Pleistocene Park: A Feasibility Study Using System Dynamics

Zachary Lucas and James Enos
Department of Systems Engineering
United States Military Academy
West Point, NY 10996

Abstract: Climate change is a major concern of the international community. Scientists have formed international teams to try to tackle the problem, and various solutions now exist. One of the more radical approaches comes from Russian scientist Sergei Zimov who is attempting to reintroduce megafauna such as mammoths to alter the ecosystem of northern Siberia to slow climate change. By reintroducing megafauna, Zimov hopes to slow carbon emissions by harnessing the natural process of the carbon cycle. Zimov, who helped identify a store of carbon larger than that in all forests and the atmosphere combined, already established a wildlife refuge in Siberia to test his theory. Pleistocene Park is Zimov's experiment to prove his theory, which he has already expanded and intends to continue expanding. By addressing the issue of snow insulation and permafrost thawing, Zimov aims to keep carbon trapped in Siberian permafrost, slowing and even reversing climate warming. Zimov's experiment is considered radical and has implications such as other fields like conservation and genetics. This literature review is a precursor to a system dynamics model and evaluation of Zimov's theory. The model will examine the feasibility of Pleistocene Park, determining if and when the park will produce significant results, and how effective this approach could be. This work begins with a literature review on Pleistocene Park that expands to the carbon cycle and carbon dynamics in freezing climates. This work is the basis for modeling the system that includes current work on reintroduction genetics, specifically that involved with bringing back woolly mammoths. Pleistocene Park is a viable option, and although it is impossible to predict all the implications, the research indicates that it could help slow, and even reverse, climate change over the next couple hundred, and even thousand, years.

Keywords: Pleistocene Park, climate change, carbon cycle

1. Introduction

Pleistocene Park is the brainchild of Sergei Zimov, a Russian ecologist and director of the Northeast Science Station is Cherskiy in the Republic of Sakha (Andersen, 2017). The park is named for the era that ended 12000 years ago, commonly known as the Ice Age (Andersen, 2017). While a conservation effort exists within the park's purpose, the real purpose is to slow the thawing of permafrost, leading to fewer carbon emissions and more (Andersen, 2017). The Zimovs' goal is encouraging the return of the Mammoth Steppe ecosystem, aided by Arctic megafauna and even mammoths (Andersen, 2017). The disappearance of the Mammoth Steppe coincides with the end of the Pleistocene era, suggesting that the Mammoth Steppes of the Pleistocene effectively hindered carbon emissions, which supports the theory pinning methane emissions on the effects of the transitional period between the Pleistocene and Holocene (Zimov S. A., 2005). The park is an attempt to slow natural cycles that have been accelerated due to climate change, and maybe even reverse them. Zimov's experiment consists of three key factors: grasslands, the megafauna that call them home and the natural carbon cycle impacted by both the grasslands and the animals that roam them (Andersen, 2017). Zimov is attempting to bring animals back from the Pleistocene era to modify the landscape to resemble the mammoth steppe in northern Siberia, trapping atmospheric carbon in the vast permafrost that covers Siberia and much of the North (Andersen, 2017). Using the work of geneticists and natural selection, Zimov hopes to bring back megafauna such as woolly mammoths to act as the tools that would achieve his vision (Zimov S. A., 2005). His goal is not to bring back mammoths and other megafauna that lived during the Pleistocene, but to slow climate change before it heats the Siberian permafrost, (Andersen, 2017), releasing the vast stores of carbon it holds (Vonk, et al., 2013). The process of reintroducing mammoths requires deliberate consideration, since its effects would bleed into other areas, specifically conservation (Brand, 2014). This review examines the historical and potential effects of imprisoned carbon, while considering the process of reintroducing the woolly mammoth and other species, as well as the potential consequences of each of these actions.

1.1 Megafauna and Their Ecosystems

"Give [Nikita Zimov] 100 mammoths and come back in a few years…you won't recognize this place" (Andersen, 2017). Megafauna is the basis of Pleistocene Park. Bring back the giant herbivores, bring back the grasslands, and the result is reduced carbon emissions (Donlan J. , 2005). The theory that supports Pleistocene Park is that once megafauna are reintroduced to Siberia, the park's supporters would only have to manage the park like they would a nature preserve to see results (Andersen, 2017). The way the theory sees the park's residents functioning is in the winter months they roam searching for grasses, trampling the snow that insulates the ground during winter (Zimov S. A., 2005). In the summer, the beasts would continue to graze and roam, using some of their energy to destroy trees and expand their pastures, reintroducing the Mammoth Steppe to Siberia (Andersen, 2017). From there, the natural processes, specifically the carbon cycle, kick into effect and make their impact on climate change (Andersen, 2017). The key to the megafauna's effectiveness lies in their size, and currently the only land-mammal species that weigh more than a ton are elephants, hippos, rhinos, and giraffes (Andersen, 2017). Currently, the park holds bison, musk oxen, and wild horses, but these are not enough for Zimov's vision (Andersen, 2017).

1.2 Gene Editing and Reviving Megafauna

Harvard geneticist George Church and his team of scientists began modifying elephant DNA in 2014 using CRISPR, the genome-editing technology (Andersen, 2017). Church is a supporter of Pleistocene Park and argues that bringing back mammoths and other extinct creatures aligns with the goal of adapting existing ecosystems to radical modern environmental changes and possibly reversing them (Church, 2013). Scientists have comprehensively catalogued the hundreds of genetic variations that differentiate modern Asian elephants from the mammoths of the Pleistocene (Callaway, 2015). De-extinction is now within reach (Zimmer, 2013). Sergei Zimov blames humans, rather than climate change, for the decimation of the migratory animals that maintained the grasslands of Siberia (Zimov S. A., 2005). Likewise, paleontologist Michael Archer disagrees with the idea is like playing God, stating "I think we played God when we exterminated these animals" (Zimmer, 2013). The idea is reminiscent of Jurassic Park, but instead of completely recreating DNA, scientists only need to reconstruct most of the genes of a mammoth and insert them into an elephant stem cell (Zimmer, 2013). Asian elephants are closer to mammoths in DNA than they are to African elephants, with only about 1.4 million DNA letters differentiating them (Callaway, 2015). Currently, whole genomes, both nuclear and mitochondrial ancient DNA, have been sequenced and reassembled by scientists for eight extinct species, one of them being the woolly mammoth (Brand, 2014). Brand (2014) simplifies how to bring back these extinct species down to patching into the living genome of the mammoth's closest relative, the Asian elephant.

A blend of current technology and natural processes brought de-extinction within reach (Zimmer, 2013). Natural selection enables serves to maintain and improve a population by adapting it to its environment, and in a relatively short time after megafauna is reintroduced, it will be adapted to its environment (Andersen, 2017). It took Yakutian wild horses less than a millennium to regrow long coats after they returned to the Arctic (Andersen, 2017). Three million years ago, elephants left Africa, and by the time they crossed the land bridge to the Americas they had grown coats of fur (Andersen, 2017). Realistically, scientists would only need to work to the point where proxy species exist (Donlan, et al., 2006). A less dramatic approach succeeded in the mid-1970s as the yellow-crowned night heron was introduced as a proxy for the endemic night heron that disappeared in the seventeenth century (Donlan, et al., 2006). The new heron population served to control land crabs that caused economic damage (Donlan, et al., 2006). The reintroduction of megafauna, specifically mammoths, requires special consideration, and even borders on conservation and the relatively new concept of rewilding.

1.3 Conservation and Rewilding

"Ask any kid 'Where do animals live?' and they will tell you 'The forest,'" (Andersen, 2017). According to Nikita Zimov, this thinking is wrong, he says that they should think of the grassland (Andersen, 2017). The animal biomass in grasslands far exceeds that in forests, which suggests that conservation should focus equally, if not more, on grasslands (Zimov S. , 2007). In The Netherlands, a similar park was established to restore the natural ecosystems there (Vera, 2009). The endeavor attracted species that had disappeared from The Netherlands (Vera, 2009). These results bring up the question of conservation, which similarly pertains to Pleistocene Park. Rewilding of ecosystems is the practice of reintroducing extant species back to places they disappeared from in the past several hundred years (Rubenstein, Rubenstein, Sherman, & Gavin, 2006). Pleistocene rewilding would involve introducing current habitats to extant species that are descended from species that lived there during the Pleistocene or reintroducing modern-day ecological proxies for the extinct species (Rubenstein, Rubenstein, Sherman, & Gavin, 2006).

