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Anthropogenic landscapes? Modelling the role of hunter-gatherers in interglacial ecosystems in Europe

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APPENDICES

Appendix I Supplementary data to Nikulina et al. (2024b)

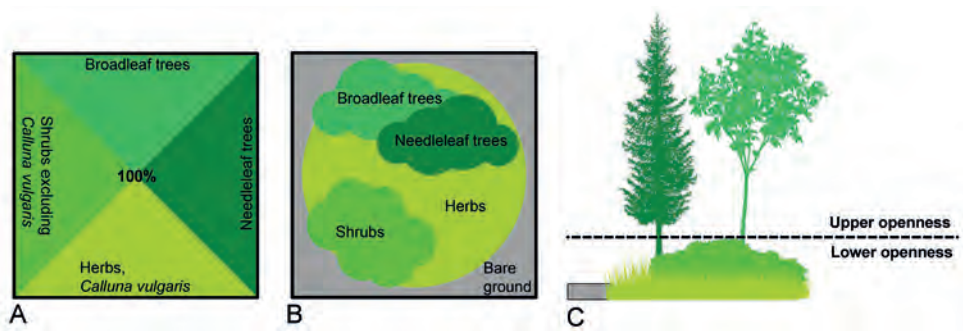
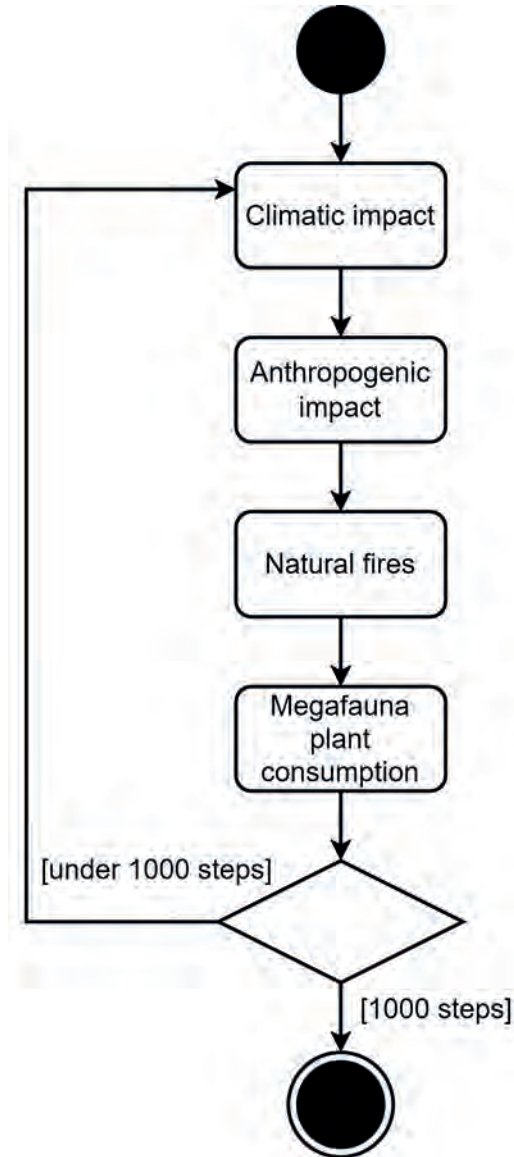


Figure AI.1 Vegetation openness representation in REVEALS (A) and in CARAIB (B, C).

Table AI.1 CARAIB and REVEALS conflicting grid cells excluded from the analysis.

CARAIB	REVEALS	Reason
PNV openness is higher than observed vegetation openness	Maximal observed vegetation openness (i.e., estimated vegetation openness + standard error) is lower than PNV openness.	In the current ABM PNV openness cannot be higher than pollen-based vegetation openness.
First dominant PFT: herbs/shrubs	First dominant PFT: trees	In the current ABM trees cannot dominate if climatic conditions only allow dominance of herbs or shrubs.
First dominant PFT: trees/herbs	First dominant PFT: shrubs	In the current ABM shrubs cannot dominate if climatic conditions only allow dominance of trees or herbs.



A1

Figure AI.2 HUMLAND activity diagram.

Table AI.2 Existing estimates of FRI / fire frequency from sediment sites dated to the Early–Middle Holocene in Europe.

Region	Vegetation	Dates	FRI/fire activity	Reference
60 km northeast of city of Tampere (southern boreal vegetation zone)	The establishment of Picea in the area dated to 5290 BP	5290–1700 BP	Fire frequency was 60–90 years or probably 130–180 years (natural fire regime)	Pitkänen et al., 2001
Mediterranean basin	Open landscape that developed into rather closed forests	11,700–10,400 BP	High IFF (inferred fire frequency) (FRI: 50–350; fire frequency 2,5–4,8 episodes per 500 years)	Vannière et al., 2008
	Deciduous forests	10,400–8600 BP	Even more frequent fires (FRI: 50–350; fire frequency 2–5 episodes per 500 years)	
Lowlands of the Transylvanian Plain	Less open deciduous woodland	7100–4700 BP	317-year mFRI and a maximum FF of 3 fires/1000 years (gradual increase of anthropogenic impact)	Feurdean et al., 2013
Eastern Latvia	Open landscape (dominance of grass)	11,700–9500 BP	1–4 fires per 1,000 years	Feurdean et al., 2017
	Boreal forest	9500–7500 BP	Shorter FRI (200 years)	
Balkan Peninsula	Boreal forest	8050–4000 BP	Low-to-moderate CHAR values, a 300-year mFRI (200–400 years) and 12 charcoal peaks for this time interval. Other mountain boreal forests: FRI of 50–100 (Bulgaria), 60–250 (Carpathians and Bohemia), 80–100 (Mediterranean) years	Feurdean et al., 2019
Central part of the East European Plain	Series of consecutive phases of birch and birch-pine forests with an admixture of broadleaved trees	6850–5600 BP	100 years and was frequently in the range of 10–20 years (presence of anthropogenic impact)	Novenko et al., 2018
	After 5000 BP the expansion of woodland coverage (to 60–70%), the increase in the proportion of broadleaved trees and the appearance of spruce (mixed forest)	5600–3000 BP	Fire frequency is 300–500 years (presence of anthropogenic impact)	

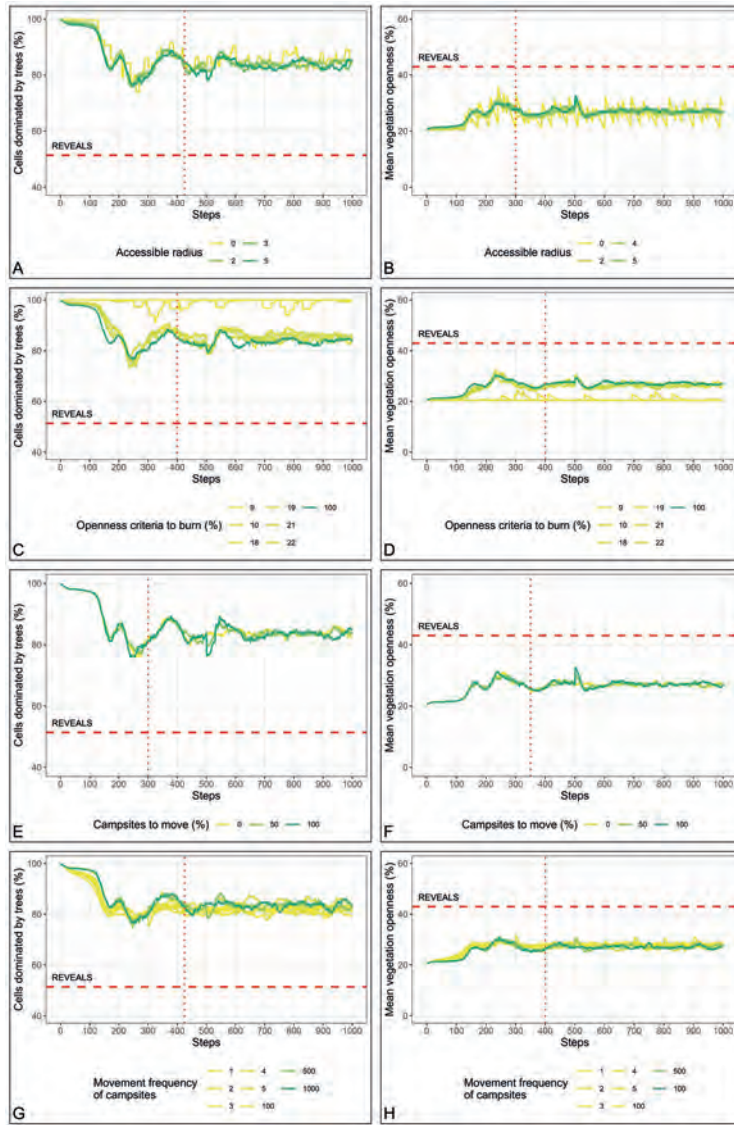


Figure A1.3 Results of experiments conducted for 100 hunter-gatherer groups: A–percentage of grid cells dominated by trees after the accessible radius was varied; B–mean vegetation openness after the accessible radius was varied; C–percentage of grid cells dominated by trees after the openness criteria to burn was varied; D–mean vegetation openness after the openness criteria to burn was varied; E–percentage of grid cells dominated by trees after the percentage of moving campsites was varied; F–mean vegetation openness after the percentage of moving campsites was varied; G–percentage of grid cells dominated by trees after the movement frequency was varied; H–mean vegetation openness after the movement frequency was varied. Each line depicted on the experiment output graph represents the mean of 30 simulation runs. The horizontal dashed line indicates REVEALS estimates, and the vertical dotted line shows the step when simulations reach equilibrium.

Table AI.3 Experiment results for human-induced vegetation changes caused by 100 groups with different other parameter values. Equilibrium indicates the step when the simulation output does not vary dramatically. Minimum varied parameter values show the starting impact of the agent, and maximum varied parameter values define the maximal possible impact of an agent (i.e., when REVEALS estimates are reached).

Sources of impact	Varied parameters	Constants	Equilibrium reached (steps)		Minimum varied parameter values and mean of standard deviation	Maximum varied parameter values and mean of standard deviation		
			Parameters	Value		Trees	Openness	Trees
Humans	Accessible_ radius	Territory_impacted_by_thunderstorms	False					
		Megafauna	False					
		Openness_criteria_to_burn	50	425	300	0 (5.8*, 2.7**)	3 (5.3*)	2 (2.7**)
		Campsites_to_move	50					
	Openness_ criteria_to_ burn	Movement_frequency_of_campsites	500					
		Territory_impacted_by_thunderstorms	False					
		Megafauna	False					
		Accessible_radius	5	400	400	9 (0*, 0**)	21 (6.2*)	19 (3**)
	Campsites_ to_move	Campsites_to_move	50					
		Movement_frequency_of_campsites	500					
		Territory_impacted_by_thunderstorms	False					
		Megafauna	False					
	Campsites_ to_move	Accessible_radius	5	300	350	0 (5*, 2.5**)	0 (5*)	0 (2.5**)
		Openness_criteria_to_burn	50					
		Movement_frequency_of_campsites	500					
		Territory_impacted_by_thunderstorms	False					
	Movement_ frequency_of_ campsites	Megafauna	False					
		Accessible_radius	5	425	400	3; 4*** (3.6*; 1.8**)	1 (2.7*)	1 (1.4**)
		Openness_criteria_to_burn	50					
		Campsites_to_move	50					

*this value represents the mean standard deviation calculated for the proportion of grid cells dominated by trees between steps 450 to 1000

**this value represents the mean standard deviation calculated for the mean vegetation openness between steps 450 to 1000

***the first value indicates minimal impact for the percentage of grid cells dominated by trees; the second number indicates minimal impact for the mean vegetation openness

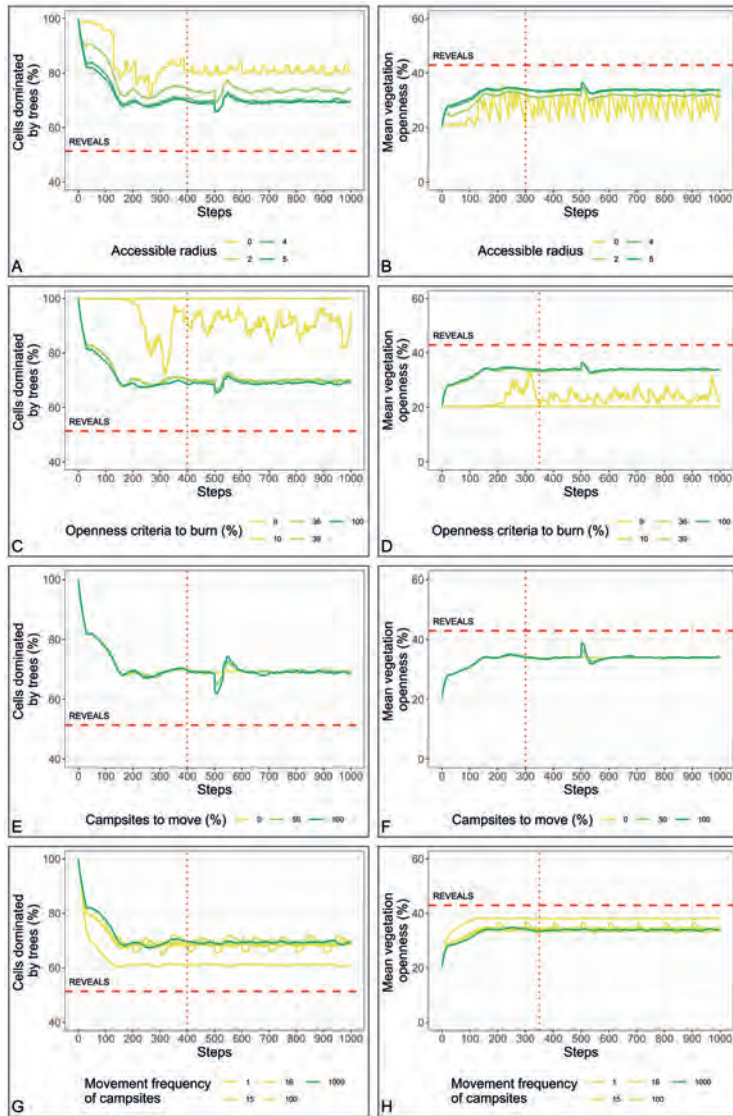


Figure AI.4 Results of experiments conducted for 1000 hunter-gatherer groups: A–percentage of grid cells dominated by trees after the accessible radius was varied; B–mean vegetation openness after the accessible radius was varied; C–percentage of grid cells dominated by trees after the openness criteria to burn was varied; D–mean vegetation openness after the openness criteria to burn was varied; E–percentage of grid cells dominated by trees after the percentage of moving campsites was varied; F–mean vegetation openness after the percentage of moving campsites was varied; G–percentage of grid cells dominated by trees after the movement frequency was varied; H–mean vegetation openness after the movement frequency was varied. Each line depicted on the experiment output graph represents the mean of 30 simulation runs. The horizontal dashed line indicates REVEALS estimates, and the vertical dotted line shows the step when simulations reach equilibrium.

Table AI.4 Experiment results for human-induced vegetation changes caused by 1000 groups with different other parameter values. Equilibrium indicates the step when the simulation output does not vary dramatically. Minimum varied parameter values show the starting impact of the agent, and maximum varied parameter values define the maximal possible impact of an agent (i.e., when REVEALS estimates are reached).

Sources of impact	Varied parameters	Constants	Equilibrium reached (steps)		Minimum varied parameter values and mean of standard deviation	Maximum varied parameter values and mean of standard deviation	
		Parameters	Value	Trees	Openness	Trees	Openness
Humans	Accessible_ radius	Territory_impacted_by_thunderstorms	False				
		Megafauna	False				
		Openness_criteria_to_burn	50	400	300	4 (1.7*)	4 (0.8**)
		Campsites_to_move	50				
		Movement_frequency_of_campsites	500				
		Natural_fires	False				
	Openness_criteria_to_burn	Megafauna	False				
		Accessible_radius	5	400	350	39 (1.7*)	36 (0.8)
		Campsites_to_move	50				
		Movement_frequency_of_campsites	500				
	Campsites_to_move	Territory_impacted_by_thunderstorms	False				
		Megafauna	False				
		Accessible_radius	5	400	300	0 (1.6*)	0 (0.8**)
		Openness_criteria_to_burn	50				
		Movement_frequency_of_campsites	500				
	Movement_frequency_of_campsites	Territory_impacted_by_thunderstorms	False				
		Megafauna	False				
		Accessible_radius	5	400	350	15; 16*** (1.4*, 0.6**)	1 (1*)
		Openness_criteria_to_burn	50				
		Campsites_to_move	50				

*this value represents the mean standard deviation calculated for the proportion of grid cells dominated by trees between steps 450 to 1000
**this value represents the mean standard deviation calculated for the mean vegetation openness between steps 450 to 1000
***the first number indicates minimal impact for the percentage of grid cells dominated by trees; the second number indicates minimal impact for the mean vegetation openness

Table AI.5 Experiment results for human-induced vegetation changes caused by 4000 groups with different other parameter values. Equilibrium indicates the step when the simulation output does not vary dramatically. Minimum varied parameter values show the starting impact of the agent, and maximum varied parameter values define the maximal possible impact of an agent (i.e., when REVEALS estimates are reached).

Sources of impact	Varied parameters	Constants		Equilibrium reached (steps)		Minimum varied parameter values and mean of standard deviation		Maximum varied parameter values and mean of standard deviation	
		Parameters	Value	Trees	Openness			Trees	Openness
Humans	Accessible_radius	Natural_fires	False						
		Mega fauna	False						
		Openness_criteria_to_burn	50	300	200	0 (1.3*; 0.6**)		5 (0.9*)	4 (0.5**)
		Campsites_to_move	50						
		Movement_frequency_of_campsites	500						
	Openness_criteria_to_burn	Natural_fires	False						
		Mega fauna	False						
		Accessible_radius	5	325	300	9 (0*; 0**)		58 (0.8*)	46 (0.5*)
		Campsites_to_move	50						
		Movement_frequency_of_campsites	500						
	Campsites_to_move	Natural_fires	False						
		Mega fauna	False						
		Accessible_radius	5	200	200	0 (0.9*; 0.4*)		0 (0.9*)	0 (0.4*)
		Openness_criteria_to_burn	50						
		Movement_frequency_of_campsites	500						
	Movement_frequency_of_campsites	Natural_fires	False						
		Mega fauna	False						
		Accessible_radius	5	200	300	21; 19*** (1*; 0.5**)		1 (0.7*)	1 (0.4*)
		Openness_criteria_to_burn	50						
		Campsites_to_move	50						

*this value represents the mean standard deviation calculated for the proportion of grid cells dominated by trees between steps 450 to 1000
**this value represents the mean standard deviation calculated for the mean vegetation openness between steps 450 to 1000
***the first number indicates minimal impact for the percentage of grid cells dominated by trees; the second number indicates minimal impact for the mean vegetation openness

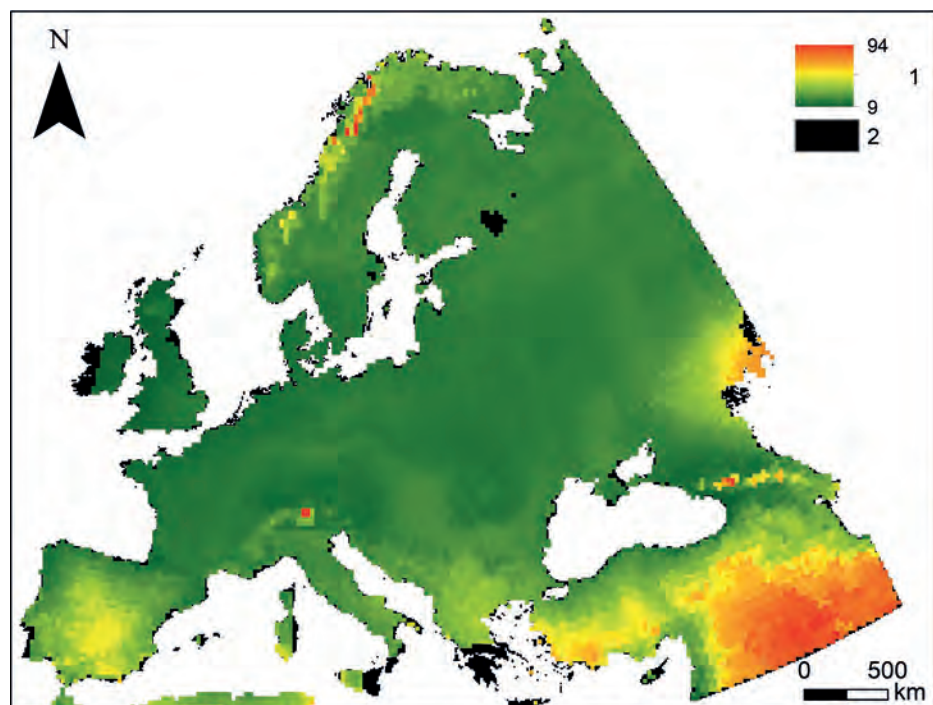


Figure AI.5 CARAIB bare ground. Legend: 1–fraction of bare ground in percentages; 2–no data.

