A Simulation of Anthropogenic Mammoth Extinction

Matthew Klapman
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I. Introduction

Research Question: Could humans alone have caused the extinction of the Columbian mammoth?

One hypothesis for the extinction of megafauna in North America at the end of the Pleistocene Epoch is overkill. The overkill hypothesis was first proposed by Paul Martin in 1975. The timeline of human migration lines up very well with the mass extinction of megafauna in North America. The overkill hypothesis claims that early humans, migrating into North America via the Bering Strait land bridge and the ice-free corridor, hunted mammoths and other megafauna to extinction.

Previous work has been done by Frank et al researching the extinction of the Columbian mammoth. Using an ordinary differential equations model, we built upon this research by creating a more realistic and more efficient discrete stochastic model.

II. ODE Model

The previous work by Frank et al. explored the overkill hypothesis using an ordinary differential equations model. We built upon this research by creating a more realistic and efficient discrete stochastic model.

The ordinarly differential equations model given below:

\[
dH_{i,j} = \alpha_i M_{i,j} \left(1 - \frac{H_{i,j}}{K_{i,j}} - \sum_{g=1}^{b} \sum_{h=1}^{a} j_{g,h} H_{i,j} \right) \]

\[
dM_{i,j} = r_{i,j} \left(1 - \frac{M_{i,j}}{A_{i,j}} - \sum_{g=1}^{b} \sum_{h=1}^{a} M_{i,j} - \sum_{g=1}^{b} \sum_{h=1}^{a} j_{g,h} M_{i,j} \right)
\]

Where the parameters with respective units and value ranges are shown below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Value Range</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>Mammoth predation saturation constant</td>
<td></td>
<td>0.1</td>
<td>literature</td>
</tr>
<tr>
<td>( K )</td>
<td>Allee effect critical population size</td>
<td></td>
<td>10</td>
<td>literature</td>
</tr>
<tr>
<td>( b )</td>
<td>Migration rate</td>
<td></td>
<td>[0, 10]</td>
<td>experimentally obtained</td>
</tr>
<tr>
<td>( r )</td>
<td>Human growth rate</td>
<td></td>
<td>[0, 1]</td>
<td>literature</td>
</tr>
<tr>
<td>( A )</td>
<td>Human carrying capacity</td>
<td></td>
<td>10</td>
<td>literature</td>
</tr>
<tr>
<td>( j_{g,h} )</td>
<td>Human-plant interaction rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( M_{i,j} )</td>
<td>Human population</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( H_{i,j} )</td>
<td>Mammoth population</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ODE Model Results:

- Each parameter set tested went to extinction.
- Extinction times were overly conservative due to conservative initial conditions and the nature of the differential equations model.
- Simulation runtime averaged 12.6 minutes.

III. Discrete Stochastic Modeling

We built a discrete stochastic model to simulate early humans hunting mammoths.

- This model is more realistic as it represents the individuals in the population as whole numbers and adds randomness to the simulation.
- The probability of each event occurring was calculated using the separate terms from the ODE model equations.
- Event types: Human birth/death, Mammoth birth/death, Human gain from hunting, Mammoth loss from hunting, Human migration, Mammoth migration.
- First, we ran simulations using the parameter sets of Frank et al.’s work to show that our new model is analogous.
- Next, we calibrated the migration parameter to make it more appropriate.
- Finally, we ran simulations on a new set of parameters for our final results.

The model was simulated using MATLAB, with regression analyses run using SAS.

IV. Model Comparison

Differences between ODE and Discrete Stochastic model:

- Continuous: Each species population is treated as continuous.
- Time constraint: One 100-patch simulation took 12.6 minutes on average.
- Discrete: Represents individual members of the population as whole numbers.
- Stochastic: Adds randomness to the simulation.
- It is significantly faster, taking 54 seconds on average (14 times faster).

Features of the metapopulation model:

- Is an \( n \times n \) spatial grid where each patch represents 10 square miles.
- Each simulation was a series of events occurring individually in the \( n^2 \) patches.
- Initial conditions: 250 mammoths in every patch and 10 humans in the northwest corner patch.
- Extinction criteria: When the mammoth population drops below \( A \), the Allee threshold, in every patch.

After showing that our new model is analogous to the ODE model, we wanted to look into using more realistic migration parameters.

First, we compared migration rates between the two species using constant multipliers.

- Results are shown in the figure to the right.
- An independent human migration rate significantly influences extinction time.
- An independent mammoth migration rate does not.

Conclusion: model requires one migration parameter.

Finally, we looked into having a new range on our single migration parameter, more closely aligned with the accepted time span of human migration.

- We ran simulations with exit criteria of at least one human in the southeast corner of the grid.
- Calibrated the migration parameter to fit archaeological evidence of complete North American human habitation.

V. Results

- We created 10 parameter sets using latin hypercube sampling with our calibrated migration parameter.
- Some initial conditions (250 mammoths in every patch, 10 humans in northwest patch)
- 200 simulations for each parameter set, 10 for each value of \( n \) from 1 to 20.
- Linear regression analysis for prediction and prediction interval:

VI. Conclusion

- Our results were based on anthropological evidence of human migration.
- With latin hypercube sampling, this encompasses a spread of parameter possibilities.
- 7 out of 10 parameter have extinction times between 1000-2500 years, which shows overkill is plausible.

Acknowledgements

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