Currently, the conservation and rewilding benchmark is the Columbian landfall of AD 1492, but some scientists call for a less arbitrary benchmark (Donlan, et al., 2006). The arrival of humans during the end of the Pleistocene and the contemporaneous extinctions of many species, specifically megafauna, is enough criteria to argue for a new benchmark (Donlan, et al., 2006). However, Donlan et al. (2006) concedes that this benchmark is illogical in some places, such as parts of North America. Rubenstein et al. (2006) give a pessimistic view, noting that translocating megafauna from the developing world to fix past ecological mistakes could cripple, rather than assist, the conservation movement worldwide. One critic notes that rewilding North America with Pleistocene megafauna will not restore the continent's evolutionary potential because the species in question are evolutionarily distinct (Rubenstein, Rubenstein, Sherman, & Gavin, 2006). The critic continues, saying that the effort will not restore ecological potential of North America's modern ecosystems because of their continued evolution since the disappearance of the megafauna, and that adding these exotic species to modern ecological systems could devastate populations of the indigenous, native animals and plants (Rubenstein, Rubenstein, Sherman, & Gavin, 2006). Other issues with the park includes the inevitable unexpected consequences, transmission of disease, and impact on other species (Donlan J. , 2005). Another issue is predators in the parks. Reintroducing large predators poses a risk to the populations that would live near the parks, but Sergei Zimov argues that this is a nonissue in Siberia, where the human population is sparse (Andersen, 2017). An alternative is lion and elephant-proof fences, which would constitute large expenses (Caro, 2007).

Reintroduction proved its potential with the reintroduction of gray wolves into Yellowstone National Park (Donlan, et al., 2006). Through the wolves' interactions with species already in the park, they helped stop the erosion caused by rivers and streams in the park and stabilized the ecosystem there (Donlan, et al., 2006). However, reintroduced animals can destroy ecosystems as easily as they can repair them. Another effect of rewilding regions is that it increases the population numbers and viability by augmenting genetic diversity of the animals reintroduced (Donlan, et al., 2006). To conserve some of the species that Zimov would reintroduce in his park, Donlan (2005) suggests relocating small populations in places where they are already in captivity. The African cheetah is an at-risk species, and Donlan (2005) suggests rewilding some of the captive animals in the southwestern United States, which might just save the species from extinction.

1.4 Other Benefits of Rewilding

Proponents of rewilding North America look at the United States national parks and San Diego's Wild Animal Park for how rewilding can benefit economically (Donlan, et al., 2006). In Yellowstone, the reintroduction of wolves brings in economic and social benefits totaling around $6 to $9 million per year at a cost of $0.5 to $0.9 million per year (Donlan, et al., 2006). Eventually, in Pleistocene Park, humans could visit on bullet trains built on elevated tracks, go on Arctic safari tours, and even hunt in a limited capacity (Andersen, 2017). Additionally, increased interest would encourage improved public understanding of ecological and evolutionary history, which would strengthen overall support for the conservation of biodiversity and wildness (Donlan, et al., 2006). It is difficult to estimate the additional benefits of rewilding North America with Pleistocene megafauna, and the same goes for those in Pleistocene Park. However, as shown in Yellowstone, the possible benefits could be worth the costs.

1.5 Paper Structure

The remainder of this paper is separated into three additional sections, background literature, methodology, model findings and analysis, and a conclusion. The background literature provides a basis for developing the structure of the model that includes the carbon cycle and the impact of snow cover on the artic stores of carbon. The methodology section presents an overview of system dynamics as the approach to modeling this system and describes the causal structure of the system. This section also describes the resulting stock and flow structure that generates the dynamic behavior of the system. The model findings section presents the results of the model and the potential impact of introducing megafauna into the Pleistocene Park. Finally, the conclusion section summarizes the findings of this work and proposes additional future work to further the research.

2. Background Literature

In order to better understand the problem of thawing permafrost and the resulting increase in carbon emission, one must understand the underlying carbon cycle. This section presents a discussion on terrestrial carbon stores, emissions, and the overall carbon cycle. This literature provides the basis for the model, specifically the carbon cycle, and provides initial variables to include in the model. The discussion on the carbon cycle describes how carbon naturally cycles between terrestrial stores, plant life, and the atmosphere. Additionally, it describes the impact of snow cover on the artic carbon stores that contain large amounts of carbon in a frozen state. The section also discusses the linkages between carbon emissions and global temperatures that are key elements in the model.

2.1 Terrestrial Carbon Stores

Permafrost contains the largest store of organic carbon (C) in the terrestrial system (Koven, Riley, & Stern, 2013). The terrestrial permafrost area is approximately 15.3 km^2, a substantial area containing up to 1700 Pg (billion metric tons) of organic carbon (OC), more than twice the estimated carbon in the atmosphere's C pool (Spencer, et al., 2015). More than a quarter of this (>500 Pg C) is stored in Siberian-Arctic Pleistocene-age permafrost, called yedoma (Vonk, et al., 2013). This yedoma is highly biolable, meaning that it has high potential biodegradability (Vonk, et al., 2013). This means that warming the permafrost would likely release the stored carbon, in the form of carbon dioxide (CO_2) and methane (CH_4), which I will discuss later (Soussana, et al., 2004). There is variation between scientists about how much carbon is stored in the terrestrial system, but most estimates hover around 1600-1700 Pg. Most of these deposits formed during the late Pleistocene in Siberia prior to the invasion of glaciers and covered around 1 million km^2 there (Vonk, et al., 2013). Regardless, the amount of carbon stored in the Siberian yedoma is equal to the amount of carbon stored in the total global forest biomass (Vonk, et al., 2013).

2.2 Emissions

If greenhouse-gas induced climate warming continues, the permafrost will melt and about 500 gigatons of carbon, or 2.5 times that of all rainforests combined, will release into the atmosphere (Zimov S. A., 2005). Methane has a global warming potential that is 23 times that of carbon dioxide over a century-long timeline (Soussana, et al., 2004). If the permafrost in the Arctic melts, it could release more greenhouse gas than all the world's forests would if they burned to the ground (Church, 2013). When permafrost thaws, microbes consume the organic contents, emitting carbon dioxide (Andersen, 2017). When this process occurs at the bottom of lakes created by melted permafrost, it emits bubbles of methane that float to the surface and enter the atmosphere (Andersen, 2017). Methane's greenhouse effects are an order of magnitude more effective than carbon dioxide's (Andersen, 2017), up to 23 times stronger than carbon dioxide (Soussana, et al., 2004).

During the shift from the Pleistocene to the Holocene, about 11-18 thousand years ago, global methane emissions doubled from 100 Tg per year to 200 Tg per year (Zimov & Zimov, 2014). During this time, a gradient appeared in interhemispheric methane, indicating that the methane was largely coming from the north, while the gradient was stable over the course of the Holocene (Zimov & Zimov, 2014). The rogue methane source contributed anywhere to 40 to 70 Tg per year over this time, which is significant considering that modern rice paddies and livestock release 70 to 90 Tg of methane per year respectively (Zimov & Zimov, Role of Megafauna and Frozen Soil in the Atmospheric CH4 Dynamics, 2014). In northern Siberia alone, local permafrost thawing contributed up to 25 Tg per year, added to similar amounts from American, European, west and south Siberian, and Chinese permafrost, as well as that of the southern hemisphere such as Patagonian permafrost (Zimov & Zimov, 2014). During the entire deglaciation of Siberia, permafrost is estimated to have emitted 400 Pg of methane (300 Pg of carbon) into the atmosphere (Zimov & Zimov, 2014). When compared to current global methane emissions of 500 to 600 Tg of methane per year, that number is immense (Dlugokenchy, Nisbet, Fisher, & Lowry, 2011). However, when there is an estimated 1700 Pg of carbon sitting in permafrost, including both methane and carbon dioxide, current emissions are dwarfed by the potential (Spencer, et al., 2015). Current risk assessments estimate that up to 100 Pg of carbon could be released from its permafrost prison by 2100 due to rising temperatures (Schuur, et al., 2008). Based on estimates and experiments, a group of scientists estimated the potential release in Siberia to be 40 Pg C over four decades if Siberian soils thawed to 5°C, while another scientist estimated that 48 Pg C could be released from Canadian permafrost over the 21st century if the mean annual air temperature increased by 4°C (Schuur, et al., 2008).