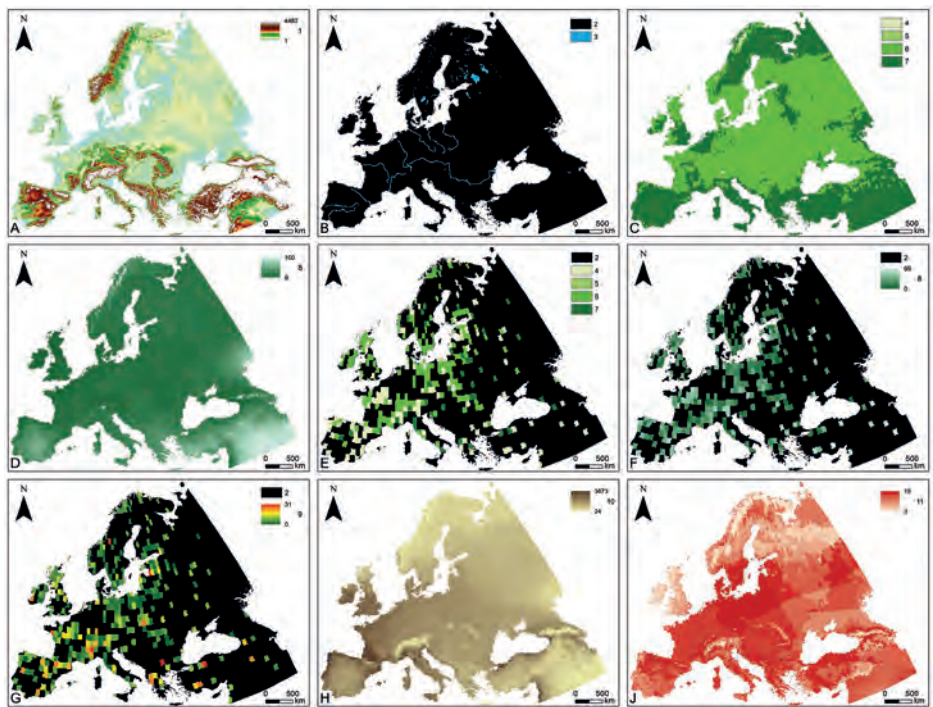


Figure AI.6 Datasets used in the current ABM: DEM (A), major rivers and lakes (B), CARAIB distribution of first dominant PFTs (C) and vegetation openness (D), REVEALS distribution of first dominant PFTs (E) and vegetation openness (F) and its standard errors (G), CARAIB NPP (H), megafauna vegetation consumption (I). Legend: 1–elevation (m); 2–no data; 3–major rivers and lakes; 4–herbs; 5–shrubs; 6–broadleaf trees; 7–needleleaf trees; 8–vegetation openness in percentages; 9–standard errors for REVEALS vegetation openness; 10–CARAIB NPP (g/m^3); 11–megafauna vegetation consumption (g/m^3).

Table AI.6 Confusion matrix for CARAIB and REVEALS PFT comparison.

	Predicted Positive	Predicted Negative
Actual Positive	5	0
Actual Negative	7776	8225

A1

Table AI.7 Experiment results for megafauna, thunderstorm and climatic impact on vegetation. Equilibrium indicates step at which the simulation output reaches a stable state. Minimum varied parameter values show the starting impact of the agent, and maximum varied parameter values define the maximal possible impact of an agent (i.e., when REVEALS estimates are reached).

Sources of impact	Varied parameters	Constants		Equilibrium reached (steps)		Minimum varied parameter values and mean of standard deviation		Maximum varied parameter values and mean of standard deviation	
		Parameters	Value	Trees	Openness			Trees	Openness
Thunderstorms	Territory_impacted_by_thunderstorms	Humans	False	450	450	0.1 (1.5*, 0.8**)		7 (0.5*)	4.7 (0.3**)
		Megafauna	False						
Thunderstorms, megafauna	Territory_impacted_by_thunderstorms	Humans	False	375	375	0.1 (1.4*, 0.7**)		7 (0.5*)	4.7 (0.3**)
		Megafauna	True						

*this value represents the mean standard deviation calculated for the proportion of grid cells dominated by trees between steps 450 to 1000

**this value represents the mean standard deviation calculated for the mean vegetation openness between steps 450 to 1000

Table A1.8 Experiment results for human-induced vegetation changes caused by different group numbers. Equilibrium indicates the step at which the simulation output reaches a stable state. Minimum varied parameter values show the starting impact of the agent, and maximum varied parameter values define the maximal possible impact of an agent (i.e., when REVEALS estimates are reached).

Sources of impact	Varied parameters	Constants		Equilibrium reached (steps)		Minimum varied parameter values and mean of standard deviation		Maximum varied parameter values and mean of standard deviation	
		Parameters	Value	Trees	Openness			Trees	Openness
Humans	Number_of_hunter-gatherer_groups	Territory_impacted_by_thunderstorms	False						
		Megafauna	False						
		Accessible_radius	5	325	230	1 (20.8*, 9.6**)		3167 (1.1*)	3128 (0.5**)
		Openness_criteria_to_burn	50						
		Campsites_to_move	50						
		Movement_frequency_of_campsites	500						

*this value represents the mean standard deviation calculated for the proportion of grid cells dominated by trees between steps 450 to 1000

**this value represents the mean standard deviation calculated for the mean vegetation openness between steps 450 to 1000

Table AI.9 Confusion matrix for HUMLAND and REVEALS PFT comparison.

	Predicted Positive	Predicted Negative
Actual Positive	3925	3854
Actual Negative	3856	4371

Appendix II

HUMLAND ABM 1.0 Overview, design concepts and details (ODD) protocol

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AII.1 Purpose

Humans started transforming their environment long before the emergence of agriculture and industrialization. Foraging societies conduct niche construction activities including vegetation burning which significantly modifies the occupation area of hunter-gatherers. Currently available evidence suggests that both Neanderthals and Mesolithic humans practiced vegetation burning. Due to the scarcity of evidence and the absence of a common research protocol to study the anthropogenic impact on landscapes, there are gaps in research about the dynamics of interglacial environments and the role of hominins in landscape changes. Particularly, the extent of vegetation burning organized by hunter-gatherers is still a focal point of research.

Landscape dynamics are complex and include variable components such as climatic fluctuations, megafauna impact, natural fires, and anthropogenic activities. Thus, there is a need for further research which can allow us to assess different possible scenarios for anthropogenic impact which play a role in landscape change. Therefore, the purpose of this model is to track and quantify the intensity of different impacts on landscapes on the continental level and to determine the most influential factor in transformation of interglacial vegetation with specific focus on burning organized by hunter-gatherers. This model accumulates different types of spatial datasets (Section AII.6) which are used as input and target for ABM results. Additionally, the study incorporates recently obtained specifically for this research continental-scale estimates of fire return intervals (FRI) and speed of vegetation regrowth in the current simulation. The obtained results include maps of possible scenarios of modified landscapes in the past and quantification of input of each agent (climate, humans, megafauna and natural fires). The model has been implemented in *NetLogo* (version 6.2.2) and is accessible via the CoMSES model depository (<https://www.comses.net/>, search for HUMLAND; DOI: 10.25937/fxdq-fn86).

AII.2 Entities, state variables, and scales

The following entities are included in the model: agents representing hominin groups (one agent is one group, Table AII.1), campsites (turtles, have only one static variable `my_hominin` which indicates the group occupying this campsite) and grid cells (patches, Table AII.2).

Table AII.1 Hominin state variables.

Variable name	Variable type and units	Meaning
my_home	Dynamic, patch	A patch where a campsite is located (home patch of a group)
my_campsite	Dynamic, turtle	Campsite is the home of a hominin group

Table AII.2 Grid cells state variables.

Variable name	Variable type and units	Meaning
patch_elevation	Static, float, meters	Absolute elevation (a.s.l.)
patch_natural_pft	Static, integer	CARAIB (CARbon Assimilation In the Biosphere) first dominant PFT: 1–herbs, 2–shrubs, 3–needleleaf trees, 4–broadleaf trees, -1–no data
patch_pollen_pft	Static, integer	REVEALS (Regional Estimates of VEgetation Abundance from Large Sites) first dominant PFT: 1–herbs, 2–shrubs, 3–needleleaf trees, 4–broadleaf trees, -1–no data
patch_pft_updating	Dynamic, integer	Current dominant PFT: 1–herbs, 2–shrubs, 3–needleleaf trees, 4–broadleaf trees, -1–no data, 0–burnt/fully consumed area
patch_natural_openness	Static, float, percentage	CARAIB vegetation openness: 0–minimal value (0%, totally closed), 100–maximal value (100%, totally open), -1–no data
patch_pollen_openness	Static, float, percentage	REVEALS vegetation openness: 0–minimal value (0%, totally closed), 99–maximal value (99%, totally open), -1–no data
patch_pollen_openness_se	Static, float	REVEALS vegetation openness standard error (se)
patch_pollen_openness_max	Static, float, percentage	Maximal possible REVEALS openness: patch_pollen_openness + patch_pollen_openness_se
patch_openness_updating	Dynamic, integer, percentage	Current vegetation openness: 0–minimal value (0%, totally closed), 100–maximal value (100%, totally open), -1–no data
rivers_lakes	Static, integer	Presence of big rivers and lakes: 0–no rivers/lakes, 1–presence of rivers/lakes, -1–no data
fri	Static, integer, years	FRI values for each PFT
patch_natural_npp	Static, float, g/m ²	CARAIB NPP
megafauna_npp_consumption	Static, float, g/m ²	Megafauna carbon consumption
fire_delay_after_consumption	Dynamic, integer	Delay in the frequency of natural fires after partial megafauna consumption of vegetation
openness_regrowth_rate	Dynamic, float	Openness regrowth speed per step after impact

Variable name	Variable type and units	Meaning
last_burning_episode	Dynamic, integer	Simulation step of the last fire episode of a patch
next_burning_episode	Dynamic, integer	Possible next natural fire event when probability of ignition is 100%.
last_partial_consumption_episode	Dynamic, integer	Step of the last partial consumption episode of a patch
last_agent_impacted_pft	Dynamic, integer	Last agent that changed a dominant PFT of a patch: 1–humans, 2–natural fires, 3–climate, 4–megafauna
last_agent_impacted_openness	Dynamic, integer	Last agent that impacted a patch: 1–humans, 2–natural fires, 3–climate, 4–megafauna
herbs_regeneration_step	Dynamic, integer	Step when herbs will regrow after vegetation burning or consumption
shrubs_regeneration_step	Dynamic, integer	Step when shrubs will regrow after vegetation burning or consumption
needleleaf_trees_regeneration_step	Dynamic, integer	Step when needleleaf trees will regrow after vegetation burning or consumption
broadleaf_trees_regeneration_step	Dynamic, integer	Step when broadleaf trees will regrow after vegetation burning or consumption
agent_that_could_impact_neighbouring_patches	Dynamic, integer	Agent that can potentially cause burning on neighbouring patches: 1–humans, 2–natural fires, 3–climate, 4–megafauna
hominin_accessible_area	Dynamic, integer	Defines if the patch is within accessible area for humans: 1–within the area, 0–not accessible for humans
raster_layer	Dynamic, integer/float	Used to create an ASCII file with modelling results

The model is two-dimensional, and its spatial extent is a rectangle with 544 x 430 patches. Each cell of input raster datasets (Section AII.6, Table AII.6) is resampled (i.e., spatial resolution was changed) to 10 km × 10 km in size. The world wraps horizontally and vertically. The current version of the model imports all spatial datasets for one time window (9200–8700 BP). One simulation step equals one year, and the current simulation does not account for seasonal variability. One run is 1000 time steps.

AII.3 Process overview and scheduling

Simulation starts with setup when input datasets are imported, entities are created, their state variables are set, and the conflicting cells are removed. In HUMLAND, more closed vegetation can only switch to more open vegetation after a disturbance event (fire, grazing). In our data comparison, where CARAIB shows a greater degree of openness in vegetation than REVEALS, we exclude these locations:

the ABM will not be able to generate vegetation that is comparable to REVEALS as it is constrained by the CARAIB-prescribed PNV. As a result, the similarity between ABM output and REVEALS datasets can only be improved for grid cells where initial vegetation openness is equal to or lower than observed estimates. These are the conflicting grid cells which are not taken into account when the primary observations (mean vegetation openness and percentage of dominant PFTs for cells with both REVEALS and CARAIB data) during the simulation runs are taken.

The process overview of simulation runs is shown in Figure All.1. Plots update at each step, and the simulation stops after 1000 steps. Each of them starts with vegetation regeneration. This submodel (Section All.7) executes only for patches which were previously (i.e., during the earlier step) burnt or consumed.

Hominins are the first agent that reduces vegetation cover. The anthropogenic fire submodel (Section All.7) is executed via three phases. During the first phase, hominins randomly move towards one of neighbouring patches within the area defined by accessible radius around their campsites. When a hominin reaches a patch with trees or shrubs as a dominant PFT and vegetation openness smaller or equal to a number defined via the `Openness_criteria_to_burn` variable, this patch is burnt. During the second phase, fire spread is initiated. Finally, the current vegetation openness of burnt patches and dominant PFT are compared with REVEALS data.

The natural fires submodel (Section All.7) is initiated after hominin impact. During the setup the number of patches, that will be hit by thunderstorms per step, is calculated based on a value of the `Territory_impacted_by_thunderstorms` variable. Every simulation step random patches are chosen and impacted by thunderstorms. Thunderstorms can occur in high mountains, lakes and rivers, but these episodes never lead to ignition. Depending on the probability of ignition of a patch which are not water bodies or high mountains, patches can be burnt after thunderstorms. Similarly to anthropogenic burning, thunderstorms can cause fire spread. Finally, the current vegetation openness of burnt patches and dominant PFT are compared with REVEALS data.

Only grid cells with fully recovered vegetation can be consumed by megafauna. This assumption arises from our use of estimates for potential maximal megafauna plant consumption and the absence of data regarding partial consumption during the vegetation regrowth phase. After plant consumption, vegetation openness increases depending on the CARAIB NPP values and the maximal megafauna plant consumption estimates. Regarding megafauna impact on PFTs, it is assumed that megafauna equally consumes all PFTs present on a grid cell, i.e., besides the first dominant PFT megafauna consumes second, third and fourth dominant PFTs

in equal proportions. That is why, the first dominant PFT is replaced, only if the vegetation was entirely consumed by megafauna, and vegetation openness value after consumption is 100%. In this case, the first dominant PFT would be replaced by bare ground

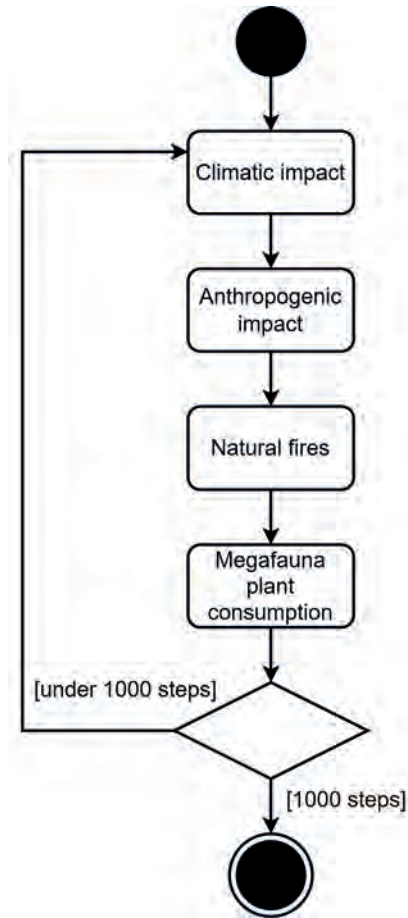


Figure AII.1 Activity diagram of process overview.

AII.4 Design concepts (after Nikulina et al., 2024b)

AII.4.1 Basic principles

The history of anthropogenic impacts on the environment spans over many years, with humans already engaging in landscape transformations before the emergence of agriculture. Ethnographic observations show that hunter-gatherers or foragers (i.e., groups that mainly depended on food collection or foraging of wild resources) influence their surroundings in several ways including modification of vegetation communities via burning. This practice was identified for all vegetation types except tundra at different spatial scales and for diverse objectives including driving game, stimulating the growth of edible plants, and clearing pathway.

Besides ethnographic data, evidence from archaeological contexts show that fire use was an important part of the technological repertoire of the *Homo* lineage since at least the second half of the Middle Pleistocene. Human-induced vegetation burning during the Late Pleistocene has been proposed as a potential factor in several case studies spanning various continents. Notably, the earliest evidence of such activities on a local scale was identified at the Neumark-Nord site in Germany, dated to the Last Interglacial (Eemian, ~130,000–116,000 BP). In addition, fire-using foragers were suggested as one of the primary drivers of vegetation openness in Europe during the Last Glacial Maximum, i.e., possibly constituting one of the earliest large-scale anthropogenic modifications of system earth.

While these Pleistocene cases are still subject to debate, human-induced vegetation burning conducted by hunter-gatherers during the Early–Middle Holocene (~11,700–6000 BP) is generally accepted, even though the quality of the data is not necessarily that different. However, the number of case studies is higher for the Early–Middle Holocene than for the Pleistocene. Most of the Early–Middle Holocene evidence comes from the European context.

Despite the presence of case studies for anthropogenic burning (intentional or not) of past landscapes by hunter-gatherers, it is still difficult to establish whether these local-scale impacts caused changes at the regional and (sub-)continental scales. Furthermore, overall landscape dynamics do not only depend on humans, and rather represent the complex interplay of natural and cultural processes at different spatio-temporal scales. Landscapes are thus complex systems where heterogeneous components interact to impact on ecological processes, and might demonstrate non-linear dynamics and emergence. Therefore, it is often challenging to distinguish different impacts on landscapes using proxy-based reconstructions (e.g., palynological datasets).

Modelling approaches offer excellent opportunities to explore how complex components of systems might interact, particularly when real-time experiments are not possible. Spatially-explicit agent-based modelling (ABM) is commonly used to explore complex systems where multiple factors intertwine and to propose possible scenarios of system functioning, and the outcomes of ABMs can be compared to empirical data. This approach has been applied in various contexts to study past human-environment interactions and land use/land cover changes. There are examples of such models for past societies that practiced agriculture and animal husbandry, and for hunter-gatherer groups. In the case of ABM developed to study foragers, the use of fire by hunter-gatherers to transform foragers' surroundings and the landscape consequences of these practices are usually not discussed.

This model includes four types of impact on vegetation: climatic impact, anthropogenic fires, thunderstorms, and megafauna plant consumption. Thunderstorms were included because lightning is one of the most general and widespread triggers of natural fire. Another source of impact is climate, and it is included as a crucial element for vegetation regeneration after fires or vegetation consumption. Finally, megafauna are also a part of the current ABM, because the herbivory activity impacts litter accumulation, and high levels of megafauna plant consumption reduce fire occurrence in many areas.

AII.4.2 Emergence

The model's key results are increase of average vegetation openness and decrease of the percentage of cells dominated by trees. These results emerge from joint (i.e., several agents together) and separate (i.e., only one agent) impacts of different agents (hominins, thunderstorms and megafauna) on vegetation. The increase of vegetation openness and change of PFT's distribution are driven by a specific combination of agents and values of variables that influence their behaviour.

AII.4.3 Adaptation

There is no adaptation in the model.

AII.4.4 Objectives

Vegetation burning is an objective for hominins. Each step hominins move randomly to one of the neighbouring patches. If it covered by shrubs or trees and its vegetation openness is equal or lower than the `Openness_criteria_to_burn` value, then the fire will be set. Otherwise, humans do not impact this patch. Megafauna and thunderstorms do not have objectives.

AII.4.5 Learning

Agents do not learn.

AII.4.6 Prediction

Agents do not predict.

AII.4.7 Sensing

Humans are assumed able to sense dominant PFT and vegetation openness of a grid cell where humans are located. Hominins can sense if their campsites and home patches are beyond accessible radius. It is useful in cases when two campsites are located nearby, and their accessible areas overlap. If a hominin is far from his campsite (does not sense his campsite anymore i.e., it is beyond accessible radius), this hominin automatically comes back to its campsite.

AII.4.8 Interaction

Hominins directly affect patches. If a hominin decides to burn a patch, its state variables are modified.

AII.4.9 Stochasticity

Stochasticity is used in initializing the model when random distribution of hominins within the study is set. Additionally, hominins randomly choose one of neighbouring patches on which hominins move around campsites. Finally, humans randomly choose patches when the campsites will be moved during simulation runs. This happens with a specific frequency defined via the `Movement_frequency_of_campsites` variable.

Thunderstorm impact also includes stochasticity. The number of patches are defined via the `Territory_impacted_by_thunderstorms` parameter. Several random inland patches are selected every simulation step to potentially have natural fire. The actual natural vegetation burning depends on a probability of ignition $P(I)$ (AII.1):

$$P(I) = \frac{T-B}{F} \quad (\text{AII.1}),$$

where B is the step when the last burning episode occurred, F —FRI, and T —the number of simulation steps (ticks) since the beginning of the simulation. Once $P(I)$ is calculated, a random float number between 0 and 1 is chosen. If $R \leq P(I)$, this patch will be burnt. Similarly to ignition caused by natural fires, fire can spread on neighbouring patches after natural and human-induced fires. For the

neighbouring patches the $P(I)$ is calculated, and the fire event can occur depending on the obtained $P(I)$ and random a random float number.

AII.4.10 Collectives

There are no collectives in the model.

AII.4.11 Observation

The primary model observations are distribution of dominant PFT (percentage of patches covered by each PFT) and mean vegetation openness for patches which have both REVEALS estimates and CARAIB values (i.e., not all patches are considered). These values are provided via plots on the model interface and extracted tables. The ABM output is considered similar to REVEALS data if the simulation produced the same percentage of first dominant PFTs and mean vegetation openness values or if the difference between ABM output and REVEALS data varies within $\pm 5\%$ (the range of change is 10%). Additionally, the different types of impact (i.e., the number of grid cells modified by each type of impact) are tracked via recording which impact caused openness and PFT changes.

AII.5 Initialization (after Nikulina et al., 2024b)

First, the environment is created during the initialization. Patch state variables at the end of the initialization step are described in Table AII.3. In HUMLAND, more closed vegetation can only switch to more open vegetation after a disturbance event (fire, grazing). In our data comparison, where CARAIB shows a greater degree of openness in vegetation than REVEALS, we exclude these locations: the ABM will not be able to generate vegetation that is comparable to REVEALS as it is constrained by the CARAIB-prescribed PNV. As a result, the similarity between ABM output and REVEALS datasets can only be improved for grid cells where initial vegetation openness is equal to or lower than observed estimates. Secondly, there are several grid cells where climatic conditions only favour dominance of herbs or shrubs, but observed vegetation indicates dominance of trees. Besides that, shrubs cannot dominate grid cells where climatic conditions favour trees or herbs in HUMLAND. Such cases do not improve similarity between ABM output and REVEALS data, and, therefore, these grid cells were also excluded (Table AII.5).

Table AII.3 Patch state variables and their values at the end of the initialization stage.

