

Agents and the Arctic: The Case for Increased Use of Agent-Based Modeling to Study Permafrost

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Motivation

By 2050, approximately 3.6 million Arctic inhabitants will be affected by damage to infrastructure caused by permafrost thaw¹. In total, nearly 70% of the infrastructure in the arctic will be impacted¹. In addition, approximately \$15.3 trillion in defense, security and economic assets will require assessment to ensure that national interests can still be served. While a significant amount of research has been conducted over the past three decades there remain significant challenges to ensuring resilience across local, regional and national scales. Achieving such resiliency requires an adaptive and innovative approach to address the challenges facing the Arctic region, one that engages the co-production of knowledge as well as modern computational tools. Currently, field research remains a focus of arctic research, leading to both tangible and intangible burdens on often resource-limited remoted villages and communities. These burdens are shared by researchers and funding agencies who must spend a disproportionate amount of effort and fiscal resources to support these activities. Field research is infeasible in the age of COVID-19, and the future of field research must also be reevaluated, as it is unlikely that we will return to a pre-COVID-19 baseline. Agent-Based Modeling (ABM) is a computational simulation method that is part of the broader suite of so-called Artificial Intelligence and Machine Learning methods. On its own, ABM could alleviate many of the burdens placed on both researchers and remote communities in situ, enable a wider set of inputs from more diverse stakeholders and providing more precise guidance to decision and policy makers through the use of futures forecasting. The use of ABM has several benefits, including (1) the mitigation of contentious issues surrounding field work in and near Indigenous communities, (2) better leveraging data collected to date to enable a smaller and more intentional version of field research, and (3) generating a range of scenarios to not only test hypotheses but also explore the outcomes of different policy and intervention decisions. Focusing field work in this way may help to protect Arctic communities while helping to advance science for the Nation as whole and more rapidly empower appropriate policy responses.

Background

Permafrost refers to land (soil, sand, rock, and ice) which has remained below 0 degrees Celsius for two or more consecutive years². The majority found within polar regions and high mountain ranges, permafrost underlies nearly a quarter of the northern hemisphere, extending up to 1.7 kilometers into the Earth². Permafrost can be up to 70 percent ice², the melting of which results in damage to the built environment and, ultimately, the lives of people a part of Arctic communities. A global scale, the thawing of permafrost complicates our ability to forecast climate change dynamics as organic materials preserved within it are broken down by bacteria, a process which releases carbon dioxide into the atmosphere and accelerates global warming². The impacts range from affecting local livelihoods and lifestyles to the ability to maintain

and deploy national defense assets. Such a complex system necessitates a more strategic approach if we are to make evidence-based decisions with respect to economies, infrastructure, food, energy and water security (FEWS), national response assets (e.g., search and rescue, law enforcement, border protection, humanitarian response and community health and vitality), taxpayer burdens of re-locating remote communities which are no longer sustainable and other variables, all of which are interdependent on social and behavioral actions at multiple scales³.

We offer that ABM is a critical tool to advance not only our understanding of the effect of permafrost thaw on a range of stakeholders but also as a tool for co-producing potential future scenarios. An ABM utilizes autonomous agents, including humans, in a biophysical and built ecosystem (the environment) and models that behaviors of such agent who act on and change their environment, over time, to realize stated needs, goals and values⁴. Agents are reactive, autonomous, goal-oriented, and continuous. It is important to note that all software agents are programs, but not all programs are agents⁴. These software agents are often constructed in such a way that they represent real-world things, ranging from the more simple (e.g., bacteria) to the most complex (i.e., humans)⁴. The construction of human agents in ABM has evolved greatly through the combined work of a global commons of practice, ranging from present-day tribal communities in Africa to urban resource use in mega-cities³. Agents and their environments can be used to effectively simulate real-world systems because they rely on rules that are built by diverse stakeholders. ABM is generative, and therefore can be used to generate scenarios under different environmental, decision-making and social conditions. These characteristics are of great value to understanding the interplay of rapidly changing permafrost, and its effects, across Arctic regions at local to pan-arctic scales. With a high ceiling for complexity, ABM simulations can provide valuable insights, often revealing the “unknown unknowns” by running multiple scenarios in parallel. Such a tool can help guide which data are needed and ensure that scenarios, futures and the implications to policymaking are truly co-developed by the stakeholders most affected, such as local Indigenous communities.

