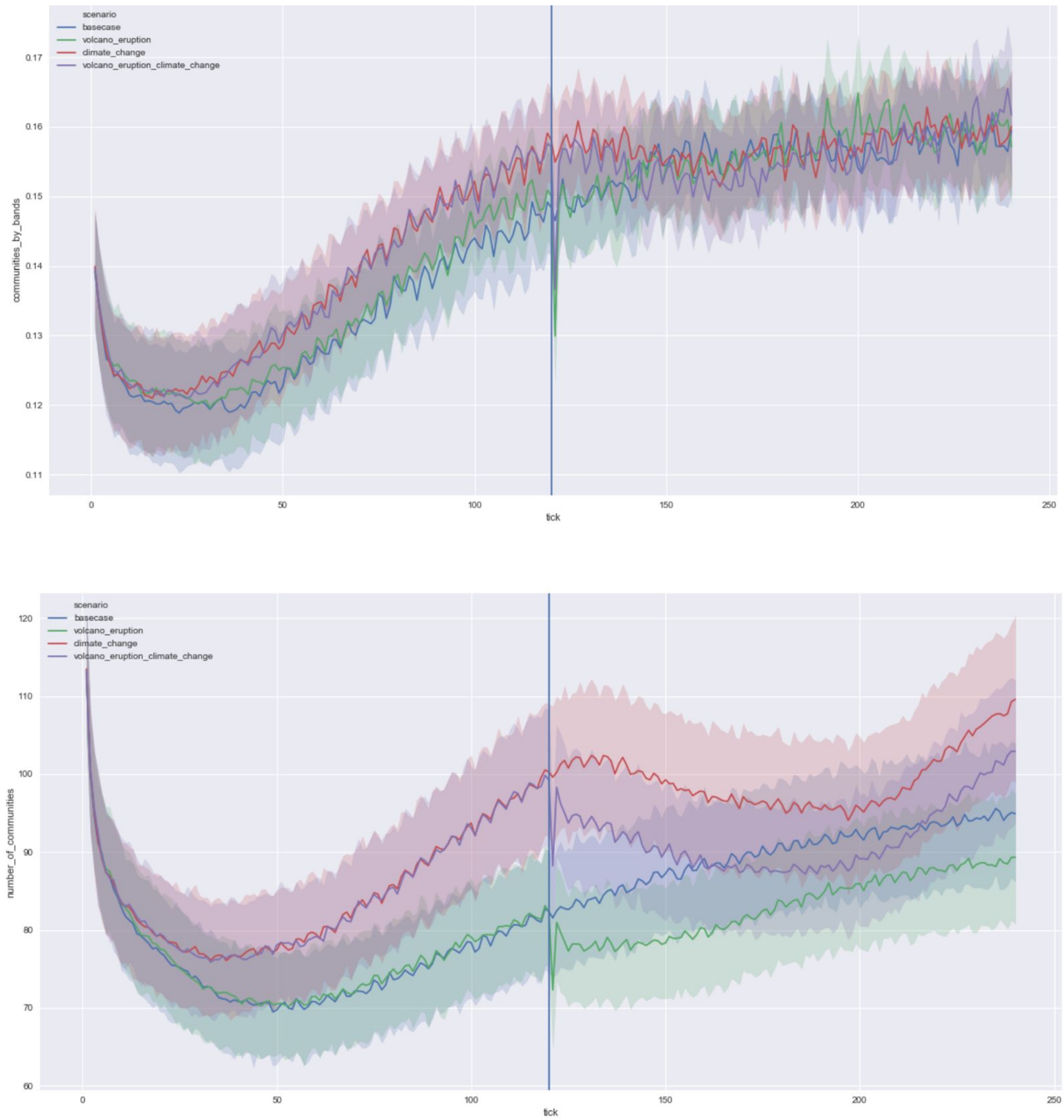


Figure 17 a and b: Number of communities per band over time for different scenarios and number of communities over time

5. Conclusion

In this concluding section, the main research question will be answered based on the results analyzed. Moreover, the limitations of these findings will be mentioned and recommendations are listed for further research. First the conclusions closely related to the model will be discussed. Then, these conclusions will be elaborated upon in both their scientific value and societal value.