Wild megafauna and other herbivores also contribute to emissions, which currently emit 2 to 6 Tg per year, but there were also more wild herbivores in the past (Zimov & Zimov, 2014). Zimov and Zimov (2014) estimate that 100 kg of methane per year per ton of animal weight is produced by wild ruminant animals (bulls, antelope, deer, goats, ect.). At the beginning of the Younger Dryas era, megafauna experienced its demise, which coincides with a strong decrease in methane inputs to the atmosphere (Brook, Servinghaus, Smith, Elliot, & Lyons, 2011). Zimov and Zimov (2014) attribute this increase in methane to a lack of natural management of permafrost by megafauna. Brook et al. (2011) attribute part, not all, of the methane increase to megafauna, but nevertheless hypothesize that the disappearance of megafauna played a significant part of the decrease. While the herbivore species that Zimov wants to bring back and expand contribute to methane emissions, he asserts that the benefit they provide outweighs the cost (Andersen, 2017).

2.2 The Carbon Cycle

While carbon emissions continue, the global increase of CO_2 levels has been less than anticipated, indicating the existence of a carbon sink in continental ecosystems (Soussana, et al., 2004). Due to the cycling of carbon being stored and released, natural processes could mitigate the doom and gloom presented above (Soussana, et al., 2004). Grasslands are the sink, and Soussana, et al. suggest that storage rates are between 0.2 and 0.5 tons C per hectare per year (Soussana, et al., 2004). In many of the planet's regions have a 0.5-meter-thick carbon-rich layer, that in northern Siberia is often dozens of meters thick, which could significantly increase the amount of carbon stored (Zimov S. , Mammoth steppes and future climate, 2007). Schuur et al. corroborate this, saying, "…permafrost thickness typically ranges between 350 and 650 meters in the continuous permafrost zone of the Northern Hemisphere…[and] in the discontinuous zone farther south, it typically ranges from less than 1 m to 50 m" (Schuur, et al., 2008).

Unlike forests, where microbes quickly devour the nutrients of every leaf that hits the ground, which then emit greenhouse gasses, grasslands keep nutrients moving as they are consumed by large herbivores which return the nutrients to the ground in the form of dung a few days later, which fertilizes the grasses (Andersen, 2017). In turn, the grasses then absorb the nutrients, storing them in the ground below, eventually turning into yedoma as new soils cover them (Andersen, 2017). This process, repeating constantly over millions of years, is why such a large store of carbon exists in Siberia and other regions in the Arctic (Andersen, 2017). The carbon is then released in the events and cycles specified in 2.2 Emissions. Other processes, such as fires and forests release the carbon back into the atmosphere for the cycle to begin again (Soussana, et al., 2004).

Snow cover significantly impacts the dynamics of Siberian carbon, acting as an insulator of soils in winter (Groffman, et al., 2001). Kreyling and Henry (2011) believe that overwinter processes can have significant effects on ecosystems that are seasonally covered in snow. Air and soil temperatures can vary due to snow cover, and reduced snow cover increases soil freezing in some regions (Kreyling & Henry, 2011). Reduction in snow cover exposes the soils to freezing temperatures, allowing permafrost to penetrate deeper and last longer during the warm summer months (Groffman, et al., 2001). The freeze-thaw of permafrost and soils increases the activity of the microbes that live in them, releasing carbon dioxide into the atmosphere (Heimann & Reichstein, 2008). This means that more permafrost thaw releases more carbon dioxide, and vice versa (Neilsen, et al., 2001). Not only do freeze-thaw cycles impact microbial activity, but wetting and drying cycles do as well (Neilsen, et al., 2001). Neilsen et al. (2001) studied the effects of freezing on carbon and nitrogen cycling in northern hardwood forest soils and determined that freezing had a significant effect on both carbon dioxide and nitrous oxide, noting that the effects on carbon dioxide were more marked. Although forest and grassland dynamics vary, similar principles apply to both, supporting Zimov's expected use of megafauna in Pleistocene Park. In Germany, scientists came to a similar conclusion, noting that the consequences of highly reduced soil freezing or even a lack of soil freezing must be considered with climate change (Kreyling & Henry, 2011)

3. Methodology – System Dynamics

System Dynamics assists in modeling scenarios that that are difficult to recreate and can project the results of a system. System Dynamics using stocks, flows, and feedback loops to simulate the effects of a complex system, matching current reference modes to the model before projecting out hundreds, even thousands of years. The model determines whether Nikolai Zimov's experiment for Pleistocene Park is viable and use it to later propose a policy to combat climate change.

3.1 Background on System Dynamics

"System Dynamics is a computer-aided approach to policy analysis and design" (Strickan, n.d.). We live in continuous, circular environment where the feedback of one cycle influences the effects of another (Forrester, 1991). One of the primary goals of system dynamics is understanding the nature of systems in which we live and impact and how they subsequently impact us (Forrester, 2009). Systems are interrelated, creating complex feedback loops, which is part of the reason policies fail so frequently (Forrester, 2009). System dynamics is applicable to any system characterized by interdependence, mutual interaction, information feedback, and circular causality (Strickan, n.d.).

System dynamics begins with defining a dynamic problem, later modeling it to gain a better understanding of the underlying systems impacting certain variables (Strickan, n.d.). It builds upon the mental models already present on the system, using computer software to better understand the intricacies of the system (Forrester, 1991). "Complex systems defy intuitive solutions" (Forrester, 1991), so by improving upon our mental models we can understand the actual effects of the system and use our understanding to predict future outcomes. After defining a problem, a causal loop diagram is used to understand the variables involved and their impacts upon each other, creating an interconnected series of loops. Causal loop diagrams are converted into stock and flow diagrams that focus on stores, or stocks, and rates, or flows. Then, using reference modes, or existing modes of behavior, the model is calibrated to ensure its viability and accuracy. From there, policies are implemented and evaluated for effectiveness.

System dynamics places an emphasis on endogenous behavior, like how an engineer designs an oil refinery (Forrester, 1991). "The engineer looks at the individual working characteristics of the chemical reactors, evaporators, and distillation towers; considers how they are interconnected and controlled; and evaluates the dynamic behavior implied by their feedback loops" (Forrester, 1991). These complex systems behave in ways that differ from our expectations, since intuition is based on simple system (Forrester, 1991). A better understanding of the problem leads to better solutions.

3.2 Causal Loop Diagrams

The natural processes at play in Pleistocene Park provide the basis to create the causal loop diagram and eventual stock and flow model for the dynamics of the Pleistocene Park. It begins with the carbon cycle loop and expands out to include the effects of Arctic snow on the process. The diagram also includs the effects of megafauna migrations, examining how the population is affected by changing temperatures. The megafauna population followed, which is based off other population models, which affects the ecosystem balance specific to the Arctic. That completed the general cycle that Zimov's experiment hopes to influence, with favorable outcomes. Figure 1 presents the overall causal loop diagram that is the basis for the system dynamics model.

