MASON NorthLands: A Geospatial Agent-Based Model of Coupled Human-Artificial-Natural Systems in Boreal and Arctic Regions

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MASON NorthLands: A Geospatial Agent-Based Model of Coupled Human-Artificial-Natural Systems in Boreal and Arctic Regions

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Abstract. Current climate change causes significant biophysical effects in the Northern Hemisphere, especially in the Boreal and Arctic regions. Rising and more variable temperatures, permafrost thawing, and snow loading are major hazards affecting human societies on multiple spatial, temporal, and risk-related scales. The MASON NorthLands computational simulation model is motivated by fundamental science and policy research questions. Preliminary results demonstrate causal processes relating ambient and soil temperature increases to measurable social impacts, mediated by biophysical effects of climate change on the built environment, as in a coupled human-artificial-natural system (CHANS).

Keywords: Agent-based modeling, climate change, Boreal region, Arctic, migration, permafrost, Arctic Council, coupled human-artificial-natural systems, complex adaptive systems

1 Introduction

The effect of climate change on humans is one of the most significant, complex, and enduring scientific puzzles in the history of civilization, as well as one of the most vexing policy issues today and for the foreseeable future. This is because the climate-society nexus is poorly understood, difficult to analyze, demonstrably complex, and a fundamental driver of societal dynamics and quality of life.

This is a progress report on an innovative informatics approach to research and policy modeling, focused on climate change consequences in the Boreal and Arctic regions—i.e., geographic areas where biophysical changes are the most extreme and societal effects are significant (affecting hundreds of millions of inhabitants and the built infrastructure they depend on).

This introduction provides motivation and background on earlier related research, followed by sections describing and discussing a novel computational model designed for analyzing climate change scenarios using an integrated coupled systems approach. The final section provides a summary.

1.1 Motivation: Research Questions

What are some significant effects on humans if estimated climatological changes—e.g., increases in temperature, precipitation, and their variability, among others—occur as predicted by the IPCC (Intergovernmental Panel on Climate Change)? What will people do? Will they stay where they reside or move? If they move, where might they go? Given each situation, will people react peacefully or violently? What difference could collective action or government policies make, given a range of climate change assumptions and local conditions on the ground? What may happen under some of the worse scenarios (e.g., Slater and Lawrence, 2013), if by 2100 the permafrost region shrinks to the Canadian Archipelago, Russian Arctic coast, and east Siberian uplands? What if estimates are off by, say, 1 to 5 percent? How would answers to these and similar questions change?

Questions such as these and others cannot be answered through traditional analytical approaches, such as equation-based dynamical systems, multivariate statistical or econometric models, forecasting techniques from the futures literature (e.g., Delphi panels), or other common quantitative social science methods and policy analysis tools. The reason is fundamental complexity of coupled human-artificial-natural systems (CHANS) driven by climate change: numerous components interacting through nonlinear dynamics, generating emergent phenomena that cannot be traced to individual actions and simple causal processes. Solutions to such systems are not available in closed-form, due to high dimensionality, non-linear interactions, spatio-temporal non-stationarity, and scaling (non-equilibrium distributions, such as power-laws).

Computational simulation modeling provides a viable scientific methodology, specifically through geospatial agent-based models (Cioffi, 2014: ch.10; Heppenstall et al., 2011; Railsback and Grimm, 2012). Such models combine a set of features, such as: (1) ability to selectively represent all empirical entities of interest (social, artificial, and natural) as computational objects endowed with (i.e., encapsulating) attribute-variables necessary to determine the state of each entity (overcoming the challenge of high dimensionality); (2) ability to model all necessary spatio-temporal features, such as weather, landscapes, and human activity that co-evolve over time (overcoming fragmentation in traditional disciplinary models); (3) ability to implement relevant systems and processes directly informed by social and biophysical theories (leveraging all necessary disciplinary knowledge within a unified framework); and (4) ability to manipulate variables and change scenarios, including at run-time, for conducting virtual experiments that yield empirically valid results (enabling experimental science *in silico*).