Above all, this report has tried to create an answer to the following research question:
What is the impact of the interaction between climate change trajectory and an extreme event, such as the Laacher See eruption, on the generational development of hunter-gatherer bands?

The base for the analyses in this report was an agent-based model, on the level of hunter-gatherer band, and runs over 60 years existing of seasonal steps. In this model, most parameters and relations have been related to literature or parameterized if literature was absent. Note that the purpose of the model is to look at compound events in relation to the development of hunter-gatherer bands, rather than a full simulation of the world 13,000 years ago. To achieve this task certain choices and assumptions were made to simplify or capture a complex concept in an abstract way. All choices and assumptions made to create this model, include our own biases and perceptions.

The model compared four different scenarios, situations with or without volcano eruption and climate change. These effects showed that in terms of resilience the bands have a high adaptive pattern allowing them to continue to exist despite these environmental changes. While the event of a volcano creates a shock lowering the population level, climate change changes the behavior. The combination of these events disrupt the normal expected pattern of population, therefore, increasing the complexity of the predictability of the population.

Hunter-gatherer bands are most successful in terms of survival and growth when their skill level is high. Independent on the presence of climate change or a volcano eruption, this is the only tested property that has a significant influence. Also, both the volcano eruption and the ice age have an impact on the survival of bands. However, this impact is only temporary. After a significant impact of the extreme event, the bands grow back to a stable situation which is equal to a situation where no extreme event took place. This can be stamped as adaptive behaviour of the bands.

Both the strength of mobility and cooperation can be seen in the gathering of knowledge and movement of bands, but not in their survival. This is partly a consequence of our modeling choices, which have a bias towards skill being more important. The finding that both mobility and cooperation are useful shows that different configurations of the model may show a significant influence of mobility and cooperation on survival as well. Although literature has reasons to believe that certain hunter-gatherer bands “lost” their knowledge on technologies due to the effect of the volcano eruption and their isolation, this can not be seen in the created model. Impacted bands either die out because of the volcano, or they manage to move towards a safer location where they can connect to other bands, which keeps their knowledge on technologies up to date. As the temporal scope of the model was seasonal as a minimum, this limited the short term behaviour during and short after the eruption which also limits the reported behaviour.

Moreover, bands actually become more connected after the volcano eruption. Instead of isolation, the bands either die or find a more populated, safe area to continue their existence. Climate change has no impact on the connectedness of the bands. Lastly, the hunter-gatherer will always “find a way” to survive. Even with the combined impact of a continuous stress (ice age) and a big shock (volcano eruption), the bands are only affected temporarily and will continue to grow in number. In the 60 years scope of the model, no stable population has been found, as enough resources and food are available to support growth.

The primary contribution to the scientific world is an additional generative methodology to observe the behavior of hunter-gatherer bands in Europe 13,000 years ago. The model is able to explore the behavior of the hunter-gatherer bands under different circumstances in the environment. This approach allows researchers to test hypotheses of hunter-gatherer bands for further understanding of the past and the present.

By taking a generativist approach the patterns emerging come from decentralized local interactions allowing the modeller to play with different bottom up approaches to behavior. The exploratory behavior of the model also enables the expansion of the model, creating different circumstances or testing different behavioral interactions.

All conclusions drawn in this research are based on hunter-gatherer interactions, which can be useful for current societies as well. An example could be the movement of bands in times of extreme events, or weak points in the clusters of bands. Also, tipping points in the survival of bands influenced by these extreme events can be useful. However, an increasingly more complex society inhabits many more factors, levers and interrelations. Although the system of 13,000 years ago can aid in the thinking process of defending current societies against compound events, it cannot be claimed that it is the full answer.

6. Limitations and recommendations

This project faces certain limitations inherent to the conceptualization, tool, and computational power. The major limitations will be described to give options for future development of the model.

All models are wrong, as they are by definition simplifications of reality. Therefore it is important to understand not only the strong parts of the model, but also the limiting parts. As the model was biased towards the importance of skill, both mobility and cooperation could have been underrepresented in the model. In further research, the parameters that influence the importance of these characteristics should be altered to more extreme values in order to find out how important they can be in a different configuration of the model.

To be able to really compare the impact of climate change and/or the volcano eruption on the generational change of hunter-gatherer bands, the GISP2 trend should be more consistent with the GIS temperature data. In the experiments, these temperature trends were too different to compare the simulations to each other.