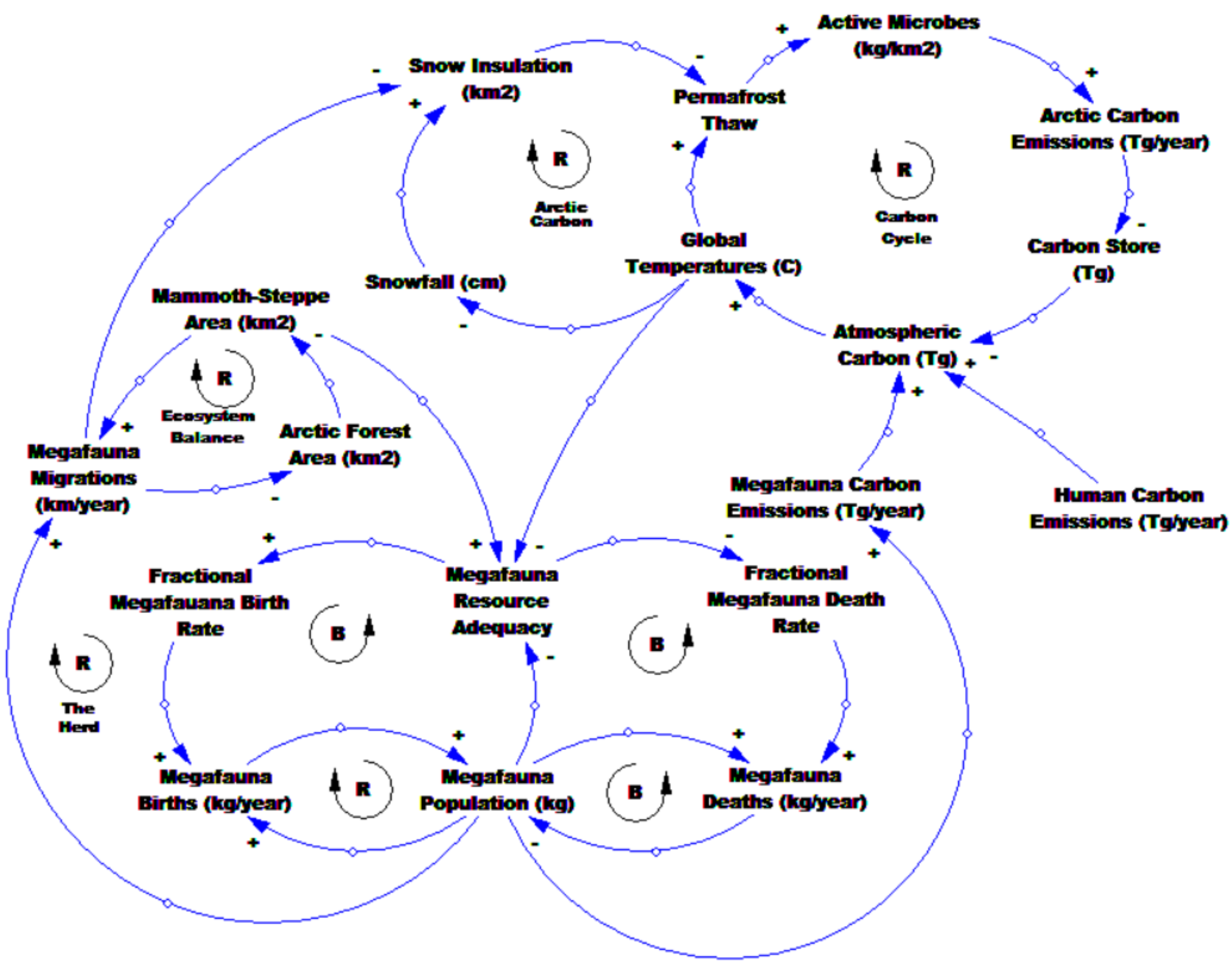

Figure 1: Overall Causal Loop Diagram

3.2.1 Carbon Cycle

The *Carbon Cycle* is the base loop for the Pleistocene Park model, Figure 2. The cycle is based on the shift from carbon to the atmosphere to terrestrial stores, the largest one being in Arctic carbon stores. When soil microbes thaw in the permafrost they become *Active Microbes*, and eat whatever organic material they can find in the yedoma, the Arctic permafrost. The microbes release stored carbon when they consume the organic material, which is released into the atmosphere, adding to the atmospheric carbon stock. With more *Permafrost Thaw*, there is more carbon emission, and with less *Permafrost Thaw*, there is less carbon emissions. The higher the concentration of

Atmospheric Carbon, the more the average *Global Temperatures* increase, which thaws more permafrost in the warm summer months. This feeds into the number of *Active Microbes*, completing the loop.

3.2.2 Arctic Carbon

In the arctic, *Permafrost Thaw* is the catalyst for microbe activity. Arctic snow provides *Snow Insulation* for the soil, keeping the soil warm and keeping the permafrost deep. When the snow is thin or not present, the freezing winter temperatures penetrate deep in the soil, extending the life of the permafrost. The permafrost thaw then feeds into the carbon cycle, which affects global temperatures, which increase or decrease snowfall depending on the shift in average global temperature. More *Snowfall* equates greater snow insulation. Figure 3 presents a portion of this causal loop and feedback mechanism that is included in the overall model.

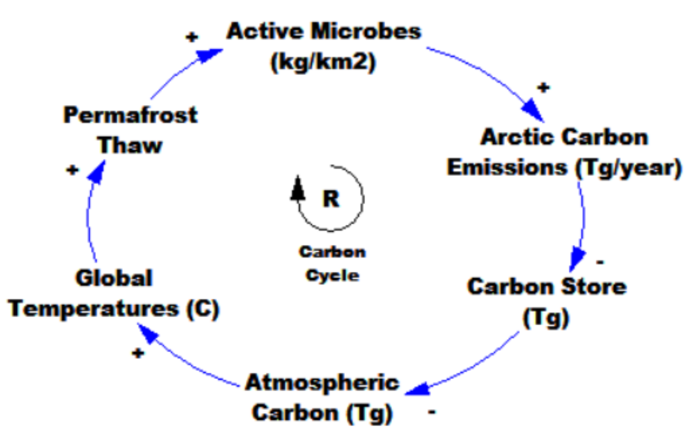

Figure 2: Carbon Cycle CLD

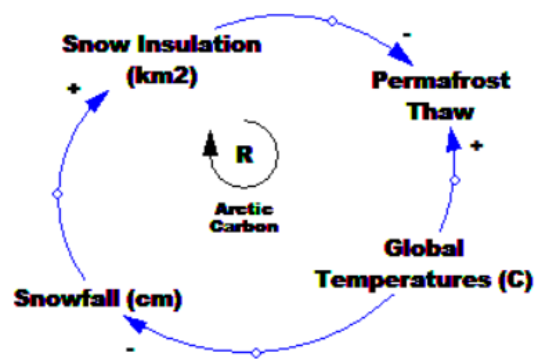

Figure 3: Artic Carbon CLD

3.2.3 Megafauna Snow Trampling

Introduction of a *Megafauna Population* into the Arctic adds on to the two natural loops of *Arctic Carbon* and the *Carbon Cycle*, altering the effects. One of the characteristics of megafauna is migration, due to the rapid use of resources in their current living area. As the megafauna deplete the resources in their living area, they move as herds, searching for more. In the snow-covered Arctic, megafauna trample the snow, removing the insulating layer on the permafrost. This allows the permafrost to freeze more, resulting in less summer thaw. This affects the carbon cycle, lessening the effect of *Arctic Carbon Emissions*. This affects the *Arctic Carbon* and *Carbon Cycle* loops, and according to the theory of Zimov, has the potential to slow and even reverse climate warming.

3.2.4 Arctic Megafauna

Arctic megafauna are large herbivores adapted to the cold climate of the Arctic. Warming temperatures force them further north until their habitat vanishes. Between the Pleistocene and the Holocene, mammoths moved south as the adapted to warmer temperatures, which led to the Asian elephant. The mammoth we know vanished and was replaced. As such, warmer temperatures force the mammoth to change. The fastest way this happens is by reducing the *Megafauna Resource Adequacy*. Rising *Global Temperatures* reduce *Megafauna Resource Adequacy*, which increases the *Fractional Megafauna Death Rate*, reducing the *Megafauna Population* in the long run. However, should the average *Global Temperatures* stay relatively close to its current level, the *Megafauna Population* in Pleistocene Park will have a chance to grow and affect the carbon cycle and arctic carbon stores, possibly slowing climate warming and maybe even reversing it. The greater the population of megafauna, the greater the *Megafauna Migrations*, increasing the amount of snow trampled, affecting the *Arctic Carbon* loop.