Variable name	Value	Explanation
patch_elevation	In accordance with GTOPO30	Value is set depending on GTOPO30 dataset
patch_natural_pft	In accordance with CARAIB first dominant PFT	Value is set between 1 and 4 depending on CARAIB dataset
patch_pollen_pft	In accordance with REVEALS first dominant PFT	Value is set between 1 and 4 depending on CARAIB dataset
patch_pft Updating	patch_pft Updating = patch_natural_pft	Variable has the same value as theoretical potential natural vegetation provided by CARAIB
patch_natural_openness	In accordance with CARAIB vegetation openness	Value is set between 9 and 100 depending on CARAIB dataset
patch_pollen_openness	In accordance with REVEALS vegetation openness	Value is set between 0 and 99 depending on REVEALS dataset
patch_pollen_openness_se	In accordance with REVEALS standard errors	Value is set depending on REVEALS dataset
patch_pollen_openness_max	patch_pollen_openness + patch_pollen_openness_se	Maximal possible REVEALS vegetation openness
patch_openness Updating	patch_natural_openness = patch_openness Updating	Variable has the same value as theoretical potential natural vegetation provided by CARAIB
rivers_lakes	0 or 1	Value depends on WISE dataset
fri	246, 426, 286 or 293	The value depends on CARAIB first dominant PFT (Table AII.4)
patch_natural_npp	In accordance with CARAIB NPP	Value is set depending on CARAIB dataset
megafauna_npp_consumption	In accordance with megafauna vegetation consumption dataset	Value is set depending on megafauna vegetation consumption data
fire_delay_after_consumption	-1	Before megafauna consumption of a patch this variable is set to -1
openness_regrowth_rate	0	Before simulation runs this value is set to 0
last_burning_episode	0	Before simulation runs this value is set to 0
next_burning_episode	last_burning_episode + fri	Defines the step when this patch has 100% chances to be burnt
last_partial_consumption_episode	-1	Before megafauna consumption of a patch this variable is set to -1
last_agent_impacted_pft	3	Before simulation starts the vegetation cover is created by climate only. Thus, all patches have value 3
last_agent_impacted_openness	3	Before simulation starts the vegetation cover is created by climate only. Thus, all patches have value 3

Variable name	Value	Explanation
herbs_regeneration_step	0	Before agent's impact all patches do not require regeneration step
shrubs_regeneration_step	0	Before agent's impact all patches do not require regeneration step
needleleaf_trees_regeneration_step	0	Before agent's impact all patches do not require regeneration step
broadleaf_trees_regeneration_step	0	Before agent's impact all patches do not require regeneration step
agent_that_could_impact_neighbouring_paths	0	This value is 0 prior to simulation runs, because there was no impact yet
hominin_accessible_area	0 or 1	If the patch is within accessible area, the value is set to 1. Otherwise, this variable equals 0
raster_layer	-	Used to create .asc file. This variable can have any value depending on chosen patch variable

Table AII.4 Mean FRI for each dominant PFT.

PFT	Mean FRI estimated via MODIS
Needleleaf trees	246
Broadleaf trees	426
Shrubs	286
Herbs	293

Table AII.5 CARAIB and REVEALS conflicting cells excluded from the analysis during initiation stage.

CARAIB	REVEALS	Reason
Possible natural (CARAIB) vegetation openness is higher than observed vegetation openness	Maximal observed (REVEALS) vegetation openness (i.e., estimated vegetation openness + standard error) is lower than possible natural (CARAIB) vegetation openness.	In the current ABM possible natural vegetation openness cannot be higher than pollen-based vegetation openness.
First dominant PFT: herbs/shrubs	First dominant PFT: trees	In the current ABM trees cannot dominate if climatic conditions only allow dominance of herbs or shrubs.
First dominant PFT: trees/herbs	First dominant PFT: shrubs	In the current ABM shrubs cannot dominate if climatic conditions only allow dominance of trees or herbs.

Once the environment is created, hominins and their campsites are randomly distributed on surfaces with vegetation. The number of campsites and hominins is defined via the `Number_of_groups` parameter. Patches around campsites are defined as accessible areas. The `Accessible_radius` parameter defines the size of this area in the number of grid cells around campsites, and the `hominin_accessible_area` state variable equals 1 for patches within the accessible area. Hominins cannot move beyond their foraging areas, on water bodies (sea, big lakes, and main rivers) high mountains. These are the patches with absolute elevations more than 2500 m. Water bodies and the most elevated areas do not have vegetation cover, and, therefore, cannot be burnt or consumed. Except for the `patch_elevation` and `patch_lakes`, patches with high mountains and water bodies have -1 for their state variables.

AII.6 Input data (after Nikulina et al., 2024b)

The simulation uses several datasets (Table AII.6). To standardize their spatial extent and resolution Spatial Analysts and Data management *ArcMap* 10.6.1 toolboxes were used. Grid cell sizes of the datasets were resampled to 10 km × 10 km.

The initial landscape before simulation runs were reconstructed via the following datasets: GTOPO30, Water Information System for Europe (WISE) and three outputs of a dynamic vegetation model CARbon Assimilation In the Biosphere (CARAIB). GTOPO30 is a digital elevation model (DEM) derived from several raster and vector sources of topographic information. We used this DEM to represent elevation data in the ABM. WISE dataset is based on the information from the Water Framework Directive database, and we used WISE to define the distribution of major rivers and lakes (natural barriers for fire spread) in the model.

In the context of this research, the CARAIB dataset represents theoretical potential natural vegetation (PNV) distribution driven by climatic conditions only. As an input climate we used climatic variables simulated by the iLOVECLIM model with embedded online interactive downscaling. The iLOVECLIM-simulated climatic variables were bias-corrected using the CDF-t bias correction technique and averaged over the studied period to get daily mean climate characteristics of our period of interest. A full description of the modelling setup and the application of the CDF-t technique within this setup is described and tested.

CARAIB outputs used in this study include distribution of fractions of 26 plant functional types (PNV PFTs), vegetation openness (PNV openness), leaf area index (LAI) and net primary productivity (PNV NPP) for the period 9200–8700 BP. Before being imported to the ABM, the mentioned CARAIB outputs were transformed. As the CARAIB dataset here represents climate-only forced vegetation, it is used in

the current ABM as the starting point (i.e., before impact of humans, natural fires and megafauna) of each simulation and as target for vegetation regrowth after impacts.

Table AII.6 Input datasets to the simulation environment (after Nikulina et al., 2024b).

Dataset	Initial data type	Initial spatial resolution/scale	Meaning, units
GTOPO30	Raster	1 km	Digital elevation model, m
WISE	Vector	1:10000000	Distribution of large rivers and lakes
CARAIB first dominant PFT	Raster	~26 km (0.25°)	Potential natural (climate-based) first dominant PFT
CARAIB vegetation openness			Potential natural (climate-based) vegetation openness, in percentage
NPP			Potential net primary carbon productivity (excluding carbon used for respiration), g/m ²
Megafauna vegetation consumption	Raster	30 km	Potential maximal megafauna vegetation consumption (i.e., metabolization of NPP), kg/km ² (converted to g/m ²)
REVEALS first dominant PFT	Vector	~100 km (1°)	Observed past first dominant PFT
REVEALS vegetation openness			Observed past vegetation openness, in percentage
REVEALS vegetation openness standard errors			Standard errors for estimates of observed past vegetation openness.

AII.7 Submodels (after Nikulina et al., 2024b)

AII.7.1 Climatic impact

The vegetation regrowth after the impact of thunderstorms, megafauna, and/or humans is determined by the climatic conditions. Therefore, this submodel only modifies grid cells that were previously burned or consumed, and during the first simulation step, it does not alter vegetation openness and PFT of patches.

The grid cells' `patch_openness Updating` and `patch_pft Updating` (Figs. AII.2 and AII.3) are changed in response to the climatic impact until they match the values of `patch_natural_openness` and `patch_natural_pft`, respectively. If the difference between `patch_natural_openness` and `patch_openness Updating` is equal to or less than 10%, the grid cell is considered to have recovered naturally, and the last agent that impacted this patch is assumed to be the climate (`last_agent_impacted_openness` = 3). Similarly, if `patch_natural_pft` is equal to `patch_pft Updating`, the last agent that impacted the PFT of this grid cell is climate (`last_agent_impacted_pft` = 3).

We used the CARAIB mean number of years to recover (Table AII.7) to calculate the vegetation openness recovery rate and to define the step when natural PFT would reestablish on the grid cell after vegetation burning and/or consumption. PFT recovery on all impacted patches always begins with herbs, which replace bare ground after seven simulation steps. Subsequently, depending on the initial dominant PFT estimated by CARAIB after the required number of years since fire or complete consumption (Table AII.7), the herbs may be replaced by trees or shrubland.

After megafauna plant consumption, natural and anthropogenic fires the rate of vegetation openness recovery (V_{or}) is calculated via the following formula (AII.2):

$$V_{or} = \frac{O_i - O_c}{\mu} \quad (\text{AII.2})$$

O_i represents the vegetation openness after the impact caused by fire or megafauna, O_c refers to the CARAIB estimates of vegetation openness, and μ – the mean number of years required for recovery of the initial vegetation openness prior to the fire event or plant consumption (Table AII.7). During each simulation step, V_{or} is subtracted from the current simulation openness until it reaches the CARAIB estimates of vegetation openness.

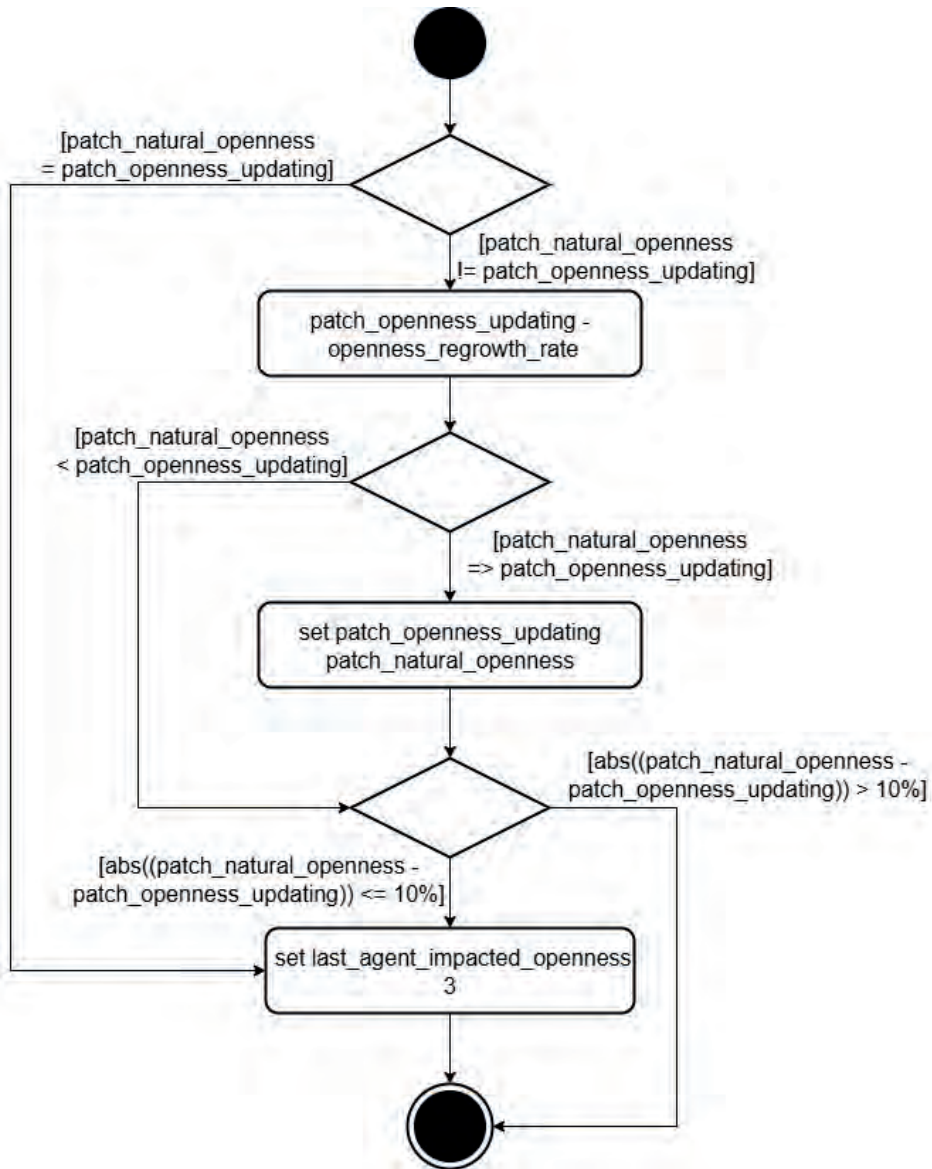
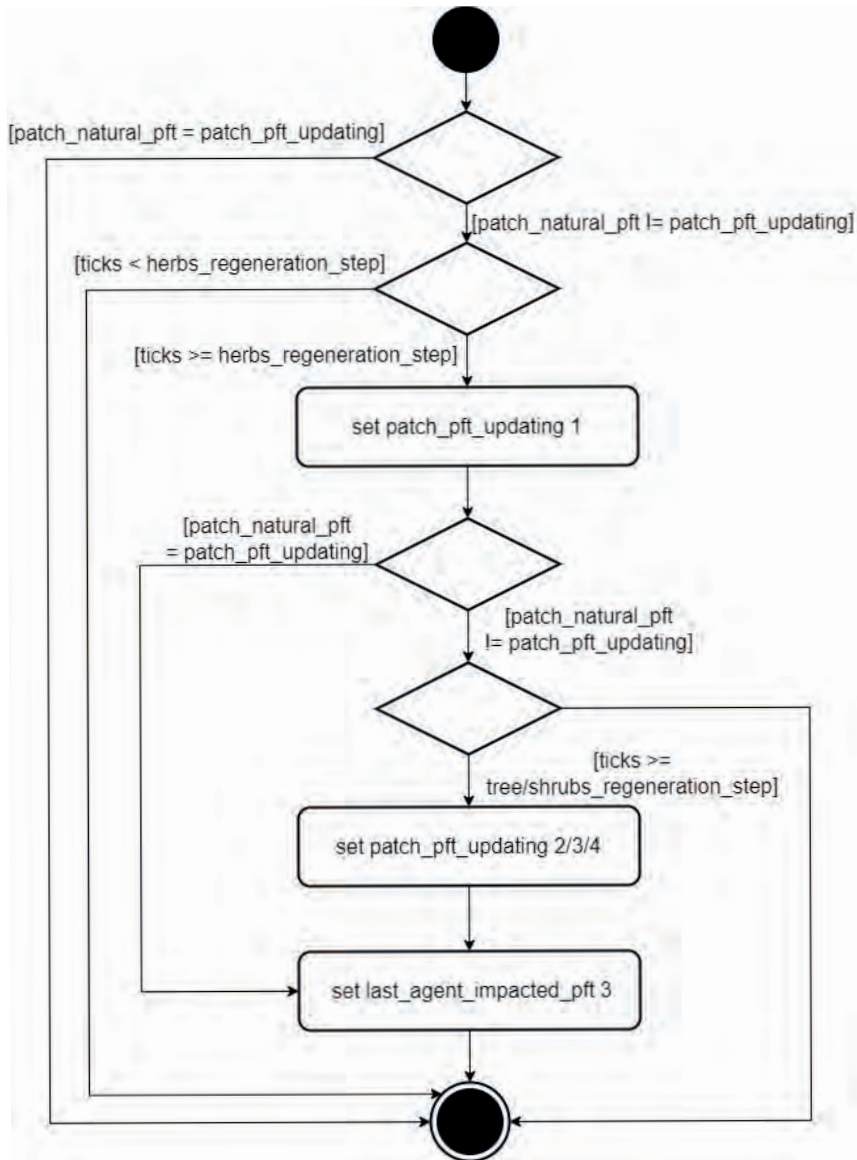


Figure AII.2 Activity diagram for climatic impact on vegetation openness.



A2

Figure AII.3 Activity diagram for climatic impact on distribution of dominant PFTs.

Table AII.7 Mean number of years to recover for each dominant PFT (after Nikulina et al., 2024b).

PFT	Number of years
Needleleaf trees	43
Broadleaf trees	30
Shrubs	43
Herbs	7

AII.7.2 Anthropogenic impact

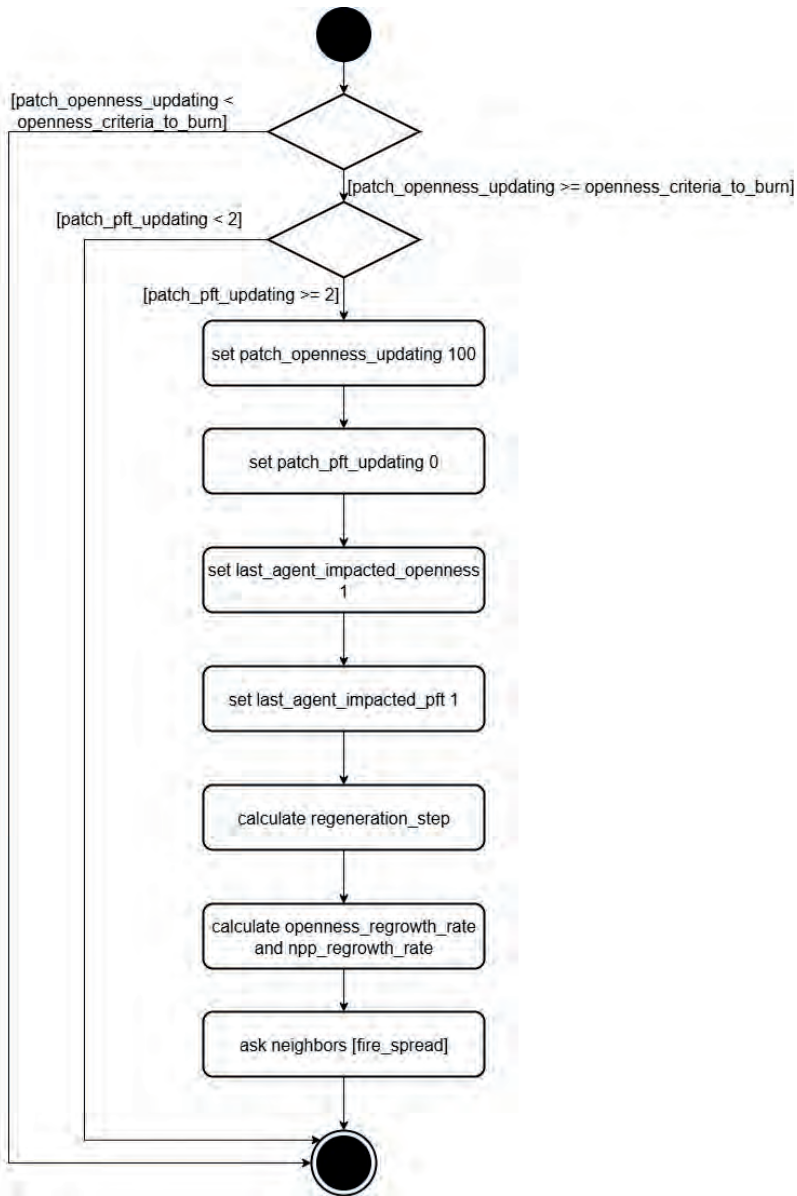
This submodel introduces changes to the vegetation through human-induced fires. There are five parameters which define human behaviour and intensity of their impact: `Number_of_groups`, `Accessible_radius`, `Campsites_to_move`, `Movement_frequency_of_campsites`, and `Openness_criteria_to_burn`.

The first parameter defines the number of hunter-gatherer groups present at the study area during one simulation run, and, therefore, this parameter is associated with human population size. The accessible radius parameter defines the territory within which humans move and set fires around campsites.

Due to the importance of mobility for hunter-gatherer lifestyle, there are two parameters associated with movements of foragers: `Movement_frequency_of_campsites` (the number of simulation steps after which a group can relocate their campsite) and `Campsites_to_move` (the percentage of groups that relocate a campsite at certain step defined by movement frequency). Due to the temporal resolution of the current simulation, hunter-gatherers' highest possible frequency of camp movements is every step (i.e., once per year). The search radius for the new grid cell to establish a site is twice bigger than the accessible radius. Any grid cell can be chosen for the new site, except the previously occupied grid cell. The newly established accessible area can overlap with the previous one.

Since hunter-gatherers have different reasons to burn landscapes, and that this practice was documented in almost all vegetation types with more cases for foragers occupying shrublands and forests, the openness criteria to burn was introduced. In the current simulation, humans only burn grid cells dominated by trees or shrubs with vegetation openness lower or equal to this criterion. A low value minimizes the number of positive decisions to start a fire, and higher values increase human-induced fires, because even relatively open areas can be burnt by people in this case.

Humans randomly move between adjacent patches within a defined area determined by the `Accessible_radius` (the number of grid cells) around campsites. When a human is present on a patch with vegetation openness that is equal to



A2

Figure AII.4 Activity diagram for anthropogenic impact.

or lower than the prescribed criteria for burning and contains shrubs or trees ($\text{patch_pft_updating} \geq 2$), this human sets fire on that patch. Consequently, the openness of the patch is updated to 100% (completely open), and its PFT ($\text{patch_pft_updating}$) is set to 0, indicating a burnt area. In this scenario, the variables $\text{last_agent_impacted_openness}$ and $\text{last_agent_impacted_pft}$ are assigned a value of 1 to denote anthropogenic impact. The time step at which this burning event occurs is recorded as $\text{last_burning_episode}$, and $\text{next_burning_episode}$ is updated based on the dominant natural PFT (Table AII.4). Subsequently, after calculating the regeneration steps (ticks + number of years from Table AII.4) and openness regrowth rates (Section AII.7.1), the spread of vegetation to neighbouring patches is initiated (Section AII.7.4).

AII.7.3 Natural fires

Based on the value of the parameter $\text{Territory_impacted_by_thunderstorms}$, the number of grid cells experiencing thunderstorms per simulation step is determined. This parameter is expressed as a percentage, and based on its value, the calculation determines how many grid cells will be affected by thunderstorms. These thunderstorms randomly occur on different grid cells within the study area. It is important to note that thunderstorms can occur over rivers, lakes, and high mountains, but these areas are not susceptible to burning.

Following the occurrence of thunderstorms, fires may initiate fire spread depending on the probability of ignition for the affected grid cells (Fig. AII.5). The spread of fire (Section AII.7.4) to neighbouring grid cells can occur after both human-induced and natural fires. Thunderstorms do not always result in vegetation burning, and the ignition of fire does not always lead to its propagation after natural or human-induced ignitions.