A major limitation is the temporal and spatial scope of the model. The model implements a slow-paced climate change into a model where local interactions happen based on time steps of a season. This time discrepancy limits the realism of the model. The model simulates the ice age through behavior by speeding the climate change up to be able to fit in the 60 years of the model time. These choices were made because of computational resources and the focus of the model lies in the behavior rather than a full simulation over thousands of years. Another limitation is that it is focused on band-on-band interaction, it misses certain cultural complexities inside hunter-gatherer bands such as the explicit transfer of knowledge through generations. These interactions are abstract in the current model but it could be of value to model these smaller interactions to see if this complexity adds value to the model.

Lastly, the parameter set that has been used in the experiments limits the insights into the model and the system. In further research, it is important to vary more of the parameters in order to get a better insight in the mechanics and interrelations of the model. Due to lack of computation resources and time for the current project it was not possible to fully explore the possibilities of the model. This may also help in showing the importance of mobility and cooperation, as both of these properties exist of more parameters that the ones we altered during experimentation.

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Appendix 1. Project description

--- Problem proposal ---

Societal Consequences of Past Compound Events:
The Laacher See eruption and the loss of technological complexity

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Agent-based model

The agents in such a model are hunter-gatherer individuals or bands, i.e. small, highly mobile and largely self-sufficient domestic economic units. These would have certain behavioural characteristics and, in order to capture both demographic and cultural changes, would need to be associated with certain biological properties (birth/death) as well as cultural traits that have costs (learning and making) and benefits (vis-à-vis resource acquisition) and which can with certain probabilities be passed on to the next generation. The interaction of these agents with the environment is critical. Resources in the form of food and certain raw materials would need to be found – and these would be strongly modulated by climate change over time and the extreme event of the eruption and its ash fallout. The aim of the model would be to explore:

(1) under which combination of drivers would we see demographic and/or cultural change.
(2) how extreme the individual drivers would have to be to cause demographic and/or cultural change.
(3) under what resource or network positions are impacts observable.
(4) how likely the changes documented archaeologically are within the model system.

In concluding, it is worth noting that also the Laacher See eruption can be employed as a scenario template for thinking about future societal impacts of extreme and compound events.

Appendix 2. Validation meetings

Synthesis meeting 1 goals

- **Core Scientific Issue**
    - Get a better understanding of the dynamics and processes of (compound) events
        - What is the impact of the interaction between climate change trajectory and an extreme event on the agents (hunter-gatherer bands)?
        - What might be driving factors behind technological complexity and the loss of technology?
    - Archeological Case (Laacher See - Volcano)
        - Use the case to set up the various parameters in a relatively simple context
        - Important to acknowledge the differences of the case to the contemporary situation such as connectivity, critical infrastructure, etc.

- **Scope of the Model**
    - Spatial scale: as realistic as possible
        - Based on the basic biological parameters from the dataset
        - Different biozones
    - Temporal scale: generational change
    - Climate change (background) interaction with the environment
        - Precipitation and temperature affect the resources on the ground
    - Stick to simple linkages with the parameters and the resources

- **Social and Cultural Relationships**
    - Rich ethnographic records of the past
    - How does population behave, how do they map socially and how does it affect their mobility?
        - Reaction of different hunter-gatherer bands
            - Bio-ability threshold: how low and how high can they actually go before extinction (uncertain: 25-500 people).
                - Size of the group is dependent on resources
                - Density of a population affects the productivity
        - Core groups are more robust than the people at the periphery
            - (?) Networks - people with a closer connection stick together more often
            - Technology and social networks affect the resilience of a group
        - Fusion and diffusion of groups
        - Mobility is very costly
            - Response to the environment (less resources) which changes due to climate

        - How vulnerable do you get if you move after a core population?
            - How do people deal in marginal environments?
            - Processes why people move to ‘difficult’ environments due to underlying processes
    - Cultural Capital (concretely: affects the technology of the hunter-gatherer band)
        - Technology loss affects the demographics of the group (efficiency and loss of clothes -> higher death rate)
        - Technological complexity: counting parts
        - Detailed information on the technology efficiency and cost
            - Costs and benefits of technology differs
            - Discrete effects of technology and continuous changes in technology as well (start with steps)
    - Transmission Dynamics from one generation to the next generation
        - Social costs: how difficult is it to learn something (related to complexity of technology)
        - Physical costs: access to raw materials
            - Ability to trade depends on the networks and mobility of the group (dependent on spatial environment)