The use of ABMs in Arctic research is not new. For instance, ABM has contributed to an integrated assessment of community sustainability by simulating how people interact with each other and adapt to changing economic and environmental conditions⁵. Permafrost thaw as a hazard affecting human societies has also been studied using the MASON Northlands computational simulation model⁶. Other applications of ABM in the Arctic have included marine transport systems⁷, animal-environmental interactions⁸, marine oil spills⁹, the study of endangered species¹⁰, and migratory processes¹¹. In addition, ABM has been used to study human-environmental systems all over the globe, integral in better understanding climate change adaptations in Mongolia¹², Thailand¹³, Germany¹⁴, Qatar¹⁵, and many other countries¹⁶. ABM is the focus of the Computational Modeling in Social and Ecological Sciences (COMSES) network³. This network includes both researchers and users and includes stakeholders ranging from Tribes and Indigenous groups to medical professionals to engineers. Studies of environment-migration linkages are particularly common since ABM can be used to model the individual decisions of human actors^{17,18}. Similarly, ABM can be used to forecast environmental conditions leading to human conflict, such as between the pastoral nomads and sedentary peasants of Sudan¹⁹. ABM has been used to study the impacts of infrastructure damage following extreme weather events in Mississippi²⁰ and Texas²¹. Other ABMs have been used to explore various aspects of human-environment interactions, including foraging and its impact on hunter-gatherer settlement patterns²², mosquito disease transmission in the Caribbean²³, and the relationship between monsoon precipitation patterns and hunter-gatherer population dynamics in India²⁴.

ABM has also been used to study many of the effects associated with permafrost thaw, making it an appropriate tool to model their collective impact in the Arctic. As an example, ABMs have been used to guide rural infrastructure policies in response to accelerating earth destabilization in Austria²⁵. Food, energy

and water security, not just for local communities, but for the Nation as whole continues to be a growing concern as permafrost thaw induces changes which directly impact FEWS, for example, in communities like the Jean Marie River First Nation, NWT Canada which has been forced to adopt actions that erode both cultural identity and sustainability²⁶. ABMs have been used to assess community food security in Malawi²⁷ and explore the use of soil conservation methods in Vietnam as erosion accelerates²⁸. Indigenous people, such as those of the Amazonian Guyana often interact with their natural environment through hunting and subsistence agriculture, which has also been studied using ABM²⁹. Hunting is dependent upon populations of wildlife in the vicinity of communities at some range, which would be impacted greatly if animal migrations were to displace this food source. Animal migration, a complex spatiotemporal phenomenon, has been studied across landscapes using ABM due to its individual-based approach which enables exploration of the underlying processes that drive animal behavior³⁰. Indigenous communities have been a part of many studies involving ABM to assess human-natural systems. Socio-environmental sustainability of indigenous lands has been studied in particular, which highlights the value of simulation models as social-ecological experiments that can synthesize interdisciplinary knowledge bases and support policy development³¹. Other effects of permafrost thaw which have been studied using ABM include, but are not limited to: Climate change³², land-use change³³, human relocation³⁴, disease transmission³⁵, and population density³⁶.

The Case for Increased Arctic ABM

The utilization of advanced ABM methods will significantly help to refine which types of traditional fieldwork and data are needed. It may also help to precisely guide strategic decision making by diversifying stakeholder inputs, generating plausible scenarios and allowing the consequences and trade-offs of policy interventions to be forecast. In this way, ABM and field work may become synergistically linked. Such a hybrid approach creates less risk for local communities, fewer costs to researchers, and overall less burden to local Arctic residents. We argue that such an approach is no longer notional but necessary in the midst, and wake, of the COVID-19 pandemic. With a warming Arctic and permafrost thaw, exposure to long-frozen pathogens is becoming more likely³⁷. A hybrid approach that makes use of ABM will be crucial in slowing foot traffic to the Arctic's remote and isolated communities, helping mitigate disease transmission, and ultimately refining interdisciplinary arctic science. As the Arctic undergoes extreme changes and as more researchers, both who genuinely wish to co-produce needed science and those who view the Arctic as an "intriguing destination", the burden to communities will grow. ABM simulation should play a role in reducing the need for field work, subsequently limiting these harms while accelerating transparent, equitable, and co-developed policies for myriad benefits. Here, we enumerate several aspects of ABM that make it a particularly powerful tool for studying permafrost thaw.