The probability of ignition $P(I)$ is determined based on the time elapsed since the last burning episode (B) and the FRI (F), obtained from the MODIS dataset (Table AII.4) (AII.3):

$$P(I) = \frac{T-B}{F} \quad (\text{AII.3})$$

Here, T represents the number of simulation steps (ticks) since the beginning of the simulation. If the probability of ignition is equal to or higher than a randomly chosen number (ignt , as shown in Fig. AII.5), the corresponding patch will be burnt. The consumption of patches by megafauna impacts the probability of ignition. Depending on the percentage of vegetation consumed (as described in Section AII.7.5), the occurrence of the next burning episode can be delayed. To calculate the probability of delayed ignition, the same formula is used, but

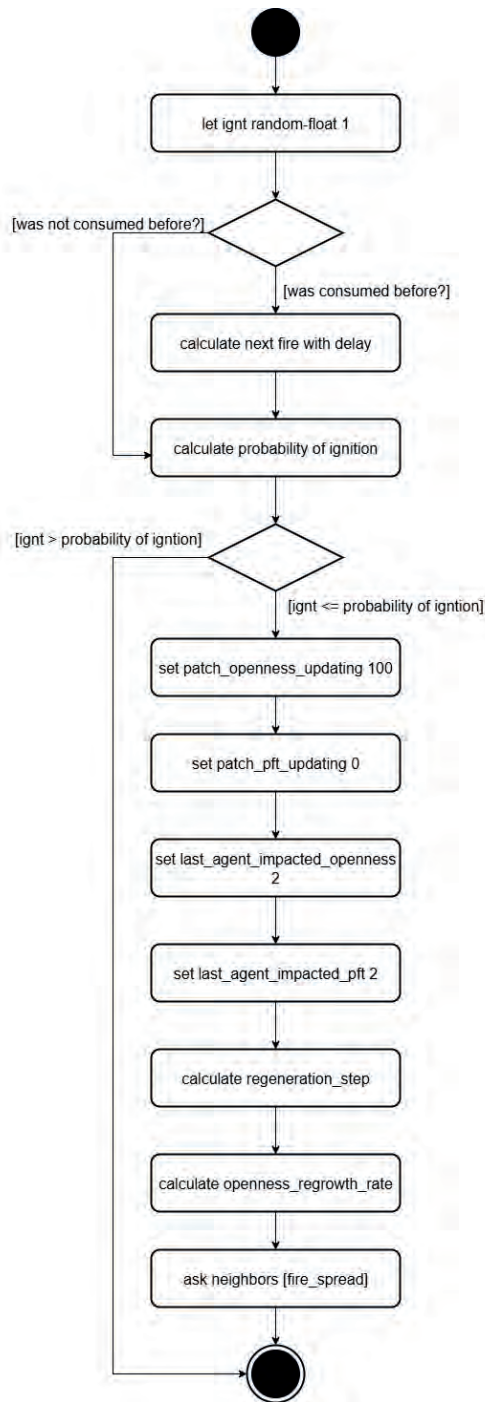


Figure AII.5 Activity diagram for thunderstorm impact.

with a modification: instead of using the current number of ticks (T), we use the sum of T and fire_delay_after_consumption. This patch state variable represents the number of years by which the next burning episode was postponed due to megafauna vegetation consumption (Section AII.7.5). The value of B is also updated as a result of megafauna impact (details provided below).

Once a patch is burned (indicated by patch_pft Updating = 0 and patch_openness Updating = 100), the regrowth rate of openness (Section AII.7.1) and the steps for PFT regeneration (ticks + number of years from Table AII.5) are determined. Additionally, the information of the last agent that impacted the patch is updated (Section AII.7.1). Subsequently, the neighbouring patches are prompted to spread the fire as explained in Section AII.7.4.

AII.7.4 Fire spread

Following natural and anthropogenic burning, fire has the potential to spread to neighbouring patches. However, the actual ignition of these patches depends on the probability of ignition, which is calculated using the same method described for natural fires in Section AII.7.3. If a patch is burnt because of fire spread, it will inherit the same values for last_agent_impacted_pft and last_agent_impacted_openness as the patch from which the fire spread originated.

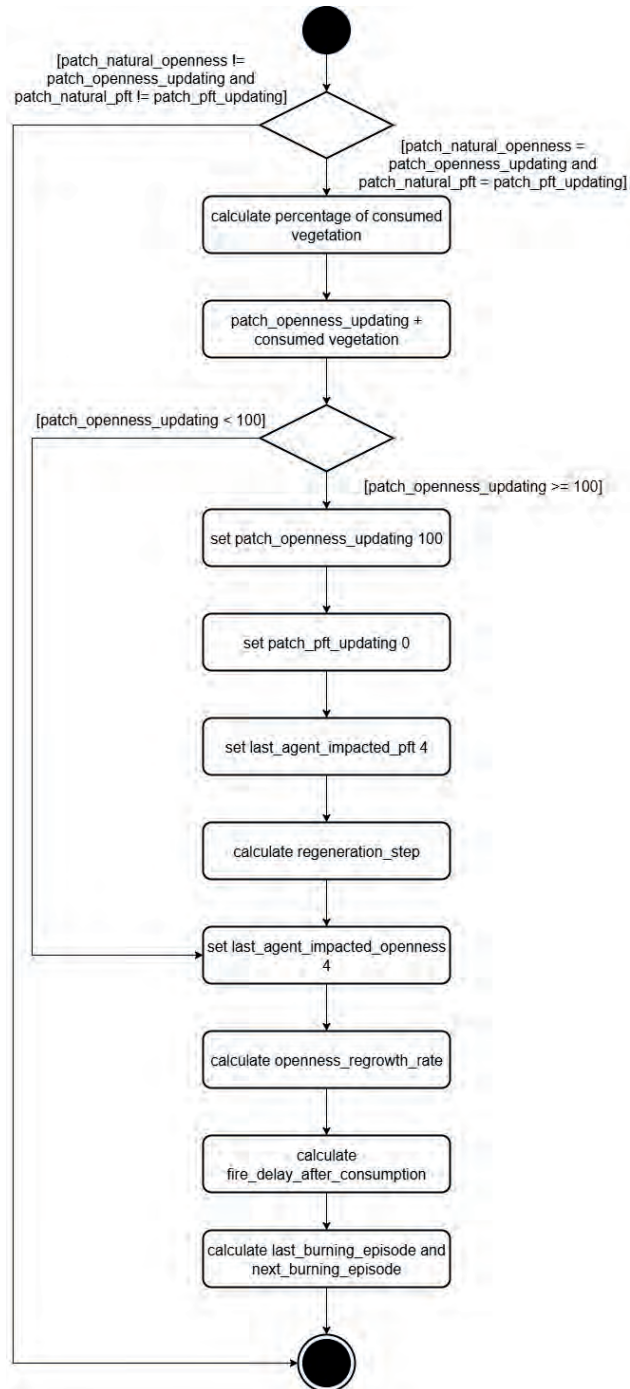
AII.7.5 Megafauna consumption

Megafauna is the final agent responsible for vegetation transformation in the model (Fig. AII.6). Only grid cells with fully recovered vegetation are susceptible to consumption by megafauna. Following plant consumption, the vegetation openness increases based on CARAIB NPP values and estimates of maximal megafauna plant consumption.

Regarding the impact of megafauna on PFTs, it is assumed that megafauna consumes all PFTs present on a grid cell in equal proportions, besides the first dominant PFT. Therefore, if the vegetation is entirely consumed by megafauna and the vegetation openness reaches 100%, the first dominant PFT is replaced with bare ground. In such cases, both last_agent_impacted_pft and last_agent_impacted_openness are assigned a value of 4, indicating that the impact was caused by megafauna. However, if the dominant PFT remains unchanged after megafauna consumption, only last_agent_impacted_openness is updated.

The percentage of vegetation consumed (V_c) is calculated for each grid cell, excluding water bodies and high mountains, using the following formula (AII.4):

$$V_c = \frac{V_m}{V_n} \times 100 \quad (\text{AII.4})$$



A2

Figure AII.6 Activity diagram for megafauna impact.

V_m represents the grid cell value for potential maximal megafauna metabolization of NPP, and V_n corresponds to the CARAIB NPP. Once the percentage of consumed vegetation is calculated for a grid cell, this value is added to the existing vegetation openness to increase it after the impact of megafauna. Furthermore, the first dominant PFT is updated based on the resulting vegetation openness after vegetation consumption.

When there is partial consumption of vegetation by megafauna (i.e., when the first dominant PFT remains unchanged), it leads to delays in fire activity because time is required to accumulate plant material that can be burnt. The number of years by which fire activity is delayed is calculated by multiplying with the FRI of the respective PFT at the patch (Table AII.4). Consequently, depending on the percentage of vegetation consumed, the time step at which the vegetation has a 100% probability of being burnt in the presence of an ignition source is postponed.

Appendix III
Supplementary data to Nikulina et al.
(in press)

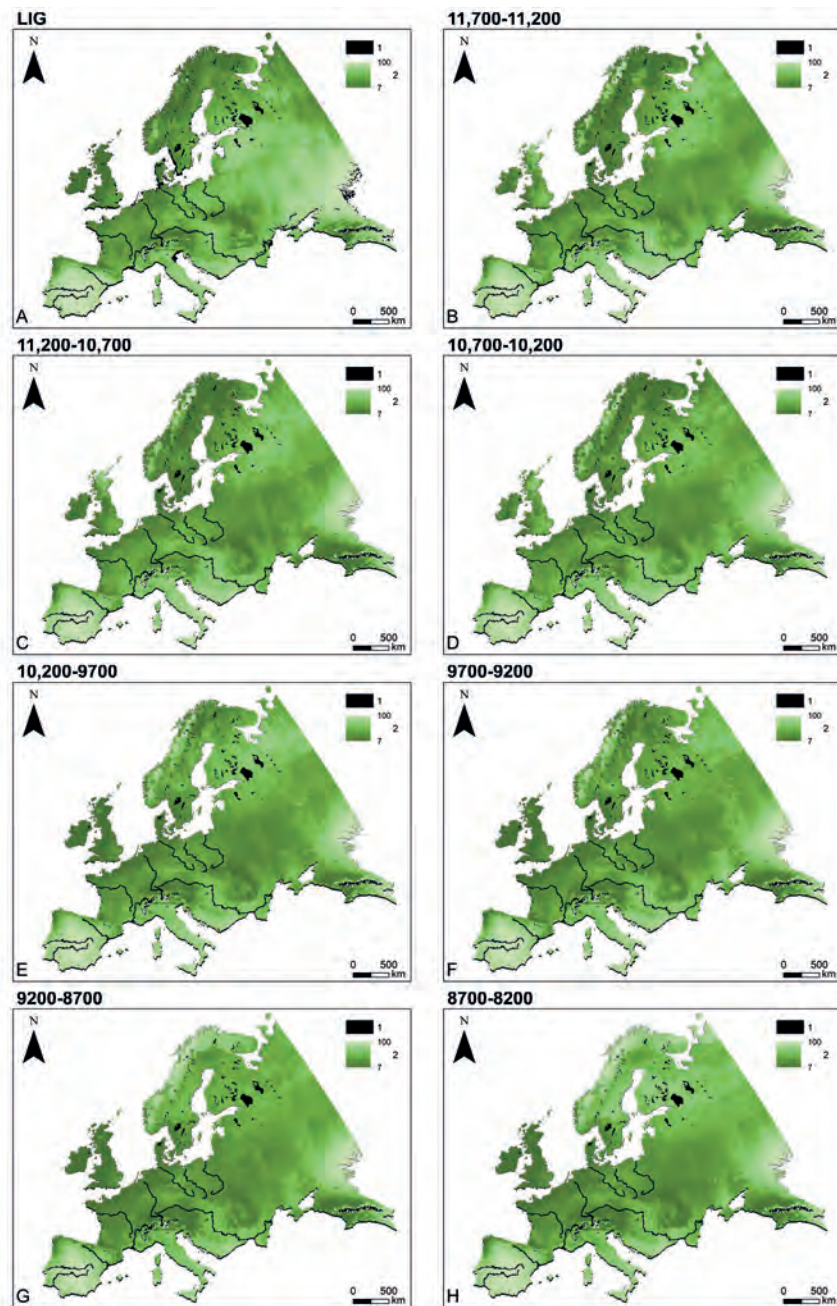
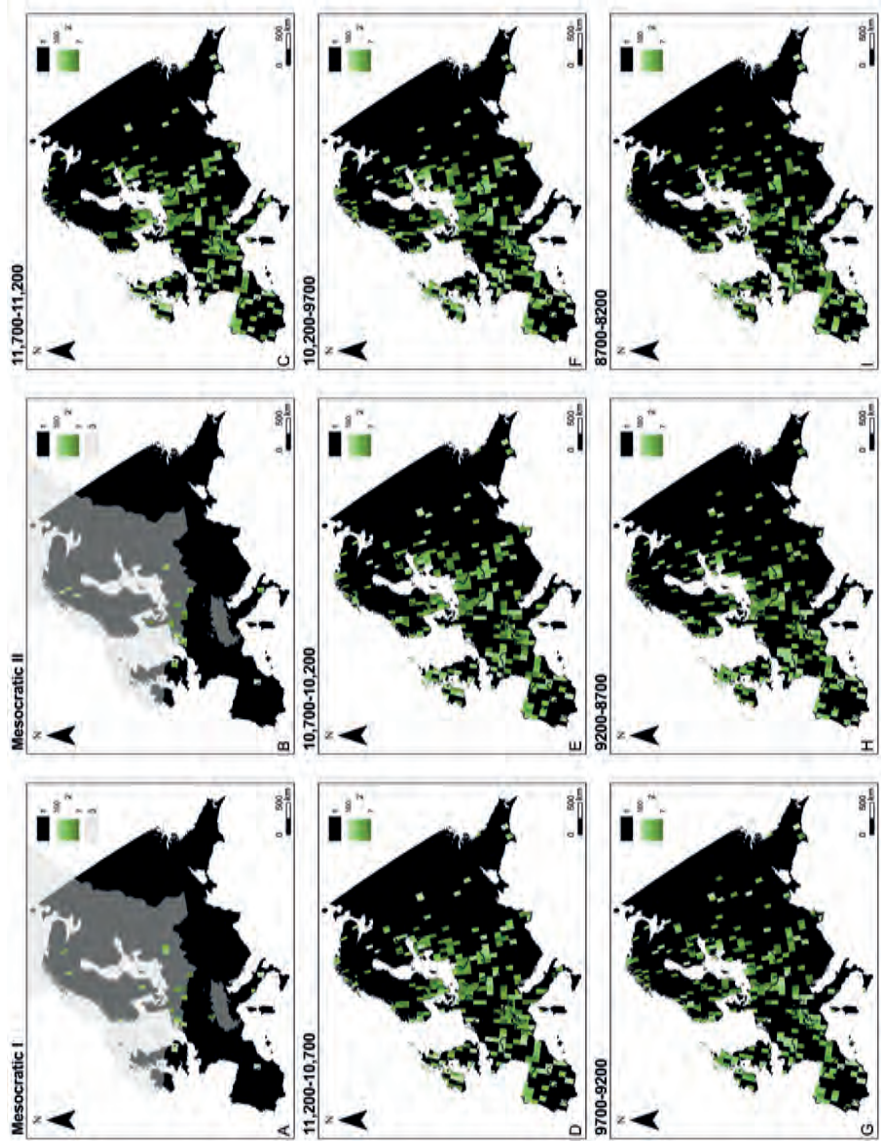


Figure AIII.1 CARAIB vegetation openness for the Last Interglacial (A), 11,700–11,200 BP (B), 11,200–10,700 (C), 10,700–10,200 (D), 10,200–9700 (E), 9700–9200 (F), 9200–8700 (G), 8700–8200 BP (H). Legend: 1–no data, 2–vegetation openness (in %).

Figure AIII.2
REVEALS vegetation
openness for
Mesocratic I (A),
Mesocratic II (B),
11,700–11,200 BP (C),
11,200–10,700 (D),
10,700–10,200 (E),
10,200–9700 (F), 9700–
9200 (G), 9200–8700
(H), 8700–8200 BP (I).
Legend: 1–no data, 2–
vegetation openness
(in %); 3–The northern
European and Alpine
Saalian glaciation
(Lehmkuhl et al., 2021;
Svendsen et al., 2004).



A3

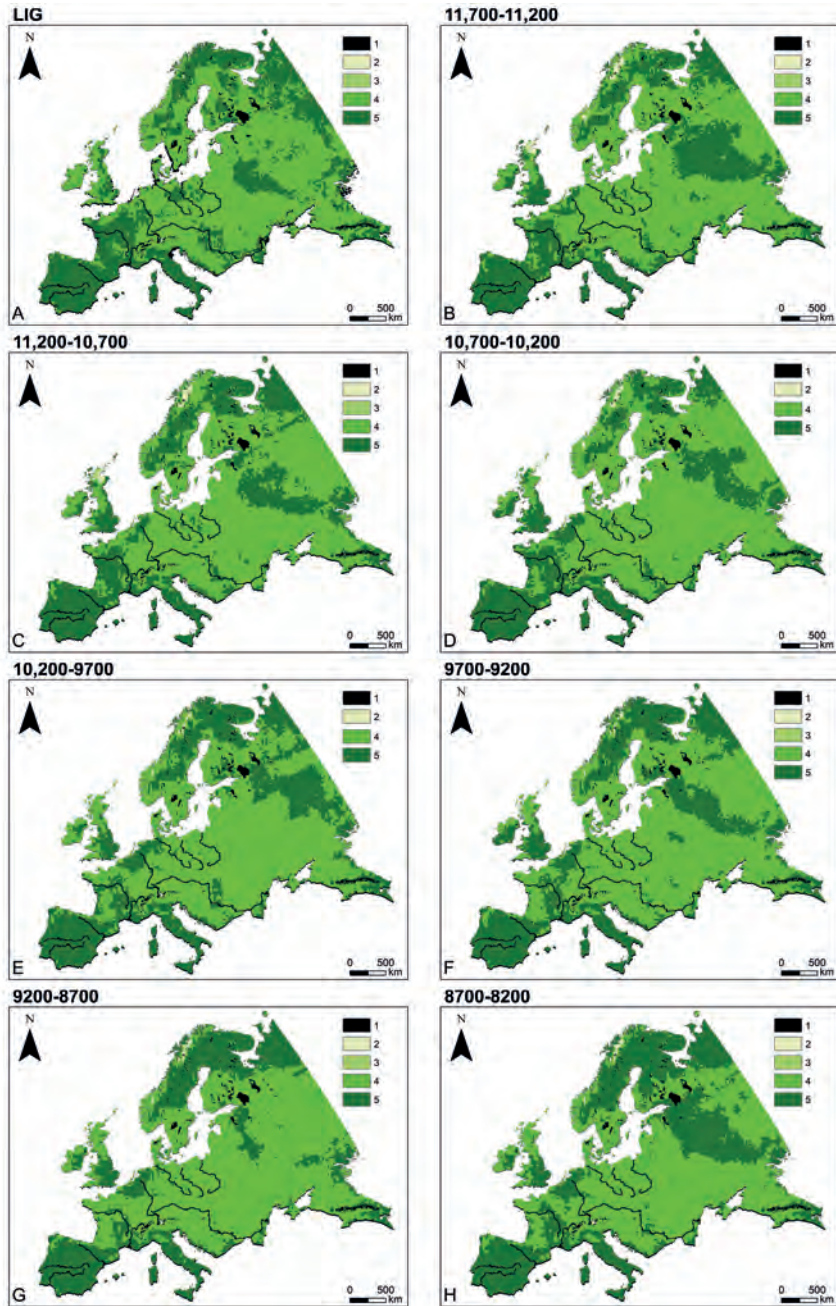
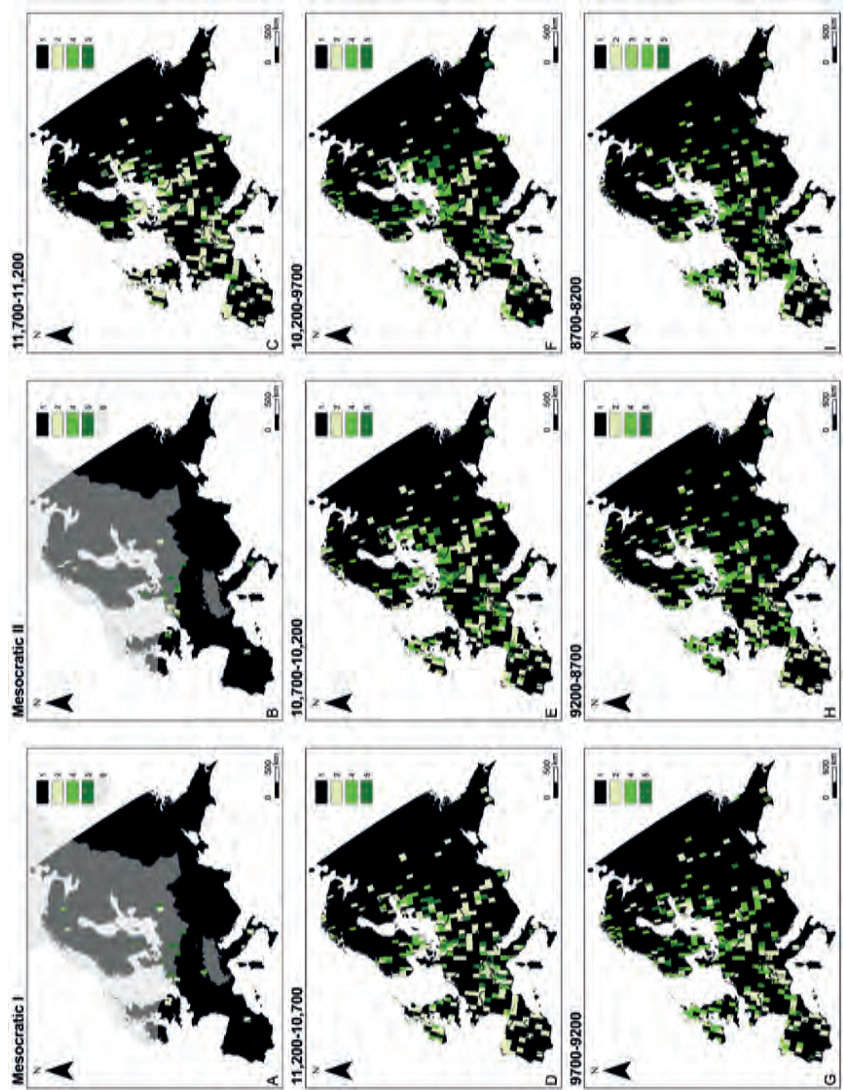


Figure AIII.3 CARAIB distribution of the first dominant PFTs for the Last Interglacial (A), 11,700–11,200 BP (B), 11,200–10,700 (C), 10,700–10,200 (D), 10,200–9700 (E), 9700–9200 (F), 9200–8700 (G), 8700–8200 BP (H). Legend: 1–no data, 2–herbs, 3–shrubs; 4–broadleaf trees; 5–needleleaf trees.