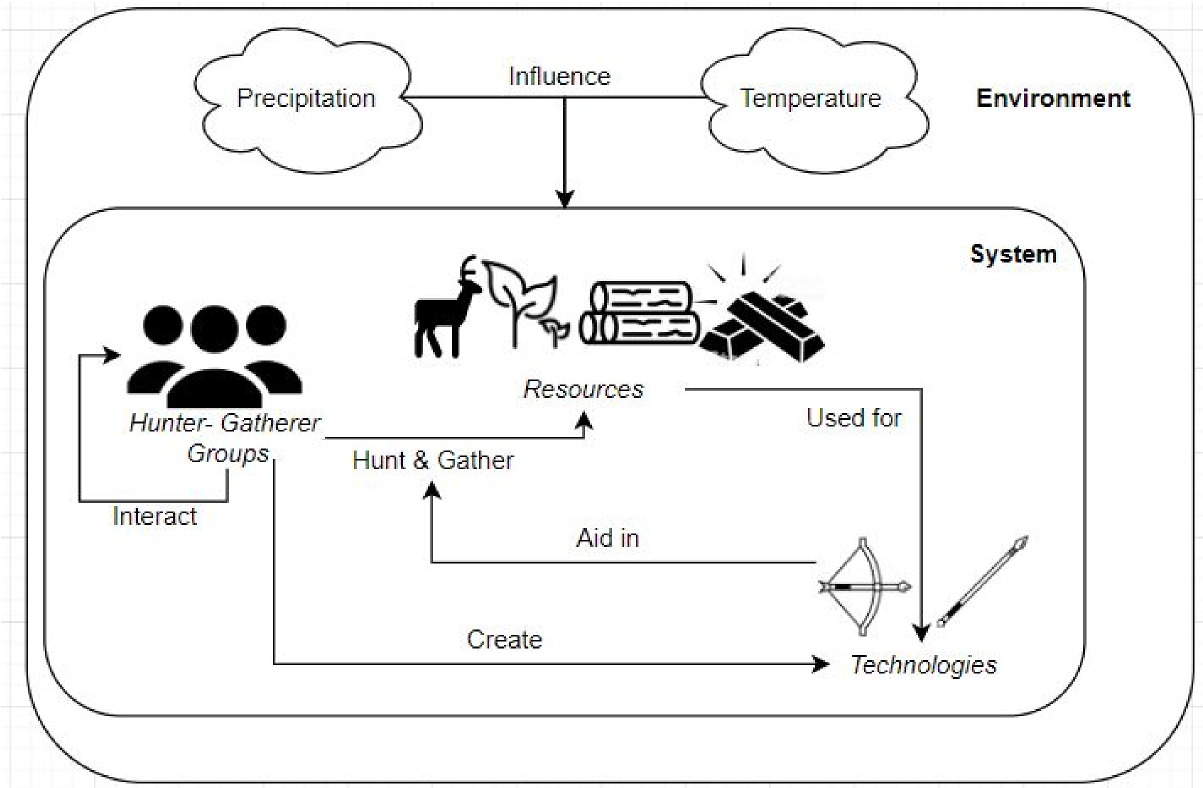
- **Metrics:**
    - Vulnerability of the group
    - Cultural Capital
    - Population Viability
        - Size
        - How many groups disappear completely