1.2 Relevant Literature

Vast bodies of literature, too large to review here, support computational research on basic science and policy modeling of *individual* human, artificial, and natural systems. There are smaller, albeit extensive bodies of literature on each *pairwise* combination of these systems: socio-natural, socio-technical, and techno-natural systems. For instance, the majority of current socio-natural models—see, e.g., An et al. (2014) and Liu et al. (2015) for recent reviews—omit significant infrastructure components, such as transportation networks, energy infrastructure, or residential buildings, such that the modeled coupling is that mostly among humans and nature. Similarly, models of socio-technological or socio-technical systems include human and artificial component subsystems, but omit nature or significant ecosystems (see, e.g., van Dam et al. 2012; Vespignani, 2012).

Research on the *complete* ecological triad of coupled human-artificial-natural systems—what may be called Herbert Simon's *ecological triad* (1996; Cioffi, 2014: 8–9)— leveraging joint domains of social, engineering, and biophysical sciences is scarce but increasingly viable (Cioffi, 2015). Modeling and simulation of the complete triad on different spatio-temporal scales constitutes a new and necessary scientific research frontier for developing improved understanding of climate change and societal consequences, based on requirements $1 - 4$ in the previous section. This is what NorthLands and similar models of coupled ecological triads attempt to accomplish (Cioffi and Rouleau, 2010; Cioffi et al., 2011).

2 The MASON NorthLands Model

This section describes NorthLands as a geospatial agent-based model of the Boreal and Arctic regions for investigating research questions on a variety of societal consequences of climate change. The description that follows is based on the standard "MDIVVA" methodology of computational social science, based on model development stages that include aspects of (1) motivation, (2) design, (3) implementation, (4) verification, (5) validation, and (6) analysis (see Cioffi, 2014: ch. 8 and sec. 10.4, for a detailed description of each phase). In addition, each of these phases with the exception of the first (motivation, which is defined in terms of research questions) was reiterated through a series of spirals as project development moved from initial prototypes to more mature models with more robust levels of verification and validation. The first aspect concerning the motivation phase for NorthLands, was introduced earlier in terms of research questions in section 1.1.

2.1 Design

Designing an agent-based model entails formal specification of selected entities and relations in the real world that are to be abstracted in the simulation model. Figure 1 provides a high-level overview of NorthLands' design, consisting of coupled, interdependent classes of human, artificial, and natural systems and their interrelationships.

Entities More specifically, NorthLands includes the following classes of entities within the overall ecological triad:

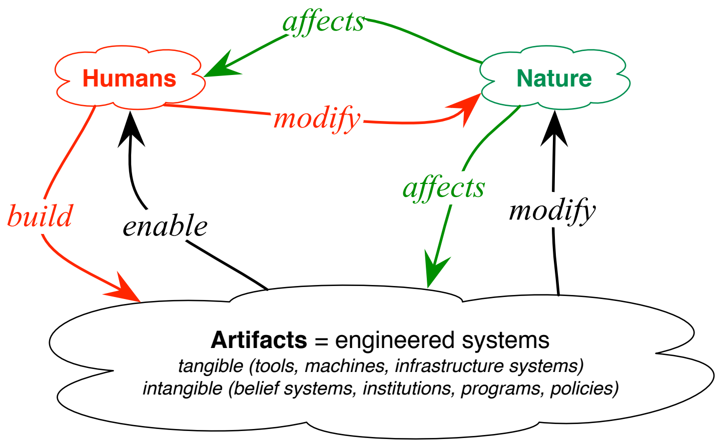

Fig. 1. Coupled human-artificial-natural system (CHANS) with six directional dependencies among pairs of the triad. Formally, such a system constitutes a 3-node directed multiplex graph and a complex adaptive system-of-systems. Source: Cioffi, 2014:8–11; adapted from Cioffi, 2015.

Human entities Represented as households (approximately 1–10 persons, depending on location and culture), with urban household size smaller than rural. For the Boreal and Arctic regions this represents approximately 205.5 million inhabitants, equivalent to approximately 30 million households (U.S. Census Bureau and UN data). Each household has a set of attribute-variables, such as location, lifestyle (urban or rural), wealth, satisfaction, and age. In turn, satisfaction depends on other variables, such as ambient weather (temperature, precipitation, among others). Satisfaction is a determinant of behavior, as discussed below.