3.2.5 Megafauna Life Cycle

The megafauna life cycle is like most mammals, except that the gestation period is significantly longer. Since the theory of Pleistocene Park rests on the reintroduction of mammoths to have the greatest effect, Figure 4 presents the birth and death rates of the mammoth's closest living relative, the Asian Elephant. The *Megafauna Population* increases and decreases according to *Megafauna Births* and *Megafauna Deaths*, or the birth and death rate. As the *Mammoth Population* increases, the *Megafauna Resource Adequacy* decreases, which decreases the *Fractional Megafauna Birth Rate* and increases the *Fractional Megafauna Death Rate*. These impact *Megafauna Births* and *Megafauna Deaths*, completing the birth and death cycles. It is difficult to determine where the megafauna population would stabilize but based on my research it will take several hundred years, if not thousands.

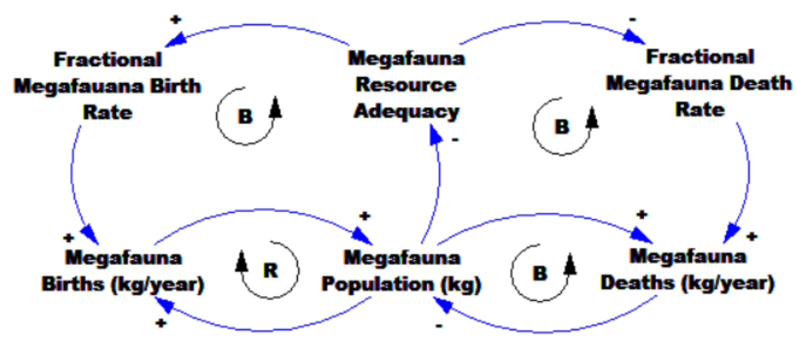

Figure 4: Megafauna CLDs

The megafauna population contributes to atmospheric carbon levels, emitting carbon through their bodies natural processing of carbon by eating, noted as *Megafauna Carbon Emissions*. While the megafauna contributes a significant level of carbon to the atmosphere, the population has an overall favorable effect on carbon emissions by influencing the *Arctic Carbon* cycle.

3.2.6 Ecosystem Balance and Megafauna-Mammoth Steppe Relationship

Another habit of megafauna is knocking down trees. Forests are the natural enemy of the mammoth's habitat, the mammoth-steppe which is noted at *Mammoth-Steppe Area*. Figure 5 presents how as the *Megafauna Population* migrates, they rub against trees and knock down saplings, reducing forests to flat grasslands. As the forest area shrinks in the Arctic, the mammoth-steppe increases, encouraging more migration. Overall, the effect is a reinforcing loop favoring the *Mammoth-Steppe Area* and *Megafauna Population*. As the mammoth-steppe area increases, so does *Megafauna Resource Adequacy*, bolstering the *Megafauna Population*, increasing migrations and affecting the rest of the cycles at play in Pleistocene Park.

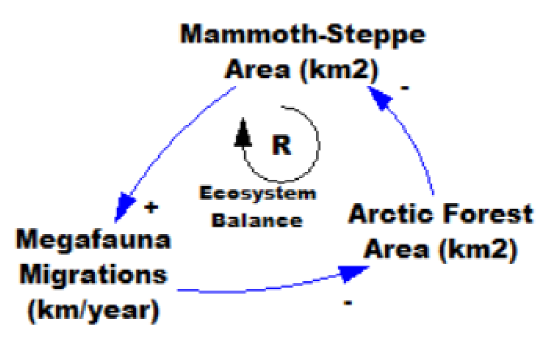

Figure 5: Ecosystem Balance CLD

3.2.7 Pleistocene Park

Pleistocene Park is the result of the specified feedback loops interacting and influencing each other. The theory of the park depends on the natural cycles interacting as specified. It cannot completely account for all the dynamics involved and cannot predict how much random effects will play into the overall model. Human emissions affect the cycle, and are presumed to increase, but there is no way to anticipate the actual effect in future years.

3.3 Stock and Flow Modeling

Modeling the problem as a stock and flow diagram began with the carbon cycle since it is the foundation for the model and the system which Zimov hopes to impact. The *Atmospheric Carbon* stock is the focus of the model, and the stock constantly shifts according to emissions and consumption by natural processes. The stock has an inflow of *Actual Carbon Emissions* and an outflow of *Natural Carbon Cycle*. The *Natural Carbon Cycle* is impacted by the *Normal Fractional Absorption*, which means that every year, a fractional amount of carbon is absorbed through natural processes. The *Natural Carbon Cycle* impacts the rate of *Arctic Absorption*, which is different than that of the *Natural Carbon Cycle*. The carbon that is absorbed is stored in the *Arctic Carbon Stock*, which is released as an outflow due to *Arctic Carbon Emissions*. The *Arctic Carbon* also impacts the *Arctic Carbon Consumption* by *Active Microbes*, at a ratio of *Microbe Carbon Consumption*. *Actual*

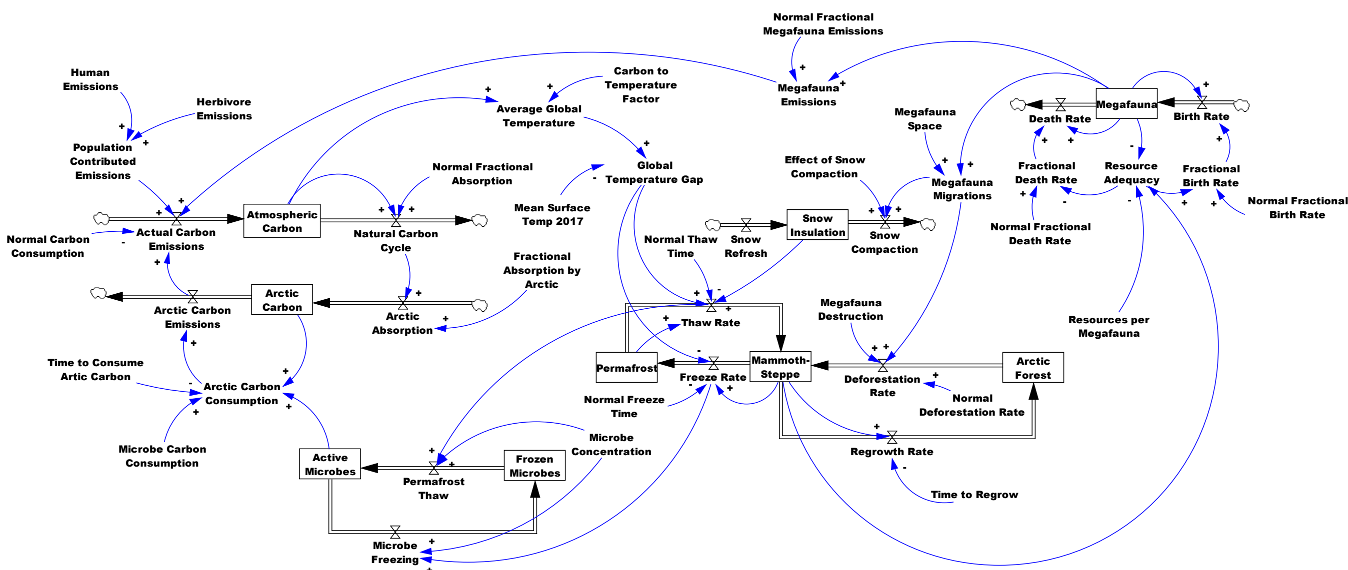

Figure 6: Overall Stock and Flow Diagram

3.3.1 Carbon Stock and Flow

Zimov's theory focuses on the transfer of carbon from the *Atmospheric Carbon* stock to the *Arctic Carbon* stock, and vice versa. Since most climate change models focus on the amount of *Atmospheric Carbon*, this is the central stock we care about, and *Arctic Carbon* is the largest stock of carbon present on the planet, which directly impacts how much carbon is in the atmosphere. The *Natural Carbon Cycle* removes carbon from the stock of *Atmospheric Carbon*, at a rate dictated by the *Normal Fractional Absorption*, determined through historical trends. The *Natural Carbon Cycle* also occurs in the Arctic, contributing to the *Arctic Absorption*, which increases the stock of *Arctic Carbon*.