ABM Accommodates Interdependent Permafrost Thaw Effects

ABM has been widely used to study complex systems due to its ability to represent several levels of interaction within a complex environment representation³⁸. Most ABMs now offer seamless integration with visualization platforms such as ArcGIS. For example, GAMA is a simulation platform which was first developed by a joint effort of the IRD/SU UMMISCO and has now grown to include industrial partners and academicians worldwide³⁹. Several workflows can be built around such tools that not only address the complexities implicit in permafrost itself, but also the less obvious-but-significant emergent complexities which could lead to unwanted surprise (essentially, the unknown unknowns). By fully leveraging the workflows, programming and unifying dialogues that ABM enables, scientists and stakeholders can collectively assess any challenge through both co-produced and Indigenous-led knowledge. Using ABM,

planners and stakeholders are able to collectively navigate the complexity of systems and responding with appropriate policies⁴⁰.

Permafrost thaw impacts many facets of the environmental landscape. These “primary impacts” are the ways in which permafrost thaw impacts the environment directly. As a result of these changes, human civilizations and the resources they cultivate, or depend on, also change. These “secondary impacts” are impacts which permafrost has on human civilizations, through environmental changes. We suggest the primary impacts which pertain to environmental changes logically lead to the secondary impacts which concern disruption of human societal systems and lifestyles. Permafrost thaw implicates both primary and secondary impacts via the interaction of a vast range of variables from geophysics, to atmospheric chemistry to cultural identities and local livelihoods to the ability to maintain and deploy military defenses. Examples of primary impacts include earth destabilization, coastal erosion, soil nutrient supply decline, climate warming, and systemic ecosystem changes. Examples of secondary impacts include resource scarcity, human relocation, disease spread, infrastructure damage, economic shifts, inability to move goods and resources, impaired defense readiness, and increased need for state and/or federal resources.

Climate and environmental changes undoubtedly impact human civilization in many ways. Impacts that have been studied using ABM include migration¹⁷, agriculture⁴¹, conflict⁴², marine resources⁴³, FEWS⁴⁴, health and ecological functions via linear feedbacks⁴⁴, and many other facets of society. Secondary impacts are often tightly coupled, which further contributes to complexity. For example, prior work using ABM to study policy decision-making processes in urban areas has demonstrated a relationship between human land-use change and population trajectories³⁶. As well, land-use change relates to the economy (both impacted by permafrost thaw in their own right), especially in coastal regions where land use decisions have been found to correlate with microeconomic motives⁴⁵. Secondary effects such as change in resource availability and regional conflict may appear to be independent, but in fact changes in sustenance are the root of increased tension in some cases⁴².

ABM Engages Diverse Stakeholders

ABM allows for a range of agent identity and flexibility that is needed when studying the effects of permafrost thaw in the Arctic. An agent can be a human, animal or an abundance of other entities, each of which is modeled to be reactive, autonomous, proactive and temporally continuous⁴. The study of permafrost thaw necessitates that the behavior of both people and animals be modeled. Climate and environmental changes in the Arctic are affecting wildlife in several ways, including, food availability, interspecies competition, predation, and increased human disturbances⁴⁶. Human migration has been observed in many parts of the Arctic in response to adverse environmental and economic changes. On exception is Alaska, where there appears to be less migration⁴⁷. This may be caused by attachment to a location, inability to move successfully, search for alternatives to moving, and reliance on methods which delay negative impact for the short term⁴⁷. These regionally dependent behaviors must be considered during research and policy development to accurately represent the Arctic in an ABM.