Artificial entities The artificial or built environment is represented by engineered structures *and* social institutions, which act as complex adaptive buffer-systems situated between humans and nature (Simon, 1996; Cioffi, 2014:8–11, 207–220). The former consist of buildings (private residential, commercial, public, or hybrids) and infrastructure (transportation, health facilities, and energy, as examples). All infrastructure systems are affected by climate change, depending on location, type of structure, and other factors, as described below. Social institutions in NorthLands consist of government (namely local and national) with policy-making capacity, similar to the earlier RebeLand model (Cioffi and Rouleau, 2010; Cioffi, 2008; 2014: ch. 2).

Natural entities Biophysical landscape in NorthLands is composed of 10×10 km cells with topography (elevation above sea level), landcover (Normalized Difference Vegetation Index, NDVI), hydrology (permafrost, ice sheets, rivers, lakes, coasts, and oceans), and weather (ground and near-surface air temperatures (TSOI and TSA, respectively), and precipitation, based on GIS (Geographic Information Systems) data in raster and vector data formats. In particular, NorthLands uses weather data from the Community Earth System Model (CESM) as input to the human, artificial, and natural entities, as described below.

Data sources on entities and dynamics (next section) are provided in the model's ODD (Hailegiorgis, 2014). Formally, these three classes within the ecological triad span a true taxonomy, not a mere classification, because the three classes are exhaustive and mutually exclusive (Cioffi, 2014: 8–9; 2015).

Dynamics Figure 2 describes the main dynamics in NorthLands by detailing entities and interactions summarized earlier in Figure 1, based on the same triadic color scheme where human, artificial, and natural are denoted in red, black, and green, respectively. The diagram reads mostly from left to right and omits anthropogenic influence on climate (outside the scope of our investigation at this stage).

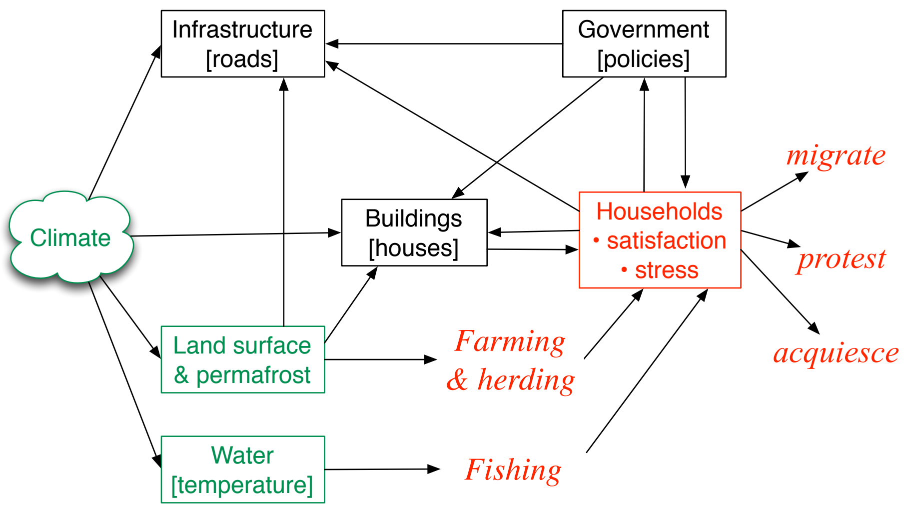

Fig. 2. Coupled human-artificial-natural system disaggregated with detail on dependencies and emergent dynamics. Human, artificial and natural entities are colored red, black, and green, respectively. Source: Adapted from Cioffi (2015).

Climate (Fig. 2, left) is assumed to affect water temperature, land surface temperatures (soil and air) and, hence, the state of permafrost, as well as affecting the stability of buildings and infrastructure that constitute the built environment. Crucially, permafrost affects load-bearing capacity, which in turn affects the stability of engineered artifacts in the built environment (residential and infrastructure). Finally, humans are affected through disruptions (and potential disasters) to household dwellings, and subsistence activities such as farming, herding, and fishing. Government policies aim at mitigating societal, infrastructural, and natural effects of climate change primarily through preparedness and response (short- and long-term), based on the standard model of a polity.