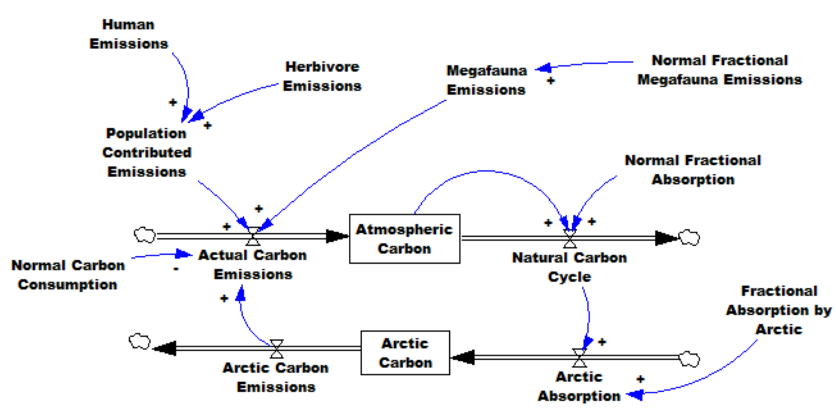

Figure 7: Arctic Carbon Stock and Flow

Thawed *Active Microbes* increase the *Arctic Carbon Consumption*, which increases the *Arctic Carbon Emissions*. The *Arctic Carbon Emissions* add on to the *Actual Carbon Emissions*, also impacted by *Normal Carbon Consumption* and *Population Contributed Emissions*. The *Population Contributed Emissions* are the sum of *Human Emissions* and *Herbivore Emissions*, set as a constant. The *Megafauna Emissions* also contribute to the *Actual Carbon Emissions* since the *Megafauna* population consumes organic carbon as well, denoted by the *Normal Fractional Megafauna Emissions*. This is one of the concerns about the reintroduction of *Megafauna*, the park's hope is that the positive effects outweigh the carbon introduced by the *Megafauna*.

3.3.2 Microbes

Active Microbes are the catalyst for *Arctic Carbon Emissions*, since they consume the organic carbon stored in the *Permafrost.* The carbon to microbe ratio is designated by the *Microbe Carbon Consumption* and the *Time to Consume Arctic Carbon*, which then increases *Arctic Carbon Emissions* overall. In the winter, *Active Microbes* freeze according to the *Microbe Freezing* rate, which increases the stock of *Frozen Microbes*. The *Permafrost Thaw* rate is directly impacted by the *Thaw Rate* of the *Permafrost Stock*, and the *Microbe Freezing* rate is directly impacted by the *Freeze Rate* of the *Mammoth-Steppe* stock. The *Permafrost Thaw* and *Microbe Freezing* both increase the number of *Active Microbes* and *Frozen Microbes*, respectively.

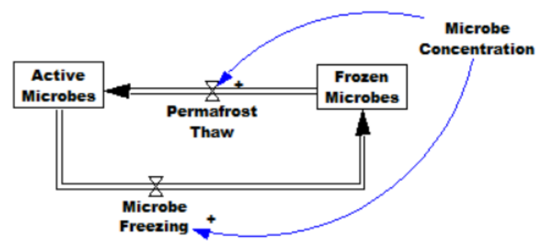

Figure 8: Microbe Stocks and Flows

3.3.3 Permafrost

Permafrost is the icy prison of the *Frozen Microbes*, keeping them dormant, which reduces the amount of *Arctic Carbon Emissions* annually. The *Mammoth-Steppe* and *Permafrost* are in a zero-sum state, since there is a limited amount of land in the Arctic. As the *Permafrost* thaws and transitions back to *Mammoth-Steppe*, the *Permafrost* releases *Active Microbes*. The *Thaw Rate* is impacted by *Snow Insulation* and *Average Global Temperature*, which is the result of *Atmospheric Carbon* and *Carbon to Temperature Factor*. As the *Mammoth-Steppe* freezes it turns into *Permafrost*, according to its *Freeze Rate* which directly impacts the rate of *Microbe Freezing*. The *Mammoth-Steppe* is dynamic, shifting according to the growth and destruction of the *Arctic Forest*, and the *Deforestation Rate* caused by *Megafauna Migrations*. The *Regrowth Rate* of trees helps cover some losses, but the presence of *Megafauna* is enough to create mass migrations which increase the overall *Deforestation Rate*. The *Regrowth Rate* is impacted by the *Time to Regrow*, which was determined from the growth rate of species found in the Arctic.

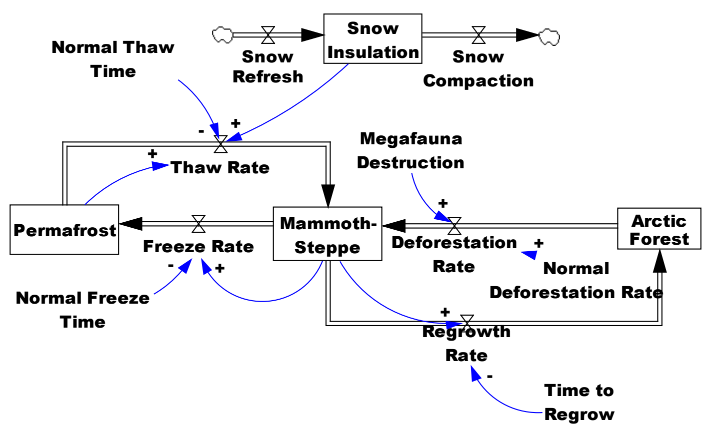

Figure 9: Permafrost Stock and Flow

3.3.4 Megafauna

Megafauna is the tool used to decrease snow insulation and boost the storing capability of the carbon cycle. The population of megafauna, denoted by the stock, *Megafauna*. The *Megafauna* population fluctuates due to its *Death Rate* and *Birth Rate*, impacted by the *Fractional Death Rate* and *Fractional Birth Rate* of other species of megafauna, relative to their size. As the *Megafauna* increase, the region's *Resource Adequacy* decreases, which is a result of the *Megafauna* consuming a ratio of resources that comes from *Resources per Megafauna*. The *Resource Adequacy* impacts the *Fractional Death Rate* and *Fractional Birth Rate*. These variables impact the *Death Rate* and *Birth Rate*, proportional to the population, and come from the *Resource Adequacy* and the *Normal Fractional Death Rate* and *Normal Fractional Birth Rate*, respectively. When the *Megafauna* population increases, the *Migration Area* increases as well since the population seeks to expand its grazing area. This goes on to decrease the *Snow Insulation*, which increases the *Thaw Rate* of *Permafrost*.

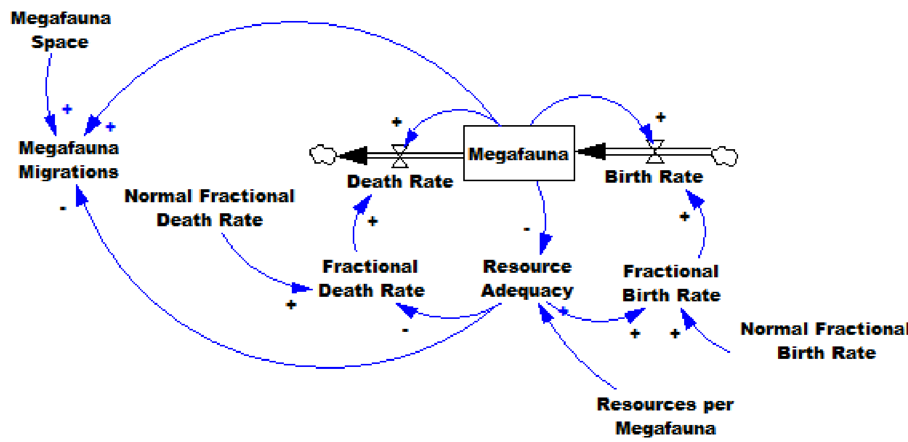

Figure 10: Megafauna Stock and Flow

3.4 Assumptions

To effectively model Pleistocene Park's effect on climate change, I had to make simplifying assumptions. The first assumption was that atmospheric carbon is only affected by actual carbon emissions and is removed through the natural carbon cycle. This allowed me to show the emissions I am focusing on in the model, without impacting the overall results with systems that I presume have negligible effect. Furthermore, I am assuming the only emissions are the ones applicable to the issue, such as megafauna emissions, population-contributed emissions, and arctic carbon emissions. For the time steps, I assumed the effects are evaluated every year, when they are in fact continuous and cyclical. However, most of the data on the issue is put in terms of years, so that is the best way to model this for the sake of a functional model.