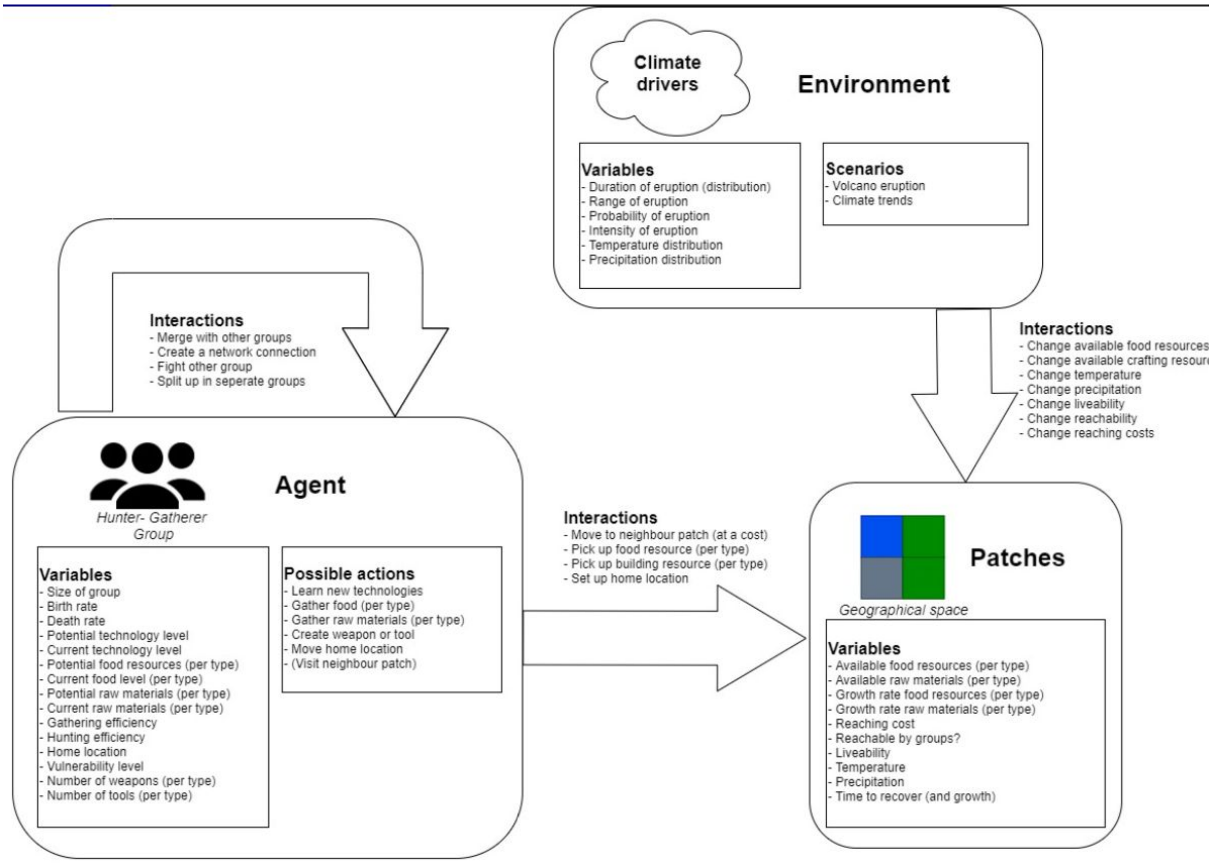
- **Policy Levers**
    - Predictability of climate for the groups
        - Safe operating space to map their future movement and the likelihood of the resources
        - Landscape learning
            - Core part of the agents: Exploration & exploitation and belief networks
        - Maintaining context through distant networks to understand the landscape

- **Scenario Discovery**
    - Disentangle the extreme events from the underlying climate change driver
        - Explore climate change in the context of interplay with an extreme event
            - What happens to the impact during different climate trends?
    - Flexibility of relationships
        - Non-stationarity of compound events (such as changes due to anthropogenic climate change, local-scale changes such as

urbanization and developments) has significant implications for how compound events should be modelled.

- Demystify black swans with the case research
    - Broaden the window in which we collect data
    - Catalogue of research patterns - how bad can it be





Attached is a synthesis of the first meeting. We have already started to create our first conceptual designs of the model which is also in the file. As this is only our initial perspective of the system based on the meeting, we would like to have your feedback on critical assumptions.