Beyond simply modeling diverse stakeholders, it is also necessary to engage them directly in scientific endeavors. A lack of understanding regarding complex human-environmental issues on the part of stakeholders puts them in position to blindly trust the insights generated by planning professionals and computer model outputs⁴⁸. ABMs can be used to represent decision making and environmental dynamics while encouraging non-expert participation in the model development and interpretation stages, resulting in effective solution building⁴⁸. When stakeholders are involved at this depth, insights on model results can lead to modifications which prevent inaccurate policy decisions⁴⁸. ABM can also be beneficial as a

collaborative planning exercise, helping stakeholders to understand and explore a range of possible outcomes⁴⁸. Disaster recovery models have been used which do not consider the will or vulnerability of stakeholders²⁰. When a bottom-up approach was implemented to inform the creation of an ABM toolkit which did take these factors into account, studies found there were higher disaster recovery rates specifically during restoration efforts in the aftermath of hurricane Katrina²⁰. ABMs enable a wide range of stakeholder inputs, reflecting the plurality inherent in communities and the tensions between local needs, regional drivers and national policies. In their Arctic Research Plan (2022-2026) the Interagency Arctic Research Policy Committee, an advisory committee spanning federal and local interests, lists “co-production of knowledge and Indigenous-led research” as a best practice⁴⁹. Using ABMs researchers can more easily ensure that more diverse stakeholders have input into scenarios development, feedback and corrections as the model is run. Serving as an inexpensive, accessible and shared space, ABMs can foster collaboration and sustain transparent, shared understanding through exploration and dialogue.

ABM Enables the Forecasting of Equitable Futures

Agent based modeling enables a wide range of interdisciplinary collaborators to contribute to and have oversight on simulation development. A quicker turnaround on hypothesis testing than other traditional methods could allow for more feedback and contributions from various groups. Serving as a boundary artifact that fosters collaboration, ABM helps interdisciplinary teams maintain a shared understanding. Drawing on ABM project experience involving political scientists, evolutionary biologists, computer scientists and economists, a set of propositions have been put forth detailing how ABM overcomes arbitrary boundaries between disciplines⁵⁰. One of those propositions states that ABM can reveal unity across disciplines⁵⁰, perhaps potentially concerning strategic interests between the Department of Defense and Tribal corporations. A model was developed to assess how scenarios associated with economic and climate change might affect the local economy, resource harvests, and the well-being of residents for the Western Arctic Canadian community of Old Crow, Yukon⁵. The model integrates information from disparate sources and disciplines to generate a set of possible long-term futures with a richness and detail that would be difficult to achieve with other methods⁵.

ABM Empowers Policy

ABM has been particularly beneficial when used in applications related to climate change, specifically concerning complex relations between international agreements and domestic policy outcomes⁵¹. In economics, ABM has been used to inform policy areas such as financial market dynamics, banking regulation, credit linkages, and monetary policy⁵². Toward a more social implementation, simulations of policy intervention impact enabled by ABM shed light on food deserts and the produce consumption of low-income households⁵³. Agricultural policy has also leveraged ABM analysis in recent years as a traditional microeconomic model⁵⁴. The agent-based agricultural policy simulator, AgriPoliS, has made it possible to analyze agricultural policy reform results⁵⁵. ABM is useful in these domains because it can readily incorporate both environmental and behavioral parameters⁵⁴. Addressing human-environment systems holistically through ABM enables the implementation effective policies to address environmental issues⁴⁰. The way in which ABMs can be used to accommodate complexity and uncertainty also makes them invaluable for environmental planning and policy creation⁴⁰. Sustainability calls for a collective responsibility of environmental issues which can be facilitated by an ABM approach including comprehensive and participatory analysis that enable communication between local and regional scales of policymaking⁴⁰. ABM adds key adaptive capability to current modeling elements and is not to be considered stagnant, but continuously changing flexibly in response to natural, socioeconomic, and institutional conditions as new

insight is gained in these areas⁴⁰. Overall, simulation models provide value as social-ecological experiments that can synthesize interdisciplinary knowledge bases and support policy development³¹.

Conclusion

The increased use of ABM to study permafrost and other arctic phenomena is critical for advancing the state of arctic research and protecting arctic communities. Although there is often an overt emphasis on fieldwork, there exist a wealth of opportunities in which ABM can be used synergistically with fieldwork to rapidly advance scientific understanding, while protecting indigenous communities from potential harms. Several aspects of ABM are particularly well-suited for permafrost research. These include the ability to accommodate interdependent effects, the possibility to engage diverse stakeholders in model construction and validation, the projection of equitable future scenarios, and the empowerment of policymakers to effect change in precise and informed ways. Perhaps most importantly, the hybrid use of fieldwork and ABM stands to accelerate transparent, equitable and co-developed science and policy while helping to reduce the potential for adverse effects on local communities. In other words, ABM can enable arctic permafrost work that is both *better* and *safer*.

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