Figure AIII.4 REVEALS distribution of the first dominant PFTs for Mesocratic I (A), Mesocratic II (B), 11,700–11,200 BP (C), 11,200–10,700 (D), 10,700–10,200 (E), 10,200–9700 (F), 9700–9200 (G), 9200–8700 (H), 8700–8200 BP (I). Legend: 1–no data, 2–herbs, 3–broadleaf trees; 4–needleleaf trees, 5–the northern European and Alpine Saalian glaciation (Lehmkuhl et al., 2021; Svendsen et al., 2004).



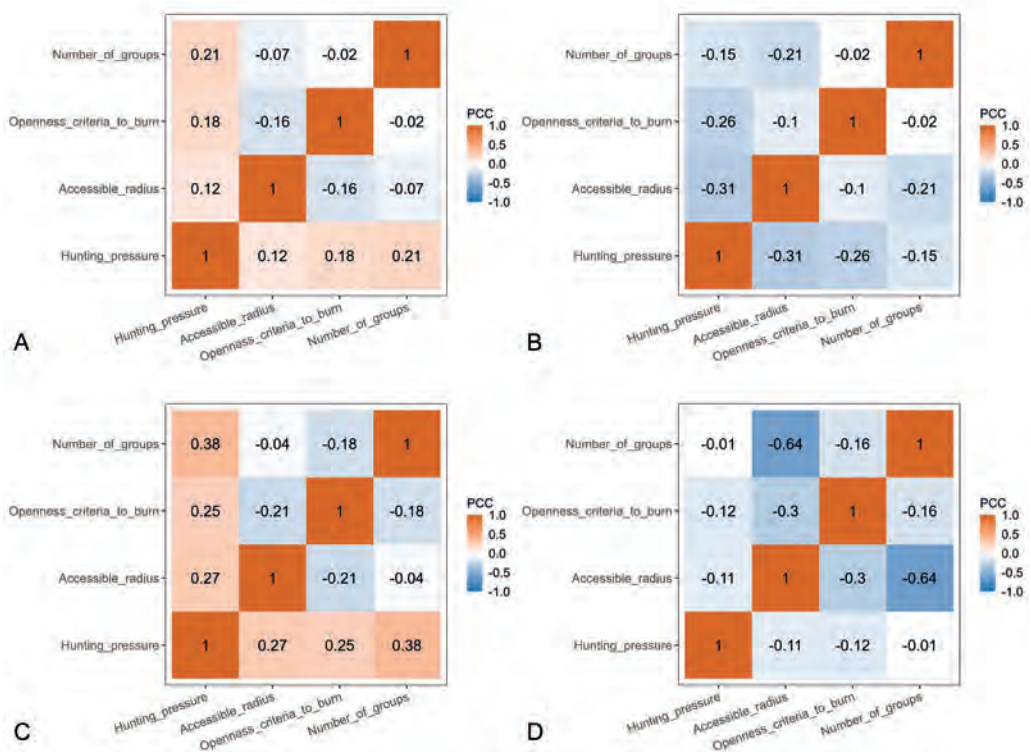


Figure AIII.5 Correlation matrices and Pearson correlation coefficients (PCC) between variables of the possible scenarios for LIG (A) and Early Holocene (B) tree distribution scenarios; LIG (C) and Early Holocene (D) vegetation openness scenarios. The experiments include the combined direct impact of all agents on vegetation: anthropogenic and natural fires, climatic impact and megafauna plant consumption. The darkest blue indicates the strongest negative correlation between the Number_of_groups and Accessible_radius parameters within the Early Holocene vegetation openness scenarios. Lighter colours represent either absent/low or modest correlations for the other parameters.

Table AIII.1 PFTs used in ABM (HUMLAND PFTs) and correspondence between CARAIB PFTs and REVEALS plant taxa (after Nikulina et al., 2024b).

CARAIB PFTs	Plant taxon / pollen morphological types	HUMLAND PFTs
Needle-leaved evergreen boreal/temp cold trees Needle-leaved evergreen meso mediterranean trees Needle-leaved evergreen subtropical trees Needle-leaved evergreen supra mediterranean trees Needle-leaved evergreen temperate cool trees Needle-leaved summergreen boreal/temp cold trees Needle-leaved summergreen subtropical swamp trees	<i>Abies</i> <i>Picea</i> <i>Pinus</i> <i>Juniperus</i>	Needleleaf trees
Broadleaved evergreen meso mediterranean trees Broadleaved evergreen subtropical trees Broadleaved evergreen thermo mediterranean trees Broadleaved evergreen tropical trees Broadleaved raingreen tropical trees Broadleaved summergreen boreal/temp cold trees Broadleaved summergreen temperate cool trees Broadleaved summergreen temperate warm trees	<i>Alnus</i> <i>Betula</i> <i>Carpinus betulus</i> <i>Carpinus orientalis</i> <i>Castanea sativa</i> <i>Corylus avellana</i> <i>Fagus</i> <i>Fraxinus</i> <i>Phillyrea</i> <i>Pistacia</i> deciduous <i>Quercus</i> t. evergreen <i>Quercus</i> t. <i>Salix</i> <i>Tilia</i> <i>Ulmus</i>	Broadleaf trees
Broadleaved evergreen boreal/temp cold shrubs Broadleaved evergreen temperate warm shrubs Broadleaved evergreen xeric shrubs Broadleaved summergreen arctic shrubs Broadleaved summergreen boreal/temp cold shrubs Broadleaved summergreen temperate warm shrubs Subdesertic shrubs Tropical shrubs	<i>Buxus sempervirens</i> <i>Calluna vulgaris</i> Ericaceae	Shrubs
C3 herbs ("dry") C3 herbs ("humid") C4 herbs	Amaranthaceae/Chenopodiaceae <i>Artemisia</i> Cerealia t. Cyperaceae <i>Filipendula</i> <i>Plantago lanceolata</i> Poaceae <i>Rumex acetosa</i> t. <i>Secale cereale</i>	Herbs

Table AIII.2 Datasets used in HUMLAND (after Nikulina et al., 2024b)

Dataset	Initial data type	Initial spatial resolution/scale	Meaning, units	Source
GTOPO30	Raster	1 km	Digital elevation model, m	https://www.usgs.gov/
WISE	Vector	1:10,000,000	Distribution of large rivers and lakes	https://water.europa.eu/
CARAIB first dominant PFT	Raster	~26 km (0.25°)	PNV: first dominant PFT	http://www.umccb.ulg.ac.be/Sci/m_car_e.html
CARAIB vegetation openness			PNV: vegetation openness (%)	
NPP			PNV NPP (excluding carbon used for respiration), g/m ²	
Mega fauna vegetation consumption	Raster	30 km	Potential maximal mega fauna vegetation consumption (i.e., metabolism of NPP), kg/km ² (converted to g/m ²)	Davoli et al., 2023, 2024
REVEALS first dominant PFT	Vector	~100 km (1°)	Pollen-based first dominant PFT	Serge et al., 2023
REVEALS vegetation openness			Pollen-based past vegetation openness (relative %)	
REVEALS vegetation openness standard errors			Standard errors for estimates of pollen-based past vegetation openness	

Table AIII.3 PCA results for the successful genetic algorithm outputs aiming to minimize the HUMLAND–REVEALS difference in mean percentage of grid cells dominated by trees. The experiments include the combined impact of all agents on vegetation: anthropogenic and natural fires, hunting, climatic impact and megafauna plant consumption.

Variables		Openness_ criteria_to_burn	Hunting_ pressure	Number_of_ groups	Accessible_ radius
Time windows					
Mesocratic I	Comp. 1 (54.2%)	0.54	0.07	0.36	-0.74
	Comp. 2 (26.1%)	-0.63	0.24	0.72	-0.08
Mesocratic II	Comp. 1 (46.7%)	0.78	0.04	-0.44	-0.42
	Comp. 2 (36.5%)	0	0.06	0.69	-0.71
10,200–9700 BP	Comp. 1 (44.7%)	-0.31	0.17	-0.67	-0.63
	Comp. 2 (36%)	-0.18	0.82	-0.17	-0.5
9700–9200 BP	Comp. 1 (48.3%)	-0.31	0.48	-0.68	0.44
	Comp. 2 (30.4%)	-0.01	0.69	0.02	-0.72
9200–8700 BP	Comp. 1 (51.2%)	-0.51	0.65	0.33	-0.43
	Comp. 2 (28%)	-0.66	0	-0.05	0.74
8700–8200 BP	Comp. 1 (47.8%)	-0.27	0.58	0.31	0.69
	Comp. 2 (33.9%)	-0.38	0.53	-0.69	0.29

Table AIII.4 PCA results for the successful genetic algorithm outputs aiming to minimize the HUMLAND–REVEALS difference in mean vegetation openness. The experiments include the combined impact of all agents on vegetation: anthropogenic and natural fires, hunting, climatic impact and megafauna plant consumption.

Variables		Openness_ criteria_to_burn	Hunting_ pressure	Number_ of_groups	Accessible_ radius
Time windows					
Mesocratic I	Comp. 1 (58.8%)	-0.74	0.09	0.40	0.51
	Comp. 2 (29.4%)	-0.02	0.11	-0.75	-0.65
Mesocratic II	Comp. 1 (45.1%)	0.77	0.01	-0.17	-0.61
	Comp. 2 (43.7%)	-0.22	0.24	-0.79	-0.51
10,200–9700 BP	Comp. 1 (59.9%)	0.16	0.25	0.63	-0.71
	Comp. 2 (27%)	-0.84	0.44	0.24	0.17
9700–9200 BP	Comp. 1 (50.3%)	-0.16	0.39	0.64	-0.62
	Comp. 2 (33.8%)	-0.83	0.1	0.2	0.49
9200–8700 BP	Comp. 1 (61.7%)	-0.14	0.09	0.67	-0.72
	Comp. 2 (21.4%)	-0.85	0.47	0.19	0.06
8700–8200 BP	Comp. 1 (56%)	0.12	0.05	0.67	-0.72
	Comp. 2 (27.8%)	-0.81	0.52	0.22	0.1

Table AIII.5 Mean, mode and standard deviation (SD) for parameter values obtained via the genetic algorithm with outputs similar to REVEALS. The distribution of parameter values is in Fig. 4.7 of the main body of the article.

Time windows	Parameters and experiment types																	
	Openness_to_burn						Hunting_pressure						Number_of_groups					
	Trees			Openness			Trees			Openness			Trees			Openness		
	Mean	SD	Mode	Mean	SD	Mode	Mean	SD	Mode	Mean	SD	Mode	Mean	SD	Mode	Mean	SD	Mode
LIG	77	14	55	49	23	48	24	29	4	34	13	21	3266	591	3323	1936	1136	563
												22						
												23						
												24						
												25						
	77	77	78	50	24	48	22	33	4	33	15	27						
												31						
												39						
												21						
												22						
Mesocratic I	79	13	78	48	22	23	27	33	4	33	15	23	3381	488	3323	2044	1122	139
												24						1087
												25						2017
												39						2515
Mesocratic II	75	15	55	50	24	48	22	25	0	35	11	27	3156	657	2943	1830	1140	563
												31						
												39						
												1						

Time windows	Parameters and experiment types																	
	Openness_to_burn						Hunting_pressure						Number_of_groups					
	Openness			Trees			Openness			Trees			Openness			Trees		
	Mean	SD	Mode	Mean	SD	Mode	Mean	SD	Mode	Mean	SD	Mode	Mean	SD	Mode	Mean	SD	Mode
Early Holocene			45			36												
			47			38												
	71	17	57	60	22	42	34	26	4	2895	691	3575	2243	957	1089	3	1	4
			59			62												
			69			69												
10,200–9700 BP						36			1									
									6									
	76	15	57	61	23	62	40	29	10	3071	462	3161	2090	759	1329	3	1	4
									44									
									74									
9700–9200 BP									82									
									35						1188			
	71	15	65	58	22	38	43	26	43	3117	543	3115	2074	897		3	1	4
									57						3453			
9200–8700 BP	68	20	45	60	21	38	28	23	4	2550	911	3453	2342	1085	1627	3	1	4
			59															
8700–8200 BP																		
															1079			
															1460			
	68	17	47	62	23	42	25	21	21	2843	608	2490	2466	998	2901	3	1	4
						69									3315			
															3336			

Table AIII.6 Details of HUMLAND runs conducted to track the extent and visibility of modifications done by each agent.

Time windows	Parameter values							
	Openness_to_burn		Hunting_pressure		Number_of_groups		Accessible_radius	
	Trees	Openness	Trees	Openness	Trees	Openness	Trees	Openness
Mesocratic I	81	29	0	21	3323	139	3	4
		29		23		1091		2
		37		26		2017		1
		28		21		2497		3
Mesocratic II	92	33	10	30	2943	563	4	4
10,200–9700 BP	87	47	42	11	3161	1329	4	5
9700–9200 BP	74	72	52	42	3123	1191	4	4
		80		74		3375		1
9200–8700 BP	81	41	75	6	3450	1627	2	1
8700–8200 BP	71	77	14	16	2488	1079	5	3
		72		9		1460		2
		92		10		2901		1
		62		7		3315		1

AIII.1 paleoenvironmental modelling setup

The potential natural vegetation (PNV) simulations in this study were conducted using a modelling framework that combines iLOVECLIM climate model, and VECODE and CARAIB vegetation models. Below, we detail the configurations and roles of each model.

AIII.1.1 ILOVECLIM: paleoclimate simulation

Climate simulations were performed with the iLOVECLIM Earth System model of intermediate complexity (Goosse et al., 2010), revised by Roche (Roche, 2013) and further expanded by Quiquet et al. (Quiquet et al., 2018). The applied version of iLOVECLIM includes the following: the atmospheric model, ECBilt (Opsteegh et al., 1998), the sea-ice ocean component, CLIO (Goosse & Fichefet, 1999), and the reduced-form dynamic global vegetation model (DGVM), VECODE (Brovkin et al., 1997). These components are used to simulate climate.

ILOVECLIM operates on a relatively low spatial resolution T21 grid (5.625° latitude/longitude), which in the current study is increased to 0.25° latitude/longitude through the use of the online interactive downscaling method embedded in iLOVECLIM, first described by Quiquet et al. (Quiquet et al., 2018) and tested within the current modelling setup by Zapolska et al. (Zapolska et al., 2023a).

We applied iLOVECLIM to simulate evolution of the climate during the Holocene and LIG through a set of transient runs. Holocene transient run was resampled to a time step that correspond to REVEALS time windows (TWs): time windows between the year 6200 BP and the year 700 BP were assigned at 500 years temporal resolution, following by fixed time windows at 350 (700–350 BP), 250 (350–100 BP), and 165 (2015 CE–1850). To simulate climate during the Last Interglacial (LIG) we first performed a transient iLOVECLIM run over the whole LIG and identified periods with high forest fraction in VECODE outputs: 120,000 BP, 124,000 BP, and 128,000 BP. For these three periods we performed equilibrium climate simulations, which were used to drive the CARAIB model. The transient experiments were initialised with states derived from 3000-year long equilibrium simulations at 11,700 BP (early Holocene) and 129,000 BP (early LIG).

For all simulations, we used the following boundary conditions: standardised boundary conditions for palaeoclimate simulations, provided by the Palaeoclimate Modelling Intercomparison Project Phase 4 (PMIP-4) (Kageyama et al., 2017), astronomical parameters from Berger (Berger, 1978), greenhouse gas levels (Raynaud et al., 2000; Schilt et al., 2010), ice sheets from the GLAC-1D reconstruction (Tarasov et al., 2012; Tarasov & Peltier, 2002) as well as evolving

bathymetry and land-ocean mask coherent with those ice-sheet geometries (with the same methodology as Bouttes et al., 2022).

To further improve reliability of the modelled results in context of intercomparison with pollen data, we applied the CDF-t bias correction technique (Vrac et al., 2012) to correct biases of iLOVECLIM modelled results (Zapolska et al., 2023b).

AIII.1.2 VECODE: dynamic vegetation modelling

To provide a necessary climate-biomass feedback loop for the climate simulations we used a reduced-form DGVM VECODE (Brovkin et al., 1997). VECODE simulates eco-physiological characteristics of vegetation and soil dynamics in a manner necessary for climate models of intermediate complexity. Vegetation in VECODE DGVM is described using two plant functional types (PFTs): trees and grass (with bare ground as a dummy type).

VECODE dynamics is coupled with atmospheric and oceanic modules of iLOVECLIM at an annual timestep, which simulates plant and soil behaviours necessary for accurately simulating the first-order vegetation-climate feedback in iLOVECLIM. However, its level of complexity is not enough to reflect fine-scale changes that are typically attributed to human impact on vegetation. Thus, iLOVECLIM-simulated bias corrected climate was used as an input for CARAIB, a more complex vegetation model.

AIII.1.3 CARAIB: high-resolution vegetation modelling

CARAIB (CARbon Assimilation In the Biosphere) is a grid-point process-based dynamic vegetation model that operates at a grid size of the provided input data (here 0.25° latitude/longitude). CARAIB is a comprehensive and mechanistic vegetation model that simulates the vegetation dynamics based on its relationship with climatic and soil conditions.

It combines several modules: hydrological budget (Hubert et al., 1998), canopy photosynthesis and stomatal regulation, carbon allocation and plant growth (Otto et al., 2002), heterotrophic respiration and litter/soil carbon dynamics, plant competition and biogeography. CARAIB outputs used in this ABM include distribution of fractions of 26 PFTs (PNV distribution), PNV vegetation openness, and potential natural NPP per 26 km × 26 km grid cell.

To simulate the potential natural vegetation during the Holocene we conducted a series of equilibrium runs with the same boundary conditions and spatio-temporal resolution as iLOVECLIM, using its simulated climate as input and obtaining CARAIB-simulated PNV.

REVEALS estimates for LIG provide data for the highest forested period during the LIG without specifying time bounds of such period. Hence, to represent the peak of forest fraction in LIG we performed three equilibrium CARAIB simulations at 120,000 BP, 124,000 BP, and 128,000 BP. These three periods were selected due to their high forested fraction in VECODE outputs (integrated vegetation module within iLOVECLIM climate model). These simulations (not shown) determined that 128,000 BP had the highest forest fraction during the LIG within our setup. The corresponding CARAIB output for this period was thus used in the HUMLAND 2.0 LIG simulations.

AIII.2 Pearson correlation coefficients and principal component analysis

In Figure AIII.5, the variables within the LIG dataset have both positive and negative correlations, while in the Early Holocene results, correlations are exclusively negative (blue). The magnitudes of the correlation coefficients between parameters are generally modest or low/absent for both LIG (-0.21–0.38) and the Early Holocene (-0.3–0) experiments. Relatively strong correlation (-0.64) is identified between the `Number_of_groups` and `Accessible_area` parameters within the vegetation openness experiments (Figure AIII.5D).

PCA results show that contribution of some variables to principal components (i.e., new variables that are derived from an original set of variables to reduce the dimensionality of data) vary through time and genetic algorithm experiment groups (i.e., minimization of the difference in mean vegetation openness or in percentage of grid cells dominated by trees). The distinct result is that the absolute loadings (i.e., how much a variable contributes to the component) of the `Hunting_pressure` parameter are overall lower for LIG results than for the Holocene runs (Tables AIII.3 and AIII.4). The absolute loadings of the `Openness_criteria_to_burn` parameter are relatively high for the LIG results regarding PFT distribution (Table AIII.4). The absolute loadings of this parameter slightly decrease for the dominance of trees experiments in the earlier part of the Early Holocene, and increase again during 9200–8700 BP (Table AIII.4). The absolute loadings for the `Number_of_groups` and the `Accessible_radius` parameter are relatively high for all time periods (Tables AIII.3 and AIII.4).

AIII.3 CARAIB–REVEALS comparison for 11,700–10,200 BP

REVEALS showed higher percentages of herbs in comparison with the percentage of trees during 11,700–10,200 BP and the inversion of these values between 10,200–9200 BP (Fig. 4.5, bottom figure). These observations might be partially explained by the position of these periods within the glacial/interglacial cycle which could entail a late arrival of some tree types (Giesecke et al., 2017; Svenning & Skov, 2004). The duration of postglacial migration lags is unclear. There are suggestions for both relatively short lags of maximally 1500 years, and substantially longer ones including estimates that many plant species have not reached equilibrium with climate even nowadays (Birks & Birks, 2008; Dallmeyer et al., 2022; Seliger et al., 2021; Svenning & Sandel, 2013). It is also unclear whether the observed species-level lags impact continental-scale distribution of forests (Dallmeyer et al., 2022). Due to that, distinguishing between the potential influences of human activities and climate could be challenging in this context for the 11,700–10,200 BP. In addition, the CARAIB vegetation model used in this study is driven by outputs from an equilibrium iLOVECLIM climate model. In the present setup, both the vegetation and climate models are in equilibrium, and hence do not capture transient changes. ILOVECLIM uses ice sheet data, which then remain static throughout the equilibrium-based simulation. This setup inherently limits representation of several aspects of the Early Holocene, including the transition to warmer conditions in the beginning of the Holocene and the associated soil changes due to deglaciation (transient change in soil composition, texture, and nutrient availability). Thus, we made a deliberate decision not to conduct HUMLAND simulations for 11,700–10,200 BP. We have directed our focus on 10,200–8200 BP and two LIG time windows.

Appendix IV

HUMLAND ABM 2.0 Overview, design concepts and details (ODD) protocol

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This document provides a comprehensive overview, design concepts, and detailed descriptions of the HUMLAND ABM 2.0. This model was developed to track and quantify the intensity of different impacts on vegetation on the continental scale and to determine the most influential factor in transformation of interglacial vegetation with specific focus on burning organized by hunter-gatherers. This document follows the Overview, Design concepts, and Details (ODD) protocol to ensure clarity and consistency in model documentation.

The model is accessible via the CoMSES library (search for HUMLAND). HUMLAND 2.0 and all associated data and scripts are licensed under the MIT License.

When referencing HUMLAND 2.0, please cite both the model and the associated publication.

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AIV.1 Purpose

Humans started transforming their environment long before the emergence of agriculture and industrialization. Foraging societies conduct niche construction activities including vegetation burning which substantially modifies hunter-gatherers' surroundings. Currently available ethnographic and archaeological evidence suggests that both Neanderthals and Mesolithic humans practiced vegetation burning during the Last Interglacial (LIG; ~130,000–116,000 BP) and the Early Holocene (~11,700–8000 BP). Due to the scarcity of evidence and the absence of a common research protocol to study the anthropogenic impact on landscapes, there are gaps in research about the dynamics of interglacial environments and the role of *Homo* in landscape changes. Particularly, the extent and visibility of vegetation burning organized by hunter-gatherers is still a focal point of research.