There is literature debating how much the global temperatures will shift from carbon increase, but for the sake of the model I am assuming that temperature increases linearly according to the atmospheric carbon concentration. Additionally, human emissions currently rise every year, but since I am not modeling the human population, I am simplifying the model by setting *Human Emissions* as a constant.

According to Zimov, mammoths and their migratory effects would dwarf that of other species, so I based the megafauna numbers off their size and other characteristics. That is an issue since the mammoth went extinct, but I used the characteristics of their closest genetic relative to determine the quantitative characteristics used in the model. Specifically, the Asian Elephant since it is the closest living relative to the Wooly Mammoth.

The Yakutian region experiences a significant amount of snowfall in the winter, but without modeling snowfall with its many variables it is difficult to incorporate snowfall into the model. For this reason, we use the simplifying assumption that *Snow Insulation* is equal to the area of the *Mammoth-Steppe* every year, and the *Megafauna Migrations* decrease the amount of insulation.

4. Model Findings and Analysis

Modeling Pleistocene Park began with the causal loop diagram, then building the stock and flow diagram based on the CLD. This section includes a discussion on the calibration and initial analysis of the model as well as potential impacts from introducing megafauna into the Pleistocene Park and beyond in the areas of artic permafrost. The initial model does not include the megafauna and examines what would happen to the global temperatures from 1830 to 2830, assuming that the Pleistocene Park could have actual megafauna within the next 10 years. The section expands on this initial analysis by examining the introduction of megafauna and the impact they have on the average global temperature and the landmass.

4.1 Calibration and Initial Analysis

Initial model testing included a check for dimensional consistence to ensure that the model was free of unit errors without the need for additional exogenous variables. Additionally, the model was calibrated to demonstrate observed behavior of an increasing global temperature and a decrease in the amount of permafrost as it is transitioned over to "Mammoth-Steppe" and eventually Arctic Forests. The goal was to create consistant model that increased as expected until the megafauna are added in. To suppress the effects of the megafauna on the *Atmospheric Carbon* and *Arctic Carbon* stocks the model included a switch to turn on the birth rate of megafauna, indicating that they had been released into the Pleistocene Park.

Figure 11 presents the results of the initial model for average global temperatures this are slightly increasing over time in degrees Celsius. Although this is a slight increase over the thousand year time frame of the model, even a slight increase like this could have dramatic affects on the overall global climate. Figure 12 presents the resulting area of land mass for the permafrost, "mammoth-steppe", and arctic forest areas of the globe. As shown, the increasing global temperatures, coupled with the snow insulation causes a thawing of the permafrost. Initially, this permafrost becomes part of the "mammoth-steppe" and is eventually taken over by forest becoming part of the arctic forests.

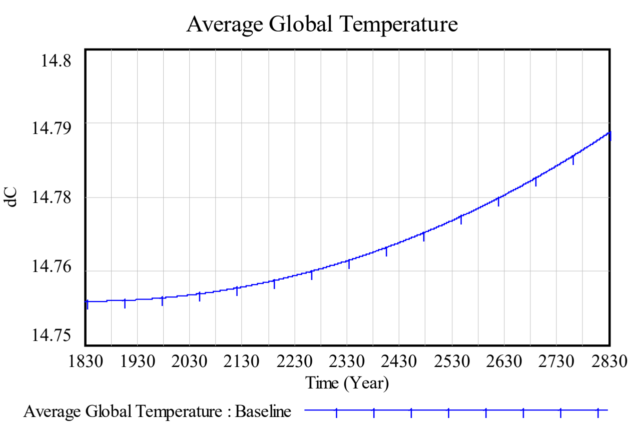

Figure 11: Global Temperature Baseline

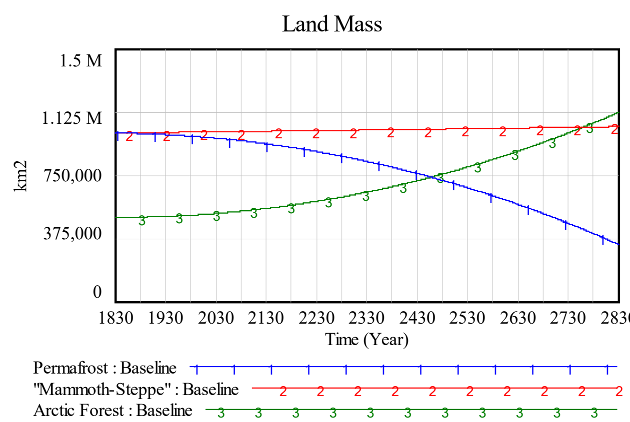

Figure 12: Land Mass Baseline

The model to this point is not very dynamic and only captures the basic feedback in the system and is highly dependent on the snow insulation to drive the increase in thaw rate for the permafrost. This portion of the model is consistent with accepted thought on the subject, but could be improved with a more through calibration against historic data for global temperatures and permafrost area.

4.2 Policy Analysis

The policy the model seeks to test is the reintroduction of megafauna to Pleistocene Park. As stated above, the hope of Nikolai Zimov is to affect atmospheric Carbon levels by reintroducing megafauna, thus decreasing the thaw rate of Siberian permafrost, reducing overall carbon emissions and reducing the *Atmospheric Carbon* stock. The policy is dependent on the reintroduction of the wooly mammoth through gene editing, and while it would not be available for the next ten or so years, if the model shows that Zimov's theory is correct then his theory might work.

The model introduces megafauna to the Pleistocene Park in 2030 and the initial population rapidly expands until it reaches a carrying capacity. Similar to other large mammals, the population and birth rates are measured in kilograms versus individual animals and fractional birth rates for Asian elephants is used as a proxy for the genetically modified megafauna. Additionally, Figure 14 and Figure 15 present the carbon levels in the Artic, those frozen in the permafrost, and the atmosphere. As shown, in the baseline case (1), the artic carbon levels are decreasing indicating that the carbon is being released into the atmosphere, which increase over time. However, in the simulation with megafauna, artic carbon levels return to normal and begin to increase as the area of permafrost increases after 2030. Likewise, the atmospheric carbon levels return to normal and begin to decrease as additional carbon is stored in the permafrost.