- Focus on groups rather than individuals.
    - Emergent properties of technology advancement inside groups will be aggregated on a group level.
    - Ability to process more agents in the model which is useful for the large spatial scale to investigate
    - Interactions between different groups can be investigated
    - Group behavior can be focused more, such as tendencies to move together, technology specialization.
- Distinction between raw materials and food resources
    - Food resources distinction gatherer and hunters
    - Raw materials distinction for tools, weapons, and buildings
- Assumption of basic necessities
    - Groups only advance technology if they meet minimum survivability aspects (food > raw material > learning)
- Climate drivers vary on the map based on distribution of temperature and precipitation
    - Every location would have different drivers

- Mechanism of increasing technology level is based on having enough food, resources, networks, and time
    - Two distinctions in technology advancement (still need to dive into the literature)
        - If groups have enough, they will increase technology level
        - If groups do not have enough, cannot find other food, cannot move, out of desperation they might increase technology

There is still a lot of work to do for us, such as:

- Information on fusion and diffusion of groups
- **Actual influence of climate drivers (volcano eruption, temperature, and precipitation) on resources and livability**
- Characteristics of technology levels – based on different forms of technology advancements
- Exact reaction of group interactions, between different groups (merges, trades, alliances, wars, ignore) – If it is even relevant

Regarding the data provided, it is important for us to have a clear view of what is available and which formats. Could you help us in obtaining the useful data considering the conceptual design? We had a difficult time navigating/finding the datasets.

Synthesis meeting 2 conceptualization

2019 / 12 / 12

1. **Model Narrative**

The appendices include the static model and flow logic, which were used in the meeting to describe the internal model logic so far.

1.1. Static Model

- Discussion on the assumption of the **hunter-gatherer group as individual agents**:
  - **Feedback**: reasonable, because they can be seen as domestic / economic units, most of the interactions are on this economic level as well.
- Reword intelligence to **cultural capital**
- Discussion on the assumption of **extreme weather influences on mobility**:
  - **Feedback**: difficult, as mobility could increase as well e.g. move over frozen rivers. There are ecological envelopes of recent periods, it might be useful to use the data to determine the mobility or health decreases.
  - **Key point:** all the things we are not certain about will be made variable.
- Book on Hunter-Gatherer Bands: can provide a lot of secondary data plus it is a nice read
  - In addition: ABM practices for archaeologists paper
- **Ticks are set to one season**
  - Weather in one tick / season will be sampled from a realistic random distribution
  - **Caution**: keep in mind the high temporal resolution and low spatial resolution; determine how detailed and realistic do we want to treat the environment?

1.2 Model Flow

- Seasonal variation have an influence on the food and resource availability on a patch
- Max time exploring is related to health status
- Patches get exhausted based on the time available
- **Compound events**: variable time when it happens
  - Suggestion: make it happen in the middle so that there is a warm-up period and what happens till the normal state (add concept: resilience?)