Landscape dynamics are complex and include variable components such as climatic fluctuations, megafauna impact, natural fires, and anthropogenic activities. Thus, there is a need for further research which can allow us to assess different possible scenarios for anthropogenic impact in landscape changes. Therefore, the purpose of this model is to track and quantify the intensity of different impacts on vegetation on the continental level and to determine the most influential factor in transformation of interglacial vegetation with specific focus on burning organized by hunter-gatherers. This model accumulates different types of spatial datasets (Section AIV.6) which are used as input and target for ABM runs. Additionally, the study incorporates recently obtained specifically for this research continental-scale estimates of fire return intervals (FRI) and speed of vegetation regrowth. The obtained results include possible scenarios (combinations of HUMLAND parameter

values) with maps of modified vegetation in the past and quantification of changes done by of each source of impact (climate, humans, megafauna and natural fires). The model has been implemented in *NetLogo* (version 6.2.2). HUMLAND 1.0 and 2.0 are accessible via the CoMSES model depository (<https://www.comses.net/>, search for HUMLAND).

AIV.2 Entities, state variables, and scales

The following entities are included in the model: agents representing hominin groups (one agent is one group, Table AIV.1), campsites (turtles, have only one static variable `my_hominin` which indicates the group occupying this campsite) and grid cells (patches, Table AIV.2).

Table AIV.1 Hominin state variables.

Variable name	Variable type and units	Meaning
<code>my_home</code>	Dynamic, patch	A patch where a campsite is located (home patch of a group).
<code>my_campsite</code>	Dynamic, turtle	A campsite which is the home of a hominin group.

Table AIV.2 Grid cells state variables.

Variable name	Variable type and units	Meaning
<code>patch_elevation</code>	Static, float, meters	Absolute elevation (a.s.l.)
<code>patch_natural_pft</code>	Static, integer	CARAIB (CARbon Assimilation In the Biosphere) first dominant PFT: 1–herbs, 2–shrubs, 3–needleleaf trees, 4–broadleaf trees, -1–no data
<code>patch_pollen_pft</code>	Static, integer	REVEALS (Regional Estimates of VEgetation Abundance from Large Sites) first dominant PFT: 1–herbs, 2–shrubs, 3–needleleaf trees, 4–broadleaf trees, -1–no data
<code>patch_pft Updating</code>	Dynamic, integer	Current dominant PFT: 1 herbs, 2–shrubs, 3–needleleaf trees, 4–broadleaf trees, -1–no data, 0–burnt/fully consumed area
<code>patch_natural_openness</code>	Static, float, percentage	CARAIB vegetation openness: 0 – minimal value (0%, totally closed), 100–maximal value (100%, totally open), -1–no data
<code>patch_pollen_openness</code>	Static, float, percentage	REVEALS vegetation openness: 0–minimal value (0%, totally closed), 100–maximal value (100%, totally open), -1–no data
<code>patch_pollen_openness_se</code>	Static, float	REVEALS vegetation openness standard error (se)

Variable name	Variable type and units	Meaning
patch_pollen_openness_max	Static, float, percentage	Maximal possible REVEALS openness: patch_pollen_openness + patch_pollen_openness_se
patch_openness Updating	Dynamic, integer, percentage	Current vegetation openness: 0–minimal value (0%, totally closed), 100–maximal value (100%, totally open), -1–no data
rivers_lakes	Static, integer	Presence of big rivers and lakes: 0–no rivers/lakes, 1–presence of rivers/lakes, -1–no data
fri	Static, integer, years	FRI values for each PFT
patch_natural_npp	Static, float, g/m ²	CARAIB NPP
patch_npp Updating	Dynamic, integer	Current patch npp which can be changed due to different types of impact during runs
npp_regrowth_rate	Dynamic, float	NPP regrowth speed per step after impact
megafauna_npp_consumption	Static, float, g/m ²	Megafauna carbon consumption
megafauna_max_consumption_restricted_hunting	Static, float	Potential maximal megafauna plant consumption restricted by hunting
continuous_consumption	Dynamic, integer	Counts the number of ticks (steps) during which megafauna continuously consumed this patch
fire_delay_after_consumption	Dynamic, integer	Delay in the frequency of natural fires after partial megafauna consumption of vegetation
openness_regrowth_rate	Dynamic, float	Openness regrowth speed per step after impact
last_burning_episode	Dynamic, integer	Simulation step of the last fire episode of a patch
next_burning_episode	Dynamic, integer	Possible next natural fire event when probability of ignition is 100%
last_partial_consumption_episode	Dynamic, integer	Step of the last partial consumption episode of a patch
last_agent_impacted_pft	Dynamic, integer	Last agent that changed a dominant PFT of a patch: 1–humans, 2–natural fires, 3–climate, 4–megafauna
last_agent_impacted_openness	Dynamic, integer	Last agent that impacted a patch: 1–humans, 2–natural fires, 3–climate, 4–megafauna.
herbs_regeneration_step	Dynamic, integer	Step when herbs will regrow after vegetation burning or consumption
shrubs_regeneration_step	Dynamic, integer	Step when shrubs will regrow after vegetation burning or consumption
needleleaf_trees_regeneration_step	Dynamic, integer	Step when needleleaf trees will regrow after vegetation burning or consumption
broadleaf_trees_regeneration_step	Dynamic, integer	Step when broadleaf trees will regrow after vegetation burning or consumption
agent_that_could_impact_neighbouring_pathes	Dynamic, integer	Agent that can potentially cause burning on neighbouring patches: 1–humans, 2–natural fires, 3–climate, 4–megafauna.
hominin_accessible_area	Dynamic, integer	Defines if the patch is within accessible area for humans: 1–within the area, 0–not accessible for humans

Variable name	Variable type and units	Meaning
occupation	Static, integer	Stores -1 for the British Isles patches for the LIG runs because this region was not occupied by hominins
raster_layer	Dynamic, integer/float	Used to create an ASCII file with modelling results

The model is two-dimensional, and its spatial extent is a rectangle with 544 x 430 patches (grid cells). Each grid cell of input raster datasets (Section AIV.6, Table AIV.6) is resampled (i.e., spatial resolution was changed) to 10 km × 10 km in size. The world wraps horizontally and vertically. The current version of the model imports all spatial datasets for two LIG and seven Early Holocene time windows. One simulation step equals one year, and the current simulation does not account for seasonal variability. One run is 1000 time steps.

AIV.3 Process overview and scheduling

Simulation starts with setup when input datasets are imported, entities are created, their state variables are set, and the conflicting grid cells are removed. In HUMLAND, more closed vegetation can only switch to more open vegetation after a disturbance event (e.g., fire, grazing). In our data comparison, where CARAIB shows a greater degree of openness in vegetation than REVEALS (maximum pollen-based estimates, which represent the sum of estimated REVEALS openness and the standard error), we exclude these locations. This decision is taken because HUMLAND will not be able to generate vegetation that is comparable to REVEALS as it is constrained by the CARAIB-prescribed theoretical potential natural vegetation (PNV). As a result, the similarity between ABM output and REVEALS datasets can only be improved for grid cells where initial vegetation openness is equal to or lower than observed pollen-based maximum estimates.

The process overview of simulation runs is shown in Figure AIV.1. Each of them starts with vegetation regeneration. This submodel (Section AIV.7) executes only for patches which were previously (i.e., during the earlier step) burnt or consumed.

Hominins are the first agent that reduces vegetation cover. The anthropogenic fire submodel (Section AIV.7) is executed via three phases. During the first phase, hominins randomly move towards one of the eight neighbouring patches within the area defined by accessible radius around their campsites. When a hominin reaches a patch with trees or shrubs as a dominant PFT and vegetation openness smaller or equal to a number defined via the `Openness_criteria_to_burn` variable, this patch is burnt. During the second phase, fire spread is initiated.

The natural fires submodel (Section AIV.7) is initiated after hominin impact. During the setup the number of patches, that will be hit by thunderstorms per

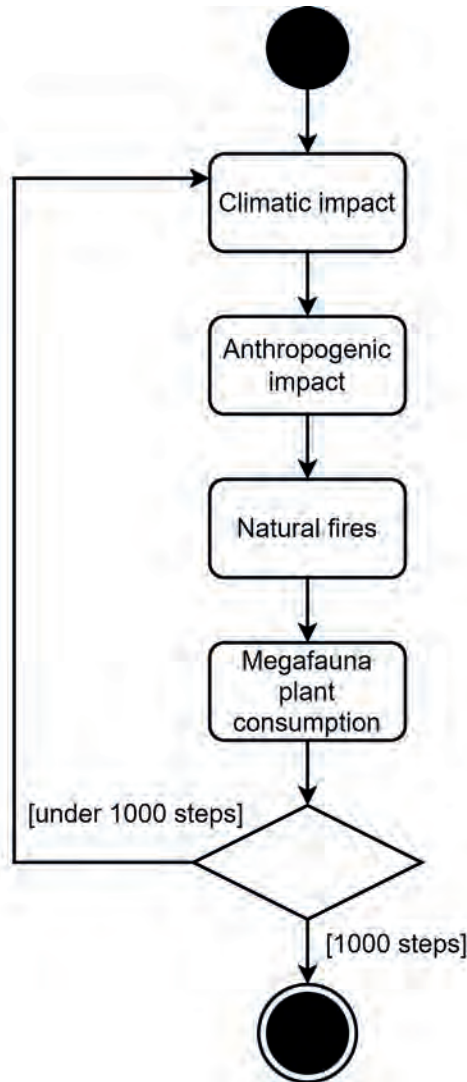


Figure AIV.1 Activity diagram of process overview.

step, is calculated based on a value of the `Territory_impacted_by_thunderstorms` variable. Every simulation step random patches are chosen and impacted by thunderstorms. Thunderstorms can occur in high mountains, lakes and rivers, but these episodes never lead to ignition. Depending on the probability of ignition of a patches which are not water bodies or high mountains can be burnt after thunderstorms. Similarly to anthropogenic burning, thunderstorms can cause fire spread.

In HUMLAND 1.0 only grid cells with fully recovered vegetation can be consumed by megafauna. In HUMLAND 2.0, both fully recovered and regenerating grid cells can be affected by megafauna. Many herbivores exhibit a preference for areas characterized by secondary vegetation and relatively open regrowth locations following disturbances such as fire because of increased nutrition and palatability of new plants. After plant consumption, vegetation openness increases depending on the CARAIB NPP, current vegetation openness of a patch and hunting pressure. Regarding megafauna impact on PFTs, it is assumed that megafauna equally consumes all PFTs present on a grid cell, i.e., besides the first dominant PFT megafauna consumes second, third and fourth dominant PFTs in equal proportions. That is why, the first dominant PFT is replaced, only if the vegetation was entirely consumed by megafauna, and vegetation openness value after consumption is 100%. In this case, the first dominant PFT would be replaced by bare ground.

Once all sources of impact have affected the study area, the current mean vegetation openness and the distribution of dominant PFTs are compared with REVEALS data. Plots are updated at each step, and the simulation stops after 1000 steps.

AIV.4 Design concepts (after Nikulina et al., 2024b, in press)

AIV.4.1 Basic principles

The history of anthropogenic impacts on the environment spans over many years, with humans already engaging in landscape transformations before the emergence of agriculture. Ethnographic observations show that hunter-gatherers or foragers (i.e., groups that mainly depended on food collection or foraging of wild resources) influence their surroundings in several ways including modification of vegetation communities via burning. This practice was identified for all vegetation types except tundra at different spatial scales and for diverse objectives including driving game, stimulating the growth of edible plants, and clearing pathway.

Besides ethnographic data, evidence from archaeological contexts show that fire use was an important part of the technological repertoire of the *Homo* lineage since at least the second half of the Middle Pleistocene. Human-induced vegetation burning during the Late Pleistocene has been proposed as a potential factor in several case studies spanning various continents. Notably, the earliest evidence of such activities on a local scale was identified at the Neumark-Nord site in Germany, dated to LIG. In addition, fire-using foragers were suggested as one of the primary drivers of vegetation openness in Europe during the Last Glacial

Maximum, i.e., possibly constituting one of the earliest large-scale anthropogenic modifications of system earth.

While these Pleistocene cases are still subject to debate, human-induced vegetation burning conducted by hunter-gatherers during the Early–Middle Holocene (~11,700–6000 BP) is generally accepted, even though the quality of the data is not necessarily that different. However, the number of case studies is higher for the Early–Middle Holocene than for the Pleistocene. Most of the Early to Middle Holocene evidence originates from Europe, with some additional evidence from Australia.

Despite the presence of case studies for anthropogenic burning (intentional or not) of past landscapes by hunter-gatherers, it is still difficult to establish whether these local-scale impacts caused changes at the regional and (sub-)continental scales. Furthermore, overall landscape dynamics do not only depend on humans, and rather represent the complex interplay of natural and cultural processes at different spatio-temporal scales. Landscapes are thus complex systems where heterogeneous components interact to impact on ecological processes, and might demonstrate non-linear dynamics and emergence. Therefore, it is often challenging to distinguish different impacts on landscapes using proxy-based reconstructions (e.g., palynological datasets).

Modelling approaches offer excellent opportunities to explore how complex components of systems might interact, particularly when real-time experiments are not possible. Spatially-explicit agent-based modelling (ABM) is commonly used to explore complex systems where multiple factors intertwine and to propose possible scenarios of system functioning, and the outcomes of ABMs can be compared to empirical data. This approach has been applied in various contexts to study past human-environment interactions and land use/land cover changes. There are examples of such models for past societies that practiced agriculture, animal husbandry, and for hunter-gatherer groups. In the case of ABM developed to study foragers, the use of fire by hunter-gatherers to transform foragers' surroundings and the landscape consequences of these practices are usually not discussed.

This model includes four types of impact on vegetation: climatic impact, anthropogenic fires, thunderstorms, and megafauna plant consumption. Thunderstorms were included because lightning is one of the most general and widespread triggers of natural fires. Another source of impact is climate, and it is included as a crucial element for vegetation regeneration after fires or vegetation consumption. Finally, megafauna are also a part of the current ABM, because the

herbivory activity impacts litter accumulation, and high levels of megafauna plant consumption reduce fire occurrence in many areas.

AIV.4.2 Emergence

The model's key results are increase of average vegetation openness and decrease of the percentage of grid cells dominated by trees and shrubs. These results emerge from joint (i.e., several agents together) and separate (i.e., only one agent) impacts of different agents and processes (hominins, thunderstorms and megafauna plant consumption) on vegetation. The increase of vegetation openness and change of PFT's distribution are driven by a specific combination of agents and values of variables that influence their behaviour.

AIV.4.3 Adaptation

There is no adaptation in the model.

AIV.4.4 Objectives

Vegetation burning is an objective for hominins. Each step hominins move randomly to one of the neighbouring patches. If it covered by shrubs or trees and its vegetation openness is equal or lower than the `Openness_criteria_to_burn` value, then the fire will be set. Otherwise, humans do not impact this patch. Megafauna and thunderstorms do not have objectives.

AIV.4.5 Learning

Agents do not learn.

AIV.4.6 Prediction

Agents do not predict.

AIV.4.7 Sensing

Humans are assumed able to sense dominant PFT and vegetation openness of a grid cell where humans are located. Hominins can sense if their campsites and home patches are beyond accessible radius. It is useful in cases when two campsites are located nearby, and their accessible areas overlap. If a hominin is far from its campsite (does not sense this campsite anymore i.e., it is beyond accessible radius), this hominin automatically comes back to the campsite.

AIV.4.8 Interaction

Hominins directly affect patches. If a hominin decides to burn a patch, its state variables are modified.

AIV.4.9 Stochasticity

Stochasticity is used in initializing the model when random distribution of hominins within the study is set. Additionally, hominins randomly choose one of the eight neighbouring patches to which hominins move around campsites. Finally, humans randomly choose patches when the campsites will be relocated during simulation runs. This happens with a specific frequency defined via the `Movement_frequency_of_campsites` variable. The parameter `Campsites_to_move` defines the percentage of campsites that will be relocated. Campsites for this action are chosen randomly.

Thunderstorm impact also includes stochasticity. The number of patches are defined via the `Territory_impacted_by_thunderstorms` parameter. Several random inland patches are selected every simulation step to potentially have natural fire. The actual natural vegetation burning depends on a probability of ignition $P(I)$ (AIV.1):

$$P(I) = \frac{T-B}{F} \quad (\text{AIV.1}),$$

where B is the step when the last burning episode occurred, F —FRI, and T —the number of simulation steps (ticks) since the beginning of the simulation. Once $P(I)$ is calculated, a random float number between 0 and 1 is chosen. If $R \leq P(I)$, this patch will be burnt. Similarly to ignition caused by natural fires, fire can spread on neighbouring patches after natural and human-induced fires. For the neighbouring patches the $P(I)$ is calculated, and the fire event can occur depending on the obtained $P(I)$ and random a random float number.

AIV.4.10 Collectives

There are no collectives in the model.

AIV.4.11 Observation

The primary model observations are distribution of dominant PFTs (percentage of patches covered by each PFT) and mean vegetation openness for patches which have both REVEALS estimates and CARAIB values (i.e., not all inland patches are considered). These values are provided via plots on the model interface and extracted tables. The ABM output is considered similar to REVEALS data if a simulation produced the same percentage of first dominant PFTs and mean vegetation openness values or if the difference between ABM output and REVEALS data varies within 10%. Additionally, the different types of impact (i.e., the number of grid cells modified by each type of impact) are tracked via recording which impact caused openness and PFT changes.

AIV.5 Initialization (after Nikulina et al., 2024b, in press)

First, the environment is created during the initialization. Patch state variables at the end of the initialization step are described in Table AIV.3. In HUMLAND, more closed vegetation can only switch to more open vegetation after a disturbance event (fire, grazing). In our data comparison, where CARAIB shows a greater degree of openness in vegetation than maximum REVEALS estimates, we exclude these locations: the ABM will not be able to generate vegetation that is comparable to REVEALS as it is constrained by the CARAIB-prescribed PNV. Secondly, there are several grid cells where climatic conditions only favour dominance of herbs or shrubs, but observed vegetation indicates dominance of trees. Besides that, shrubs cannot dominate grid cells where climatic conditions favour trees or herbs in HUMLAND. Such cases do not improve similarity between ABM output and REVEALS data, and, therefore, these grid cells were also excluded (Table AIV.5).

Table AIV.3 Patch state variables and their values at the end of the initialization stage.

Variable name	Value	Explanation
patch_elevation	In accordance with GTOPO30	Value is set depending on GTOPO30 dataset
patch_natural_pft	In accordance with CARAIB first dominant PFT	Value is set between 1 and 4 depending on CARAIB dataset
patch_pollen_pft	In accordance with REVEALS first dominant PFT	Value is set between 1 and 4 depending on CARAIB dataset
patch_pft Updating	patch_pft Updating = patch_natural_pft	Variable has the same value as theoretical potential natural vegetation provided by CARAIB.
patch_natural_openness	In accordance with CARAIB vegetation openness	Value is set between 9 and 100 depending on CARAIB dataset
patch_pollen_openness	In accordance with REVEALS vegetation openness	Value is set between 0 and 99 depending on REVEALS dataset
patch_pollen_openness_se	In accordance with REVEALS standard errors	Value is set depending on REVEALS dataset
patch_pollen_openness_max	patch_pollen_openness + patch_pollen_openness_se	Maximal possible REVEALS vegetation openness
patch_openness Updating	patch_natural_openness = patch_openness Updating	Variable has the same value as theoretical potential natural vegetation provided by CARAIB.
rivers_lakes	0 or 1	Value depends on WISE dataset
fri	246, 426, 286 or 293	The value depends on CARAIB first dominant PFT (Table AIV.4)
patch_natural_npp	In accordance with CARAIB NPP	Value is set depending on CARAIB dataset

Variable name	Value	Explanation
patch_npp Updating	In accordance with CARAIB NPP	Value is set depending on CARAIB dataset. During simulation runs this value is updated
npp_regrowth_rate	-1	No regrowth rate is calculated before impact during simulation runs
megafauna_npp_consumption	In accordance with megafauna vegetation consumption dataset	Value is set depending on megafauna vegetation consumption data
megafauna_max_consumption_restricted_hunting	Calculated depending on megafauna vegetation consumption dataset and the Hunting_pressure value	Potential maximal megafauna plant consumption after hunting pressure
continuous_consumption	0	Before megafauna started consumption this value is set to 0
fire_delay_after_consumption	-1	Before megafauna consumption of a patch this variable is set to -1
openness_regrowth_rate	0	Before simulation runs this value is set to 0
last_burning_episode	0	Before simulation runs this value is set to 0
next_burning_episode	last_burning_episode + 1	Defines the step when this patch has 100% chances to be burnt
last_partial_consumption_episode	-1	Before megafauna consumption of a patch this variable is set to -1
last_agent_impacted_pft	3	Before simulation starts the vegetation cover is created by climate only. Thus, all patches have value 3
last_agent_impacted_openness	3	Before simulation starts the vegetation cover is created by climate only. Thus, all patches have value 3
herbs_regeneration_step	0	Before agent's impact all patches do not require regeneration step
shrubs_regeneration_step	0	Before agent's impact all patches do not require regeneration step
needleleaf_trees_regeneration_step	0	Before agent's impact all patches do not require regeneration step
broadleaf_trees_regeneration_step	0	Before agent's impact all patches do not require regeneration step
agent_that_could_impact_neighbouring_patches	0	This value is 0 prior to simulation runs, because there was no impact yet
hominin_accessible_area	0 or 1	If the patch is within accessible area, the value is set to 1. Otherwise, this variable equals 0
occupation	0 or -1	If 0 can be occupied and burnt by humans. If -1 cannot be occupied or burnt by humans

Variable name	Value	Explanation
raster_layer	-	Used to create .asc file. This variable can have any value depending on chosen patch variable

Table AIV.4 Mean FRI for each dominant PFT.

PFT	Mean FRI estimated via MODIS
Needleleaf trees	246
Broadleaf trees	426
Shrubs	286
Herbs	293

Table AIV.5 CARAIB and REVEALS conflicting cells excluded from the analysis during initiation stage.

CARAIB	REVEALS	Reason
Possible natural (CARAIB) vegetation openness is higher than observed vegetation openness	Maximal observed (REVEALS) vegetation openness (i.e., estimated vegetation openness + standard error) is lower than possible natural (CARAIB) vegetation openness.	In the current ABM possible natural vegetation openness cannot be higher than pollen-based vegetation openness.
First dominant PFT: herbs/shrubs	First dominant PFT: trees	In the current ABM trees cannot dominate if climatic conditions only allow dominance of herbs or shrubs.
First dominant PFT: trees/herbs	First dominant PFT: shrubs	In the current ABM shrubs cannot dominate if climatic conditions only allow dominance of trees or herbs.