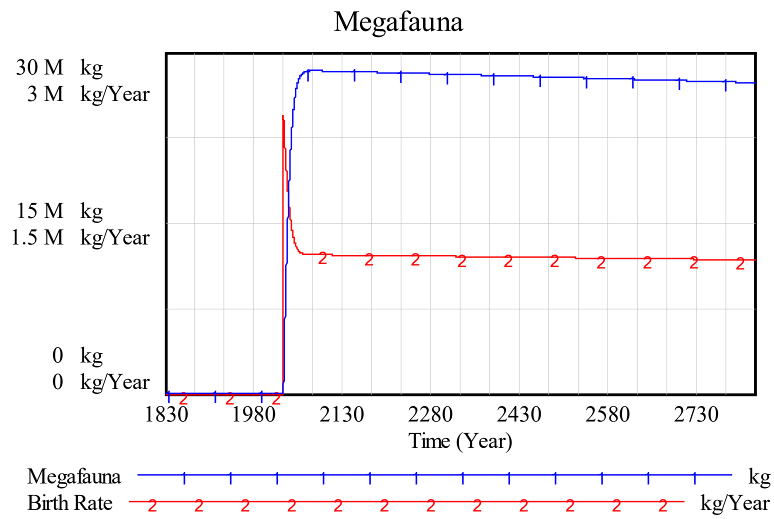

Figure 13: Megafauna Population and Births

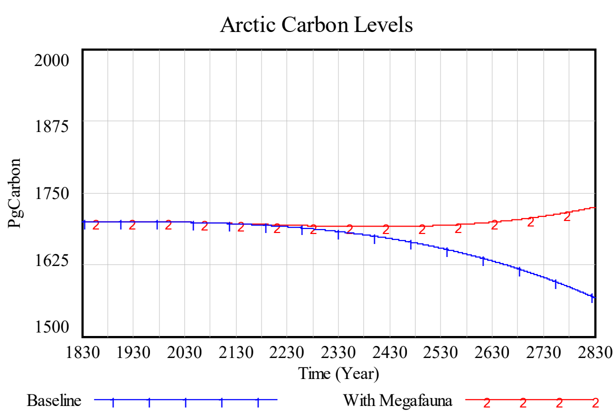

Figure 14: Artic Carbon Levels

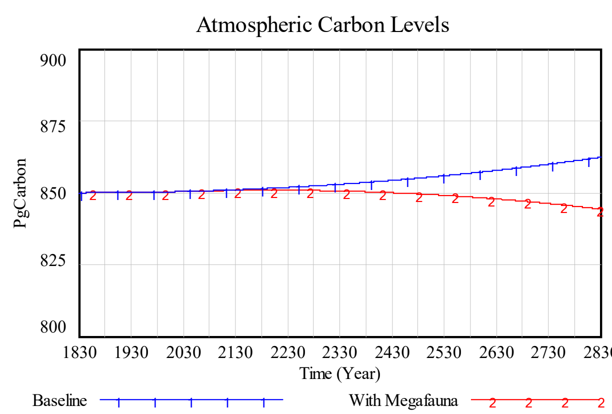

Figure 15: Atmospheric Carbon Levels

The next part of the analysis focuses on the changes to the landmass between he permafrost region and the mammoth-steppe. This is an important aspect of the model because it captures the changes to the land that contain the vast stores of carbon in the Arctic. Figure 16 presents the graphical representation of the stock of permafrost over the duration of the model. Initially, permafrost is decreasing in both the baseline and with megafauna models until the year 2030 when the genetically modified megafauna are released into the park. At this point, the megafauna begin to decrease the snow insulation and the permafrost slowly begins to re-freeze, trapping the carbon in the Arctic. Figure 17 presents the value for the mammoth-steppe that increase in the baseline model; however, as the megafauna enter the park in 2030, the area of the mammoth-steppe begins to decrease. Both of these observations are consistent with Zimov's proposition on the impact of releasing genetically modified megafauna into the Arctic.

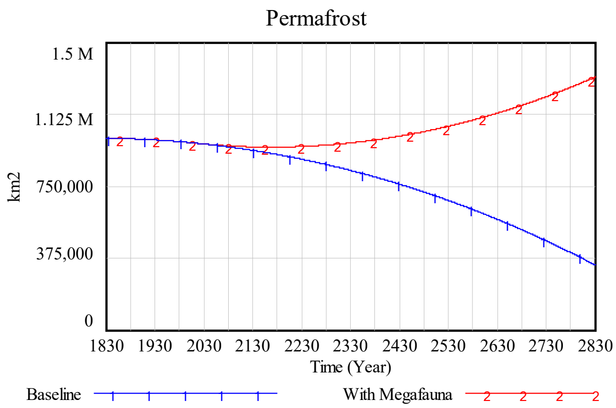

Figure 16: Permafrost Dynamics

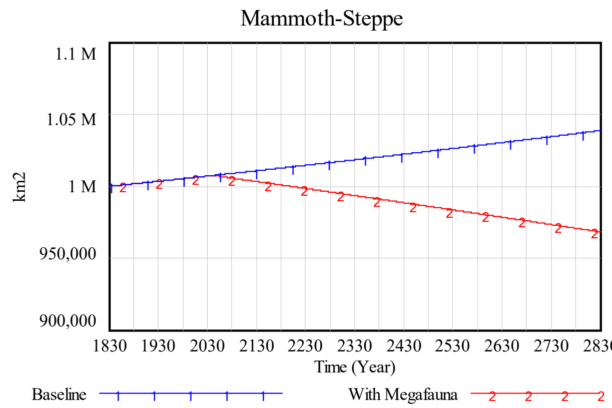

Figure 17: Mammoth-Steppe Dynamics

The overarching goal of this policy is to reduce the average global temperatures to mitigate the effect of global warming. The general consensus is that global warming will have catastrophic affects on the planet if left unchecked. Zimov's proposition to genetically modify megafauna and release them into the Arctic is one means of slowing the process of global warming and warrants investigation. Figure 18 presents the output for the average global temperatures and demonstrates how the release of megafauna into the arctic could decrease the snow insulation, leading to more permafrost and preventing the emission of extra carbon into the atmosphere. In turn, the reduction in carbon emissions would affect the average global temperature and start to offset some of the global warming.

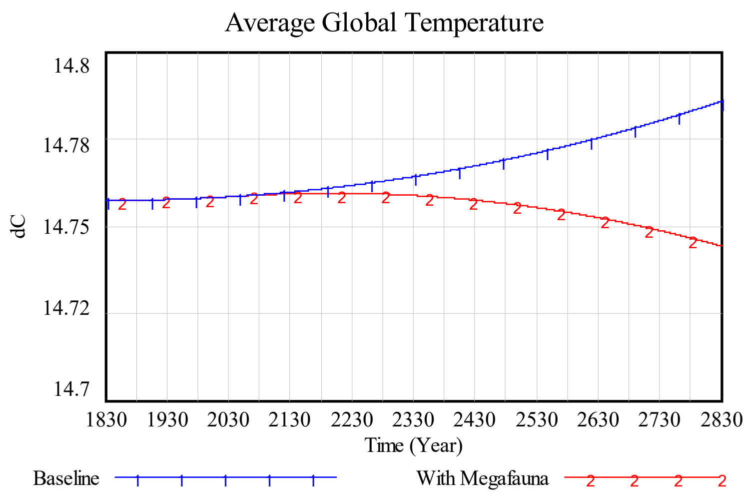

Figure 18: Average Global Temperatures

5. Conclusion

Pleistocene Park is an imperfect idea, but it might be able to slow the release of carbon to the atmosphere from vast stores locked in Siberian permafrost. Sergei Zimov submitted a paper to the journal, Science, in 1999, about the store of carbon in the Arctic and was rejected (Andersen, 2017). However, in 2006 the journal contacted him asking him to resubmit his work (Andersen, 2017). Thanks to his effort and the efforts of others it is no longer a secret that the Arctic permafrost holds more carbon than all the planet's forests and the rest of the atmosphere combined (Andersen, 2017). Improved understanding of carbon cycles and the effects of terrestrial ecosystems support Zimov's idea for the park, and its implications may go beyond climate change. Geneticists are now involved in recreating extinct creatures such as mammoths, and conservationists are considering the impacts of this endeavor. While Zimov will never see mammoths roam Siberian grasslands, his grandchildren might (Andersen, 2017). Improvements in gene editing technology made such a feat possible, and modifications could allow the same process for other species (Church, 2013). Currently, the park is 50 acres, and expanding. Within a relatively short time, the park might be large enough to have a significant impact on carbon emissions, altering the Siberian ecosystem and slowing climate change, only time will tell.

Future work for this research could expand in several different areas to better understand the dynamics involved in climate control as well as the reintegration of species. The model could be better calibrated and refined to better capture the impact of introducing the new megafauna on the arctic carbon cycle. System dynamics models could answer how many should be brought back and how much area should they be allowed to occupy. It could also better determine if the increase in carbon output from the megafauna would offset any gains from reducing the carbon emissions from thawed microbes. As with anything in nature, human intervention often results in unintended, sometimes dramatic, consequences that could negate any benefits from an experiment like the Pleistocene Park. Future modeling efforts could specifically address these areas to better understand this aspect of the research.

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