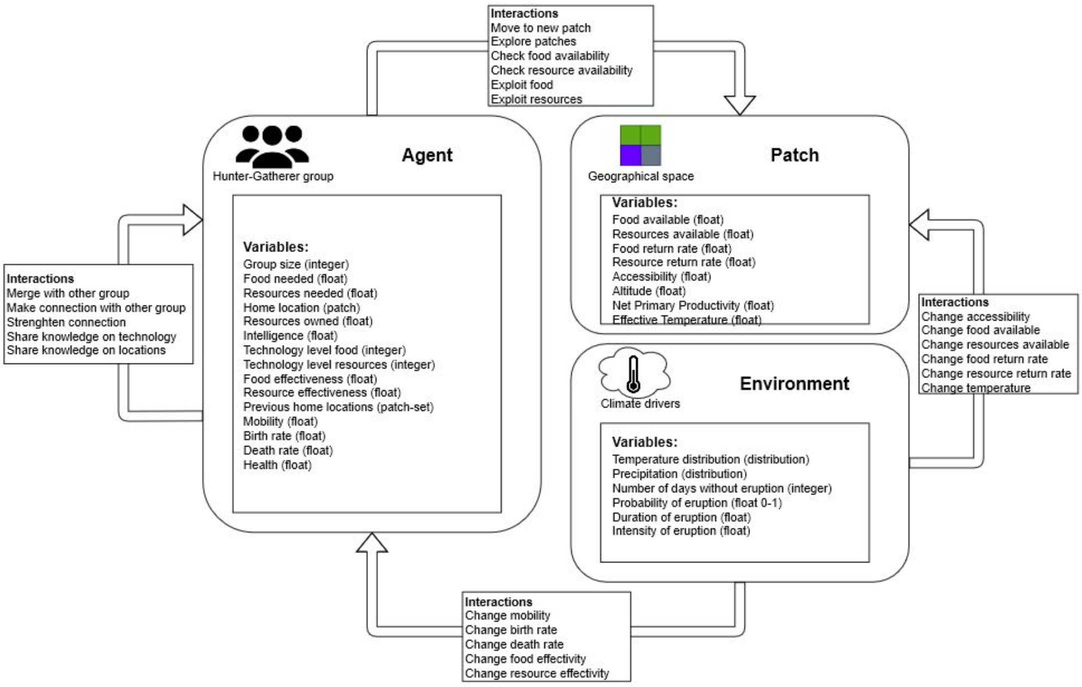
2. **Data**

Look into: PaleoView 2 and NOAA could provide good data sources on environment

3. **Reporting and Deliverables**

Focus on it from the academic angle, especially the methodology.

- Write-up; Brennen and Kevin will be available after the official deadline to help.
- OTD Method Guidelines


Interactions
Move to new patch
Explore patches
Check food availability
Check resource availability
Exploit food
Exploit resources
Agent
Hunter-Gatherer group
Variables:
Group size (integer)
Food needed (float)
Resources needed (float)
Home location (patch)
Resources owned (float)
Intelligence (float)
Technology level food (integer)
Technology level resources (integer)
Food effectiveness (float)
Resource effectiveness (float)
Previous home locations (patch-set)
Mobility (float)
Birth rate (float)
Death rate (float)
Health (float)
Patch
Geographical space
Variables:
Food available (float)
Resources available (float)
Food return rate (float)
Resource return rate (float)
Accessibility (float)
Altitude (float)
Net Primary Productivity (float)
Effective Temperature (float)
Interactions
Merge with other group
Make connection with other group
Strenghten connection
Share knowledge on technology
Share knowledge on locations
Environment
Climate drivers
Variables:
Temperature distribution (distribution)
Precipitation (distribution)
Number of days without eruption (integer)
Probability of eruption (float 0-1)
Duration of eruption (float)
Intensity of eruption (float)
Interactions
Change accessibility
Change food available
Change resources available
Change food return rate
Change resource return rate
Change temperature
Interactions
Change mobility
Change birth rate
Change death rate
Change food effectivity
Change resource effectivity

Synthesis meeting 3: Model

2020 / 01 / 16

1. **Model**
- Population dataset:
    - Ireland was not settled at all
    - Felix can provide a rough idea of population density

2. **Assumptions**
- Stability of hunting-gatherer groups (Boone, 2002) - interesting to look at that for the fluctuations
- Mobility:
    - Generally a relation between resource distribution and mobility
        - The more resources you are, the higher the mobility
        - Costs resources and time
        - Threshold where people don’t spend too much time on moving
        - Climatic deterioration would push groups to become smaller and become extinct because they have to move so much.
        - The more mobile you are, the smaller you are.
        - Hunting-gatherers move almost every season
- Food / Resource ratio
    - Create a slider for these ratios including the patch
- Band action order based on the group size.
- Merging based on (use the knowledge from the biggest group):
    - Group Size (low group band)
    - Resource Availability
        - If the patch has enough resources to support the merge group
    - Connection
- Splitting function (only if the group is big enough with a viability threshold)
- Birth rate: standard birth rate and depends on the time left
- Connection between bands should detoriate over time
- Volcano:
    - Implement the spread of the ash
    - Normal / Skewed distribution of the center
    - The effect of the ash fall is time limited
- Debate on the water craft - assumption allow a group to move across water

Experiments: interesting to experiment with the combined influence of climate and the extreme event - what background climatic conditions and with such an event
Link the extreme event to patch resources

Synthesis meeting 4: Experiments

Volcano:

- Make the impact of the volcano different to the cones
- Make the fallout zone smaller
- Exponential fall-off, the thicker the ash-fallout the more intense the impact on productivity
- Closer to the volcano, ash is worse
- The less ash falls, the less impact it has (far)

Climate Change:

- Temperature Curve (base it from the literature / NOAA website):
    - Climate change pushing the temperature down, creating a volcano.
    - GIS2 Icecore / Ingrip - Temperature trend

Experiments

- Really try to manipulate the volcano and climate change settings
- Make sure that temperature can affect the patch productivity