Once the environment is created, hominins and their campsites are randomly distributed on surfaces with vegetation. The number of campsites and hominin groups is defined via the `Number_of_groups` parameter. Patches around campsites are defined as accessible areas. The `Accessible_radius` parameter defines the size of this area in the number of grid cells around campsites, and the `hominin_accessible_area` state variable equals 1 for patches within the accessible area. Hominins cannot move beyond their foraging areas, on water bodies (sea, big lakes, and main rivers) and high mountains. These are the patches with absolute elevations more than 2500 m. Water bodies and the most elevated areas do not have vegetation cover, and, therefore, cannot be burnt or consumed. Except for the `patch_elevation` and `rivers_lakes`, patches with high mountains and water bodies have -1 for other state variables.

AIV.6 Input data (after Nikulina et al., 2024b, in press)

The simulation uses several datasets (Table AIV.6). To standardize their spatial extent and resolution Spatial Analysts and Data management *ArcMap* 10.6.1 toolboxes were used. Grid cell sizes of the datasets were resampled to 10 km × 10 km. To ensure consistency in our analysis, we made the decision to exclude specific regions, namely Anatolia, Cyprus, and the Balkans, from all time windows considered in this study. The rationale behind this exclusion is that these regions have the earliest evidence of agriculture in Europe. To account for the differences in sea levels during the LIG compared to the present, we used available reconstructions and estimates of sea level. Specifically, we utilized coastlines reconstructed for Northwest Europe. However, such detailed reconstructions were not available for the rest of Europe. Consequently, we assigned a uniform value of 6 m for the rest of Europe during the LIG. During the LIG runs, Neanderthals do not occupy or burn vegetation in the British Isles due to the absence or very sparse presence of people during this period. To ensure this region remains unoccupied, we created a specific spatial layer. Consequently, each LIG time window requires 10 spatial layers, while Early Holocene time windows require nine. For both LIG time windows, we used the same spatial layers from CARAIB, corresponding to the maximal biomass development in Europe. In total, 57 spatial layers are stored in the input data folder for HUMLAND 2.0.

The initial landscape before simulation runs were reconstructed via the following datasets: GTOPO30, Water Information System for Europe (WISE) and outputs of a dynamic vegetation model CARbon Assimilation In the Biosphere (CARAIB). GTOPO30 is a digital elevation model (DEM) derived from several raster and vector sources of topographic information. We used this DEM to represent elevation data in the ABM. WISE dataset is based on the information from the Water Framework Directive database, and we used WISE to define the distribution of major rivers and lakes (natural barriers for fire spread) in the model.

In the context of this research, the CARAIB dataset represents PNV distribution driven by climatic conditions only. As an input climate we used climatic variables simulated by the iLOVECLIM model with embedded online interactive downscaling. The iLOVECLIM-simulated climatic variables were bias-corrected using the CDF-t bias correction technique and averaged over the studied period to get daily mean climate characteristics of our period of interest. A full description of the modelling setup and the application of the CDF-t technique within this setup is described and tested.

CARAIB outputs used in this study include distribution of fractions of 26 plant functional types (PNV PFTs), vegetation openness (PNV openness), and net primary productivity (PNV NPP). Before being imported to the ABM, the mentioned CARAIB

outputs were transformed. As the CARAIB dataset here represents climate-only forced vegetation, it is used in the current ABM as the starting point (i.e., before impact of humans, natural fires and megafauna) of each simulation and as target for vegetation regrowth after impacts.

Table AIV.6 Input datasets to the simulation environment (after Nikulina et al., 2024b).

Dataset	Initial data type	Initial spatial resolution/scale	Meaning, units
GTOPO30	Raster	1 km	Digital elevation model, m
WISE	Vector	1:10000000	Distribution of large rivers and lakes
CARAIB first dominant PFT	Raster	~26 km (0.25°)	Potential natural (climate-based) first dominant PFT
CARAIB vegetation openness			Potential natural (climate-based) vegetation openness, in percentage
NPP			Potential net primary carbon productivity (excluding carbon used for respiration), g/m ²
Megafauna vegetation consumption	Raster	30 km	Potential maximal megafauna vegetation consumption (i.e., metabolization of NPP), kg/km ² (converted to g/m ²)
REVEALS first dominant PFT	Vector	~100 km (1°)	Observed past first dominant PFT
REVEALS vegetation openness			Observed past vegetation openness, in percentage
REVEALS vegetation openness standard errors			Standard errors for estimates of observed past vegetation openness

AIV.7 Submodels (after Nikulina et al., 2024b, in press)

AIV.7.1 Climatic impact

The vegetation regrowth after the impact of thunderstorms, megafauna, and/or humans is determined by the climatic conditions. Therefore, this submodel only modifies grid cells that were previously burned or consumed.

The grid cells' `patch_openness Updating` and `patch_pft Updating` (Figs. AIV.2 and AIV.3) are changed in response to the climatic impact until they match the values of `patch_natural_openness` and `patch_natural_pft`, respectively. If the difference between `patch_natural_openness` and `patch_openness Updating` is equal to or less than 10%, this grid cell is considered to have recovered naturally,

and the last agent that impacted this patch is assumed to be climate (last_agent_impacted_openness = 3). Similarly, if patch_natural_pft is equal to patch_pft_updating, the last agent that impacted the PFT of this grid cell is climate (last_agent_impacted_pft = 3).

We used the CARAIB mean number of years to recover (Table AIV.7) to calculate the vegetation openness recovery rate and to define the step when natural PFT would reestablish on the grid cell after vegetation burning and/or consumption. PFT recovery on all impacted patches always begins with herbs, which replace bare ground after seven simulation steps. Subsequently, depending on the PNV PFT estimated by CARAIB after the required number of years since fire or complete consumption (Table AIV.7), the herbs may be replaced by trees or shrubs.

After consumption or fires the rate of vegetation openness recovery (V_{or}) is calculated via the following formula (AIV.2):

$$V_{or} = \frac{O_i - O_c}{\mu} \tag{AIV.2}$$

O_i represents the vegetation openness after the impact caused by fire and/or megafauna, O_c refers to the CARAIB estimates of vegetation openness, and μ – the mean number of years required for recovery of the initial vegetation openness prior to the fire event or plant consumption (Table AIV.7). NPP recovery is calculated similarly, but instead of using the O_c , model utilizes CARAIB NPP. Instead of the O_i , HUMLAND uses the current carbon content following fire and/or megafauna plant consumption. During each simulation step, V_{or} is subtracted from the current simulation openness until it reaches the CARAIB estimates of vegetation openness. Similarly, the calculated NPP recovery rate is summarised with the current carbon content until the current NPP is the same as PNV NPP.

Table AIV.7 Mean number of years to recover for each dominant PFT (after Nikulina et al., 2024b).

PFT	Number of years
-----	-----------------

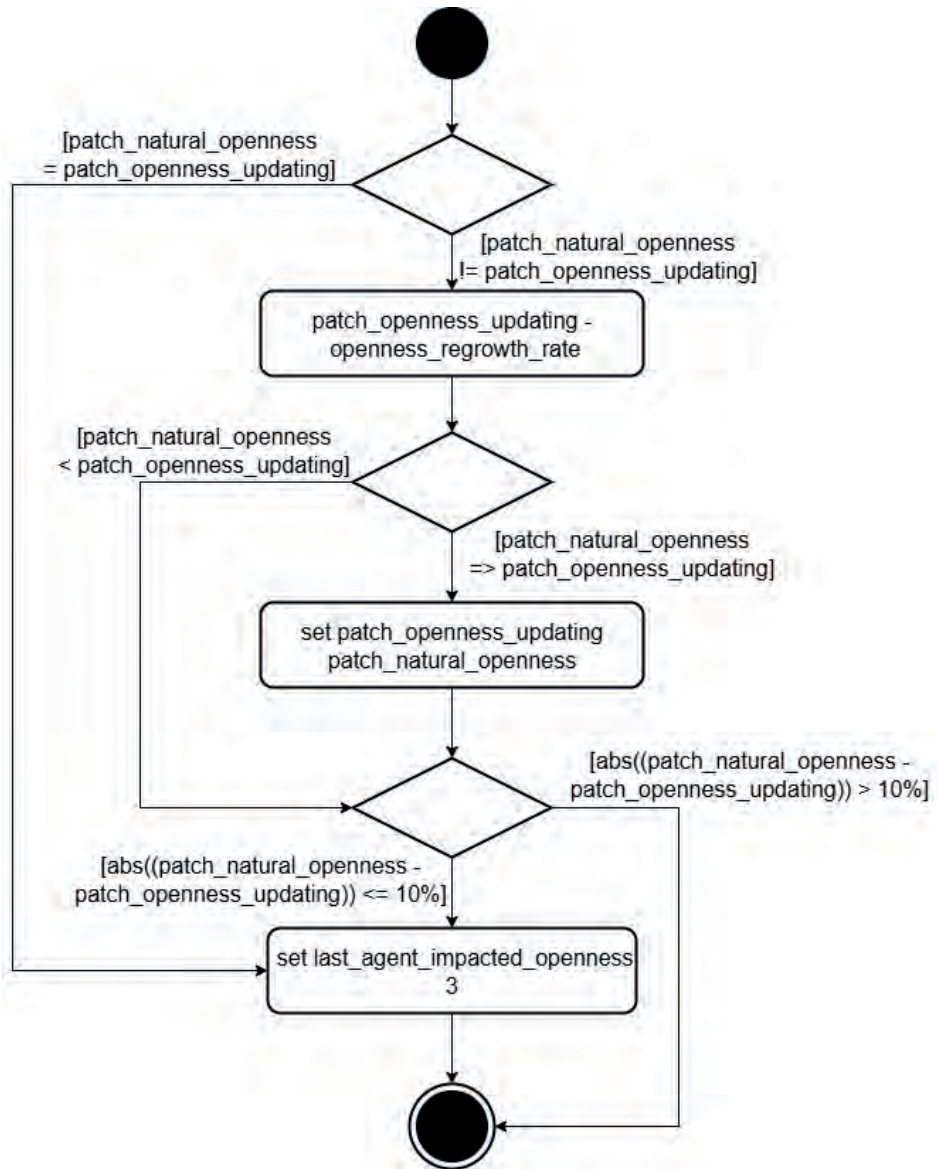


Figure AIV.2 Activity diagram for climatic impact on vegetation openness.

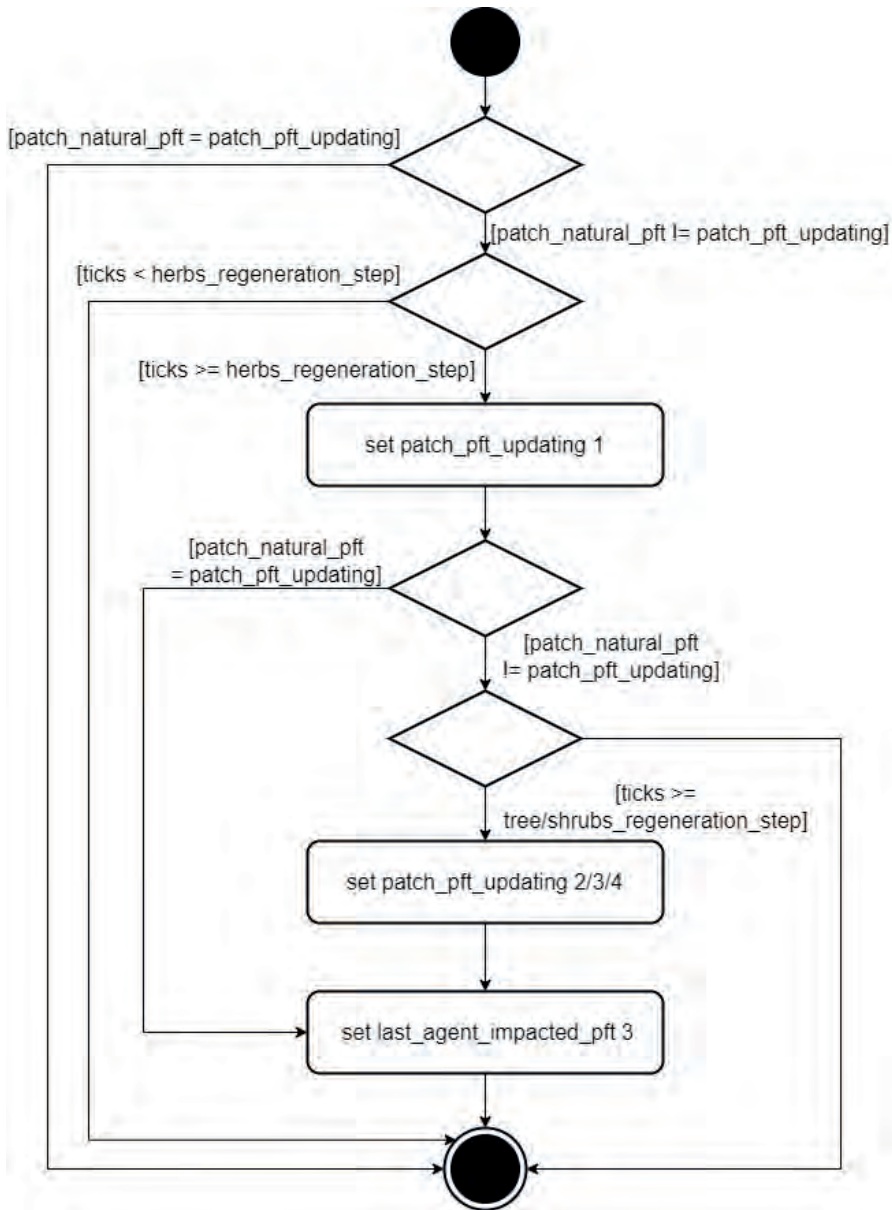


Figure AIV.3 Activity diagram for climatic impact on distribution of dominant PFTs.

Needleleaf trees	43
Broadleaf trees	30
Shrubs	43
Herbs	7

AIV.7.2 Anthropogenic impact

This submodel introduces changes to the vegetation through human-induced fires. There are five parameters which define human behaviour and intensity of their impact: `Number_of_groups`, `Accessible_radius`, `Campsites_to_move`, `Movement_frequency_of_campsites`, and `Openness_criteria_to_burn`. An additional parameter, `Hunting_pressure`, is introduced in HUMLAND 2.0.

The first parameter defines the number of hunter-gatherer groups present at the study area during one simulation run. Therefore, this parameter is associated with human population size. The accessible radius parameter defines the territory within which humans move and set fires around campsites.

There are two parameters associated with movements of foragers' campsites: `Movement_frequency_of_campsites` (the number of simulation steps after which a group can relocate their campsite) and `Campsites_to_move` (the percentage of groups that relocate a campsite at certain step defined by movement frequency). Due to the temporal resolution of the current simulation, hunter-gatherers' highest possible frequency of camp movements is every step (i.e., once per year). The search radius for the new grid cell to establish a site is twice bigger than the accessible radius. Any grid cell can be chosen for the new site, except the previously occupied grid cell, high mountains and water bodies. The newly established accessible area can overlap with the previous one.

Since hunter-gatherers have different reasons to burn landscapes, and that this practice was documented in almost all vegetation types with more cases for foragers occupying shrublands and forests, the openness criteria to burn was introduced. In the current simulation, humans only burn grid cells dominated by trees or shrubs with vegetation openness lower or equal to this criterion. A low value minimizes the number of positive decisions to start a fire, and higher values increase human-induced fires, because even relatively open areas can be burnt by people in this case.

Humans randomly move between adjacent patches within a defined area determined by the `Accessible_radius` (the number of grid cells) around campsites. When a human is present on a patch with vegetation openness that is equal to or lower than the prescribed criteria for burning and contains shrubs or trees (`patch_pft Updating` ≥ 2), this human group sets fire on that patch. Consequently, the openness of the patch is set to 100% (completely open), and its PFT (`patch_pft`

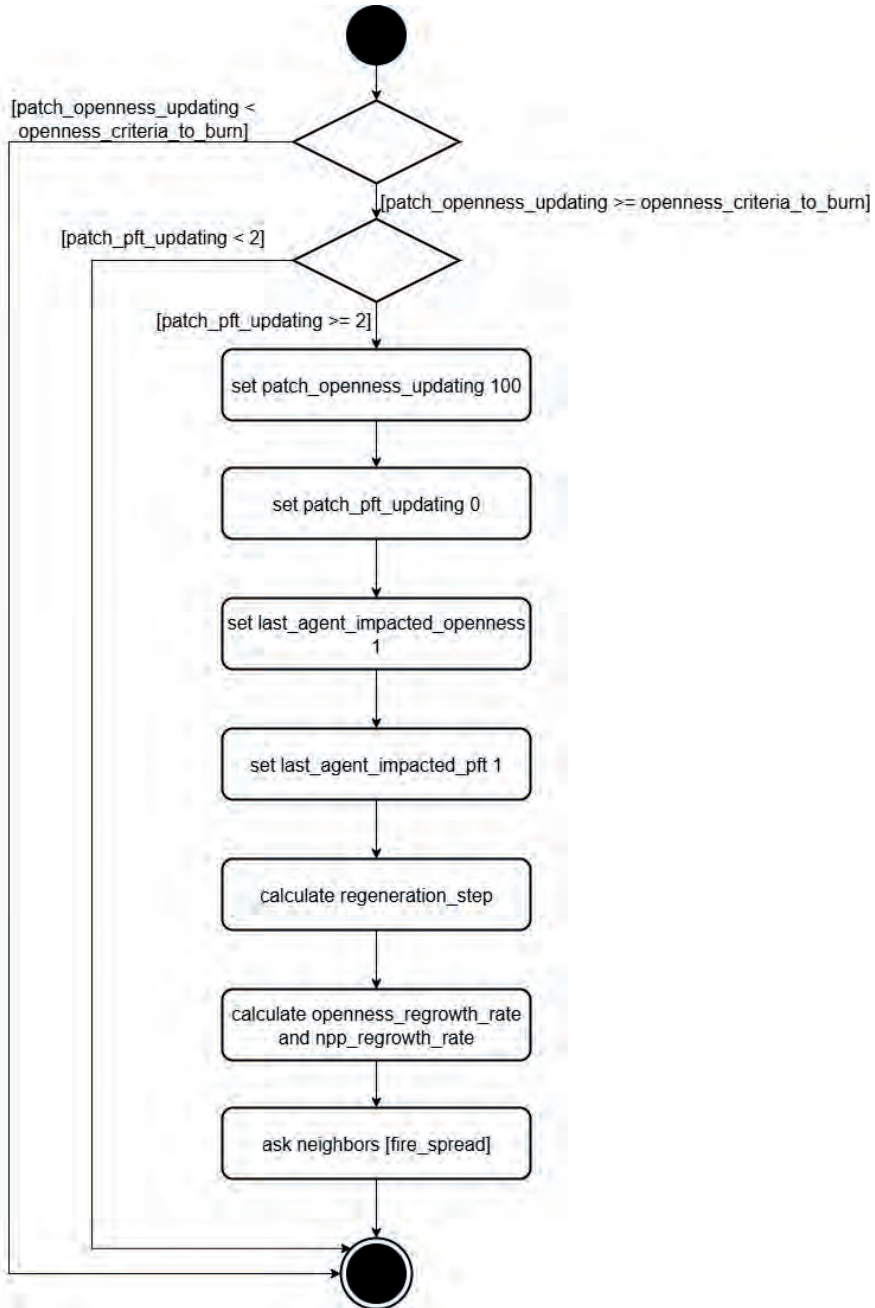


Figure AIV.4 Activity diagram for anthropogenic impact.

updating) is set to 0, indicating a burnt area. In this case, the variables `last_agent_impacted_openness` and `last_agent_impacted_pft` are assigned a value of 1 to denote anthropogenic impact. The time step at which this burning event occurs is recorded as `last_burning_episode`, and `next_burning_episode` is updated based on the dominant natural PFT. Subsequently, after calculating the regeneration steps (ticks + number of years from Table AIV.4) and openness regrowth rates (Section AIV.7.1), the spread of vegetation to neighbouring patches is initiated (Section AIV.7.4).

The `Hunting_pressure` parameter defines the percentage reduction in the potential maximum megafauna plant consumption. More details on these calculations can be found in section AIV.7.5.

AIV.7.3 Natural fires

Based on the value of the parameter `Territory_impacted_by_thunderstorms`, the number of grid cells experiencing thunderstorms per simulation step is determined. This parameter is expressed as a percentage, and based on its value, the calculation determines how many grid cells will be affected by thunderstorms. These thunderstorms randomly occur on different grid cells within the study area. It is important to note that thunderstorms can occur over rivers, lakes, and high mountains, but these areas are not susceptible to burning.

Following the occurrence of thunderstorms, fires may initiate fire spread depending on the probability of ignition for the affected grid cells (Fig. AIV.5). The spread of fire (Section AIV.7.4) to neighbouring grid cells can occur after both human-induced and natural fires. Thunderstorms do not always result in vegetation burning, and the ignition of fire does not always lead to its spread after natural or human-induced ignitions.

The probability of ignition $P(I)$ is determined based on the time elapsed since the last burning episode (B) and the FRI (F), obtained from the MODIS dataset (Table AIV.4) (AIV.3):

$$P(I) = \frac{T-B}{F} \quad (\text{AIV.3})$$

Here, T represents the number of simulation steps (ticks) since the beginning of the simulation. If the probability of ignition is equal to or higher than a randomly chosen number ($ignt$, as shown in Fig. AIV.5), the corresponding patch will be burnt. The consumption of patches by megafauna impacts the probability of ignition. Depending on the percentage of vegetation consumed (as described in Section AIV.7.5), the occurrence of the next burning episode can be delayed. To calculate the probability of delayed ignition, the same formula is used, but with a

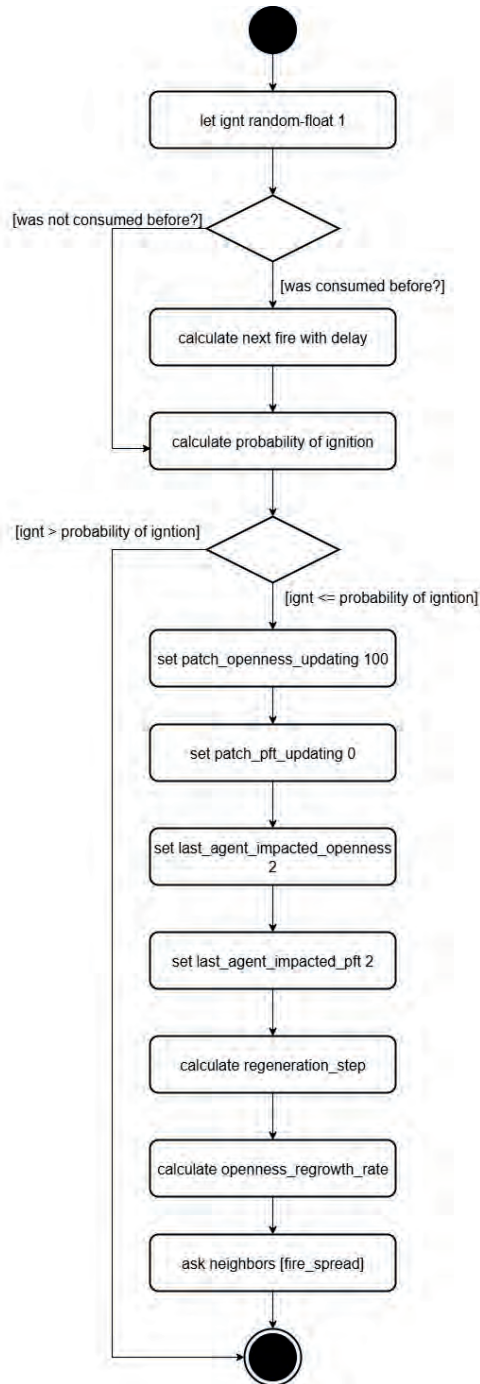


Figure AIV.5 Activity diagram for thunderstorm impact.

modification: instead of using the current number of ticks (T), we use the sum of T and `fire_delay_after_consumption`. This patch state variable represents the number of years by which the next burning episode was postponed due to megafauna vegetation consumption (section AIV.7.5). The value of B is also updated as a result of megafauna impact (details provided below).

Once a patch is burned (indicated by `patch_pft_updating` = 0 and `patch_openness_updating` = 100), the regrowth rate of openness (Section AIV.7.1) and the steps for PFT regeneration (ticks + number of years from Table AIV.7) are determined. Additionally, the information of the last agent that impacted the patch is updated (Section AIV.7.1). Subsequently, the neighbouring patches are prompted to spread the fire as explained in Section AIV.7.4.

AIV.7.4 Fire spread

Following natural and anthropogenic burning, fire has the potential to spread to neighbouring patches. However, the actual ignition of these patches depends on the probability of ignition, which is calculated using the same method described for natural fires in Section AIV.7.3. If a patch is burnt because of fire spread, it will inherit the same values for `last_agent_impacted_pft` and `last_agent_impacted_openness` as the patch from which the fire spread originated.

AIV.7.5 Megafauna consumption

Megafauna is the final agent responsible for vegetation transformation in the model (Fig. AIV.6). Compared to the previous version of HUMLAND, in this version, megafauna consumes both fully and partially recovered areas. Following plant consumption, the vegetation openness increases based on CARAIB NPP, current NPP, and estimates of maximal megafauna plant consumption.

We introduced the `Hunting_pressure` parameter which decreases the estimated potential maximal plant consumption (Table AIV.6) within a range spanning from 0% to 100%. This parameter does not impact LIG megafauna plant consumption in the British Isles because Neanderthals were not present or had very sparse occupation there during this time. Besides hunting, the intensity of megafauna impact is determined by the state of vegetation openness. Areas with greater openness tend to experience more substantial herbivore impact compared to relatively closed locations. This serves as the second determinant of megafauna impact intensity within HUMLAND 2.0. Due to the two modifications made to megafauna plant consumption in this model, megafauna affect grid cells at every simulation step in HUMLAND 2.0.

First, the potential maximal megafauna plant consumption is restricted (V_h) by the `Hunting_pressure` (H_p) percentage for each grid cell (AIV.4):

$$V_h = V_i \times \frac{H_p}{100\%} \quad (\text{AIV.4})$$

V_i is the initial potential maximal megafauna plant consumption obtained from the imported dataset (Table AIV.6). Once V_h is calculated it does not change during one simulation run. For each grid cell this value is stored as `megafauna_max_consumption_restricted_hunting`.

Following the constraints imposed by hunting pressure, the resultant value of megafauna plant consumption of a grid cell after hunting (V_h) undergoes further restriction based on the current vegetation openness (O_i) of the grid cell. This restriction yields the final estimate (V_m) of megafauna impact through the following formula (AIV.5):

$$V_m = V_h \times \frac{O_i}{100} \quad (\text{AIV.5})$$

Afterwards, the V_c value quantifies the percentage of vegetation consumed in each grid cell, excluding water bodies and high mountains (AIV.6):

$$V_c = 100 \times \frac{V_m}{V_n} \quad (\text{AIV.6})$$

V_n corresponds to the current NPP of the consumed grid cell. The resulting V_c value is then summarized with the current vegetation openness to reflect the impact of megafauna. Megafauna only impact grid cells with vegetation openness lower than 100%, i.e., there is no herbivory consumption of grid cells without vegetation. Subsequently, after the megafauna plant consumption of a grid cell, the current NPP of this grid cell is reduced based on the calculated percentage of consumed vegetation (V_c).

Regarding the impact of megafauna on PFTs, it is assumed that megafauna consumes all PFTs present on a grid cell in equal proportions, besides the first dominant PFT. Therefore, if the vegetation is entirely consumed by megafauna and the vegetation openness reaches 100%, the first dominant PFT is replaced with bare ground. In such cases, `last_agent_impacted_pft` and `last_agent_impacted_openness` is assigned to a value of 4, indicating that the impact was caused by megafauna.

However, if the dominant PFT remains unchanged after megafauna consumption, the `last_agent_impacted_openness` is updated after the patch has experienced 10 consecutive ticks of megafauna impact (`continuous_consumption` = 10) and if the difference between CARAIB and current vegetation openness is more than 10%. This decision was taken considering the relatively low-intensity impact of megafauna on all grid cells (i.e., most of the time megafauna reduces not

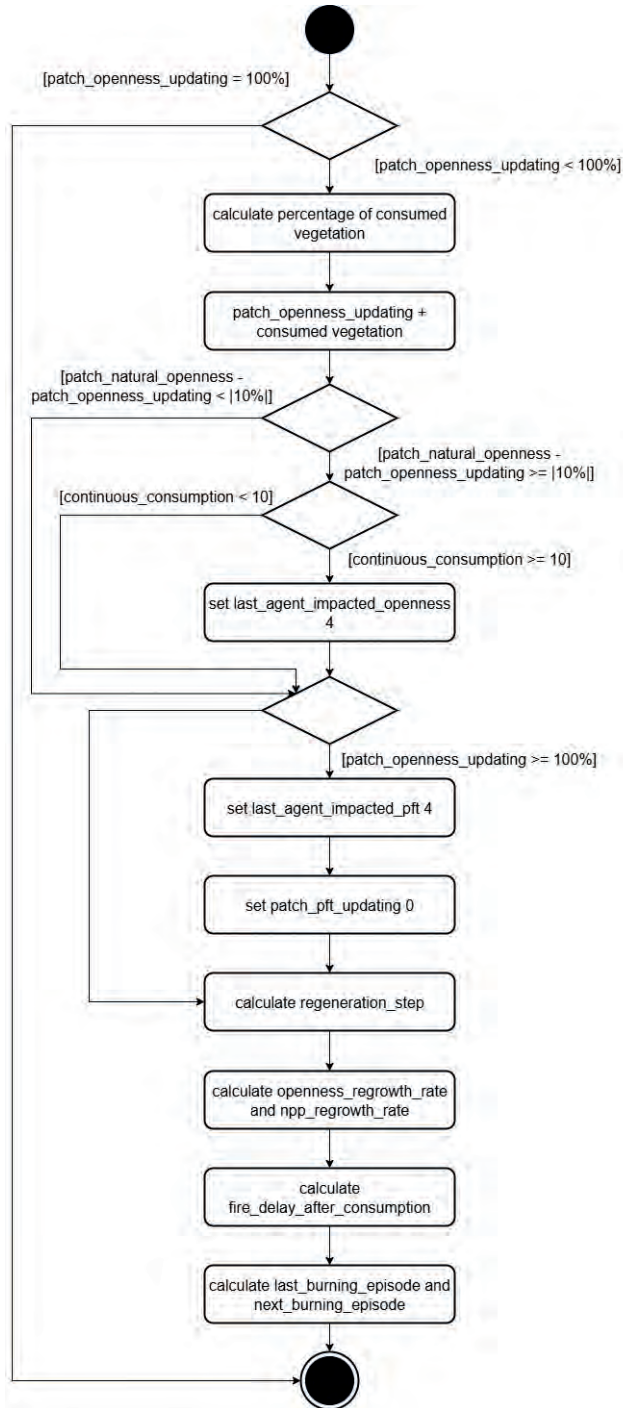


Figure AIV.6 Activity diagram for megafauna impact.

more than $V_m = 1\%$ vegetation on each grid cell per simulation step). We assumed that for megafauna to be recognized as an agent responsible for changing vegetation openness of a grid cell, herbivores must effect a transformation to some extent comparable to that induced by fires and climate per simulation step.

When there is partial consumption of vegetation by megafauna (i.e., when the first dominant PFT remains unchanged), it leads to delays in fire activity because time is required to accumulate plant material that can be burnt. The number of years by which fire activity is delayed is calculated by multiplying with the FRI of the respective PFT at the patch (Table AIV.4). Consequently, depending on the percentage of vegetation consumed, the time step at which the vegetation has a 100% probability of being burnt in the presence of an ignition source is postponed.

GLOSSARY

A

a.s.l. Above Sea Level. 93, 122, 138, 237, 281

ABM Agent-based modelling. Modelling approach used to study complex systems. In ABM heterogeneous individuals act and interact between each other and with their environment. As a result, population-level structures, patterns, and properties can emerge from this interaction. 21, 23, 25, 28, 34–39, 79–80, 82–88, 90–92, 94, 96, 107–108, 114–115, 120–121, 125, 127–129, 133, 135, 138–139, 143, 149, 154, 157–158, 162, 166–168, 170, 172–173, 175–179, 198, 203, 207–209, 214, 220, 229, 235–236, 239, 242, 244, 246–247, 267, 275, 279–280, 283, 286–289, 291–293, 315

aDNA Ancient DNA. 55, 126, 163–165, 170, 176, 179

AP/NAP Ratio of arboreal and non-arboreal pollen taxa percentages. 50–51, 53, 60, 62

B

Black carbon Fire residue produced by incomplete combustion of organic matter. 50, 56, 163, 186, 196, 206

C

CARAIB CARbon Assimilation In the Biosphere. Dynamic vegetation model which calculates carbon and water fluxes between the atmosphere and the terrestrial biosphere. CARAIB simulates the major processes of the plant development (establishment, growth, decease) as well as their geographic distributions (Plant Functional Types or species) in response to climate change. 21, 23–26, 28–29, 35–38, 83–92, 95–99, 102, 106–107, 113–116, 123–126, 128, 130–131, 134–140, 142–143, 149–150, 156, 158–159, 162, 166–171, 177, 179, 190, 215, 220, 229, 237–239, 244–249, 256, 258, 262, 264, 267–268, 274–277, 281–283, 285, 288–294, 301, 304

D

DGVM Dynamic Global Vegetation Model. 126, 149, 274–275

F

F1-score A measure of a test's accuracy in binary classification, which considers both the precision and the recall of the test to compute the score. The F1 score ranges from 0 to 1, with 1 being the best possible score, indicating perfect precision and recall. 88, 90, 97, 106, 114

Foragers (Hunter-gatherers) Populations that mainly depend on food collection or foraging of wild resources. 21, 33–34, 44, 48–50, 53, 56, 58, 76–77, 81–82, 93, 119–120, 122–123, 129, 134, 140, 143, 149, 152–153, 155, 158, 163–164, 166, 169–170, 172–177, 184–185, 187, 203–204, 241–242, 252, 285–286, 297

FRI Fire Return Intervals. The average period between fires under the presumed historical fire regime. 83, 94, 171, 222, 236–237, 243, 246, 254, 258, 281–282, 288, 291, 299, 304

G

- Genetic algorithm** An optimization technique inspired by the principles of natural selection. This technique is used to explore the space of possible solutions. 21, 38–39, 120, 125, 127, 129–130, 136, 139–141, 145–146, 149, 151–152, 157–158, 162, 168, 173–174, 176–178, 197, 204, 215, 269–271, 276
- GIS** Geographic Information System. 5, 168, 190, 314
- GTOPO30** A global digital elevation model with a horizontal grid spacing of 30 arc seconds (approximately 1 kilometre). 83–84, 135, 245, 247–248, 268, 289, 292–293

H

- HUMLAND** HUMAN impact on LANDscapes. 21–26, 28–29, 34, 36–39, 79–80, 82–84, 86–88, 90–95, 97–98, 104, 107–110, 112–115, 119–120, 125, 127–136, 138–141, 143–145, 148–152, 154–158, 162, 167–179, 203, 221, 232, 235–236, 238, 244, 267–270, 273, 276–277, 279–281, 283, 285, 289, 292, 294, 297, 301
- Hunter-Gatherers** (Foragers) Populations that mainly depend on food collection or foraging of wild resources. 1, 3, 21–22, 33–37, 39, 41–42, 44–58, 60, 62–63, 66, 69, 71, 73–76, 80–83, 91–93, 101–102, 104–105, 107–108, 110–112, 119–122, 126, 128–129, 133–135, 138, 141, 148, 150–151, 153–155, 157, 162–165, 166–167, 169–170, 172, 174–175, 177–179, 212, 223, 225, 231, 236, 241–242, 252, 280, 285–286, 297

I

- iLOVECLIM** Intermediate Level Ocean-Atmosphere-Vegetation Integrated Model. An intermediate complexity fully coupled climate Earth system model that aims at computation and understanding of the climate system on a millennial timescale. 84, 135–136, 169, 183, 206–207, 247, 274–277, 292

L

- Levoglucosan** A degradation product obtained from cellulose burning at temperatures more than 300°C. 50, 57, 163, 197, 209
- LHS** Latin Hypercube Sampling. A statistical method for generating a near-random sample of parameter values from a multidimensional distribution. It is used to perform uncertainty and sensitivity analysis on numerical models. 97, 105, 107, 110, 172
- LPJ-GUESS** Lund–Potsdam–Jena General Ecosystem Simulator. 137
- LRA** Landscape Reconstruction Algorithm. A framework of vegetation reconstruction that includes REVEALS as the first step, and LOVE (LOCAL Vegetation Estimates)–as the second step. 53

N

Niche Construction The process whereby organisms, through their metabolism, their activities and their choices, modify their own and/or other species niches. 32, 36, 39, 42–44, 46–50, 62, 73–76, 163–165, 184–185, 202, 204, 208, 211, 213, 236, 280

Non-pollen palynomorphs Remains of organisms within the size range of pollen grains (c. 10–250 µm) (e.g., fungi, zoological remains, plant fragments, algae). 50–52, 54, 60–62, 72–73, 163–164, 183

NPP Net Primary Productivity. It is the difference between Gross Primary Productivity (total amount of energy captured by photosynthesis in an ecosystem) and the energy used in respiration ($NPP = GPP - R$). NPP represents the energy available for growth and reproduction of plants and for consumption by herbivores and decomposers. 83, 85, 87, 95–96, 133, 135, 138, 156, 170, 229, 237, 239, 245, 247–248, 256, 258, 268, 275, 282, 285, 290, 293–294, 301–302

P

PAHs Polycyclic Aromatic Hydrocarbons. A group of organic compounds composed of multiple aromatic rings. They are environmental pollutants formed primarily during the incomplete combustion of organic materials such as coal, oil, gas, wood, and garbage. 50, 56, 188

Parenchyma A part of plant tissue found in most non-woody plants. 51, 58, 75, 165, 179, 206

PFT Plant Functional Type. A set of species that share similar characteristics. 36–38, 83–92, 94–96, 98, 100, 106–107, 113, 124, 127–131, 134–137, 141, 143, 145–146, 148, 153, 155–157, 166, 168, 170–172, 176, 220, 229, 232, 237–239, 242–249, 251–252, 254, 256, 258, 264–265, 267–268, 275–276, 281–283, 285, 287–291, 293–294, 296–297, 299, 301–302, 304

Phytoliths Rigid, microscopic structures made of silica, present in some plant tissues and persisting after the decay of the plant. 50–52, 55–56, 58–59, 75–76, 165, 179, 182, 189, 205, 208, 212, 214, 217

PNV Potential natural vegetation. 83–85, 87, 89–90, 128, 130–131, 135, 220, 239, 244, 247, 268, 274–275, 283, 289, 292–294

PRCC Partial Rank Correlation Coefficient. A statistical method used to measure the strength and direction of association between an input variable and an output variable, while controlling for the effects of other input variables. The PRCC value ranges from -1 to 1, and values near 0 indicating weak or no correlation. 97, 105, 107, 110, 172

R

REVEALS Regional Estimates of Vegetation Abundance from Large Sites. A method to reconstruct plant cover at a regional spatial scale of ca. 100 km × 100 km via transforming pollen data from large lakes and multiple small-sized sites. 21, 23–26, 28–29, 35–38, 83, 86–90, 96–102, 104, 106–107, 109–115, 123–130, 136–137, 139–146, 149–152, 154–156, 158, 162, 166–171, 173–177, 179, 220, 223–227, 229–232, 237–239, 244–246, 248, 263, 265, 267–271, 274, 276–277, 281–283, 285, 288–289, 291, 293

S

SEIB-DGVM Spatially Explicit Individual Based DGVM. 149

Simulation A dynamic model that incorporates changes over time. 21, 28, 37, 79, 83–85, 87–88, 90–96, 100–102, 104–105, 109–111, 128–136, 141, 144, 148, 156–157, 162, 166, 169–171, 176, 178, 183, 186, 194, 212, 215, 223–227, 230–231, 236, 238–239, 243–249, 252, 254, 274–277, 282–285, 288, 290, 292–294, 297, 299, 302, 304

T

t-value A measure used to assess whether the difference between the means of two groups is significant or if it could have happened by random chance. 90, 97, 114

V

VECODE VEgetation COntinuous DEscription model. 135, 274, 275, 276

Vegetation openness In the context of this research, vegetation openness is broadly defined as vegetation density. 22, 37–38, 45, 52–53, 56, 65–66, 80–81, 83–85, 87–90, 92–93, 95–102, 105–109, 111–113, 115, 120, 128–129, 131, 133–135, 137, 139–143, 145–146, 148, 152–153, 155–158, 166, 168, 170–174, 176–177, 220, 223–226, 229–231, 237, 239, 241–250, 252, 256, 258, 262–263, 266, 268, 270, 275–276, 281–283, 285–289, 291, 293–295, 297, 301–302, 304

W

WISE Water Information System for Europe. 37, 83–84, 135, 139, 245, 247–248, 268, 289, 292–293

CURRICULUM VITAE

Anastasia Nikulina was born on February 13, 1993, in Novosibirsk, Russia. Upon graduating from Gymnasium 1 in Novosibirsk in 2011, she began her undergraduate studies at Novosibirsk State University (Novosibirsk, Russia). In the summer of 2015, she graduated with a Bachelor's degree in History. She then pursued her Master's degree in Archaeology of North and Central Asia at the same university, graduating with honours in 2017. Since the beginning of her studies, Anastasia has participated in archaeological excavations in Russia, including Denisova Cave (Altai Krai), Afontova Gora-2 (Krasnoyarsk Krai), Tartas-1 (Novosibirsk Oblast), and Ust-Voikar (Yamalo-Nenets Autonomous Okrug), and in France at Fourneau-du-Diable (Dordogne). Anastasia has seven years of fieldwork experience on archaeological sites dating from the Palaeolithic to the Middle Ages.

During the second year of her Bachelor's program, Anastasia selected specialization in GIS for archaeological studies. She became a member of an interdisciplinary research team studying human–environment interactions in Western Siberia, with projects supported by the Russian Foundation for Basic Research (now the Russian Centre for Science Information), the Russian Science Foundation, and the Ministry of Science and Higher Education of the Russian Federation. After completing her Master's program, Anastasia was involved in the French–Russian International Associated Laboratory ARTEMIR. During this time, she expanded her expertise and applied 3D modelling in her work.

In 2019, Anastasia became a PhD candidate at Leiden University (The Netherlands) as part of the Terranova project supported by the European Union's Horizon 2020 program and recognized as a Marie Skłodowska-Curie Actions Innovative Training Network. Anastasia's research focused on the earliest human impacts on interglacial landscapes in Europe. Besides conducting research, Anastasia's involvement in Terranova included public outreach activities, including blogging about her research, and engaging in public events. Additionally, she was one of the main coordinators for the development of Terranova's massive open online course (MOOC), which is available free of charge. Furthermore, Anastasia contributed to the Terranova digital atlas, a comprehensive tool mapping landscape evolution across Europe, which is currently available to the scientific community upon request.

After completing her PhD, Anastasia joined the European Research Council (ERC) SSE1K project “Science, Society and Environmental Change in the First Millennium CE” as a postdoctoral researcher. The project focuses on human–environment interactions in the Mediterranean during the first millennium CE and is interdisciplinary, bringing together researchers from Ca’ Foscari University (Venice, Italy), the University of Basel (Basel, Switzerland), and Durham University (Durham, UK). Anastasia is based at Durham University, where she is working on ABM as part of the project.

Anastasia’s involvement in various projects has led her to present at 14 international conferences, including the INQUA Congress in 2023 (Rome, Italy) and the Computer Applications and Quantitative Methods in Archaeology (CAA) conference in 2021–2023 (online; Oxford, UK; Amsterdam, The Netherlands). In 2021, Anastasia’s presentation at the CAA conference was honoured with the Nick Ryan Bursary Award for the best talk. Additionally, Anastasia was an invited speaker at several events, including the Hortus Talks podcast series organized by the Botanical Garden in Amsterdam (The Netherlands), the Computational and Digital Archaeology Laboratory Series at the University of Cambridge (UK), the workshop “Advances in Modelling Past Human Ecosystems” at Cologne University (Germany), the symposium on “Fire in Human Evolution” at Leiden University (The Netherlands), and the graduate conference “Humans and the Landscape(s): An Everlasting Story of Mutual Interactions” at University of Basel (Switzerland).

Anastasia has also participated in various international schools and training programs, including Neural Networks for Archaeologists with Python at Pisa University (Italy). She has contributed to several multi-author, peer-reviewed papers, serving as the lead author in six instances. In addition, she has published developed ABMs after peer review in an open-access model library.