In the end, individuals (represented as households) respond by either migrating, protesting, or acquiescing (Hirschman, 1970). The polity response as a whole (i.e., governmental policies) are driven by the Canonical Theory, according to which policies may or may not emerge, depending on a process of perceptions, collective action, and performance (Cioffi, 2005). The end state of society ranges from successful adaptation to climate change to disastrous conditions, depending on numerous contingencies and a complex network of nonlinear dependencies among interacting entities in the triad of coupled human-artificial-natural systems.

2.2 Implementation

NothLands was implemented in MASON and GeoMASON (which includes full GIS facilities with vector and raster spatial data) for several reasons, the most important being that it enabled us to conveniently use ECJ for evolutionary computation. Specifically, ECJ was used to evolve an optimal set of weights of the preference function of agents, based on dimensions such as ambient temperature, desirable location, and others. Other reasons included the possibility of changing scenarios in real time, which is easy to do with MASON by stopping the simulation at runtime, changing some setting, and resuming the "same" run without reinitializing the model. A summary of other important reasons is provided in Cioffi et al. (2015: XXXX).

Implementing NorthLands' design (section 2.1), given our research questions (section 1.1), required a *federated model architecture* based on modular or component models that can also operate jointly. Each component implements distinct dynamics:

NorthLands-Permafrost Climate changes, affecting land surface properties, including load-bearing capacity, infrastructure stability, and, finally, household (di)satisfaction.

NorthLands-Movement Climate changes, affecting ambient conditions, which affect household decision-making, generating migratory movements.

NorthLands-Governance Climate changes, government recognizes the need for collective action in the form of policies, which may or may not be undertaken and may or may not succeed, leading to societal outcomes ranging from successful adaptation to disaster.

Each model is implemented so that it can operate independently or coupled with one or both of the other two, as a federated model. For example, results from the NorthLands-Permafrost model generate results on the destabilization of buildings and infrastructure (the built environment, generally), that were then used to further inform the information environment of agents in the NorthLands-Movement model. The federated architecture allowed us in this way to in fact implement significantly greater and necessary domain complexity, given the research questions, without excessive slowdown effects generated by expensive computations for updating the state of the model at run-time.

Target maximum run-time duration was set at twenty minutes for employing evolutionary computation.

2.3 Verification

Verification included the following standard procedures: code walkthrough, debugging, profiling, and parameter sweeps, among those most used for NorthLands (Cioffi, 2014: ch. 8, p. 297). The following is an illustrative summary:

Code walkthrough Teams of 2–4 coders, sometimes together with domain scientists from social science and climate science, conducted numerous code walkthrough exercises. When misspecification or better fault-proof code segments were located the code was corrected or improved. In addition, this also added to code comments and other improvements.

Debugging Initial debugging produced the first prototypes, designated as NorthLands 0.1, 1.0, and 2.0. As mentioned earlier, debugging (as well as other verification procedures, was conducted in spirals, not just once). For example, during initial analysis of model version 2.0, while conducting experiments on the human migratory patterns under a range of temperature values, we uncovered an error in the computation of household wealth values that was generating an error in the emergent Gini coefficients. The bug was found and fixed by rescaling the household wealth attribute to a new range of strictly positive values, thereby correcting the observed error and generating a proper range of Gini values between 0 and 1.

Profiling Profiling was used to verify frequency distributions consistent with model design and implemented code. Figure 3 shows model activity in CPU, memory, classes, and threads during the initial five minutes of a sample run using the Eclipse/Monitor. Graphs such as these and others allowed us to monitor a number of resources that are used by the model during it's run to ensure that runtime values lie within reasonable expectations. Because population in the model grows throughout the run, due to demographic change, it is not surprising that many resources, including CPU and memory usage, and number of classes, also grow. (This is a form diachronic, nonstationary change.) In a steady-state model, these results would be a cause for concern, but in this case they indicated normal activity, otherwise faults were investigated and corrected until satisfactory results were obtained.

Parameter sweeps Numerous parameters were swept, primarily those pertaining to climate (e.g., temperature means and variability values) and social conditions (e.g., individual household growth rate, agent vision, movement preferences, and other variables described in the supplementary documentation).

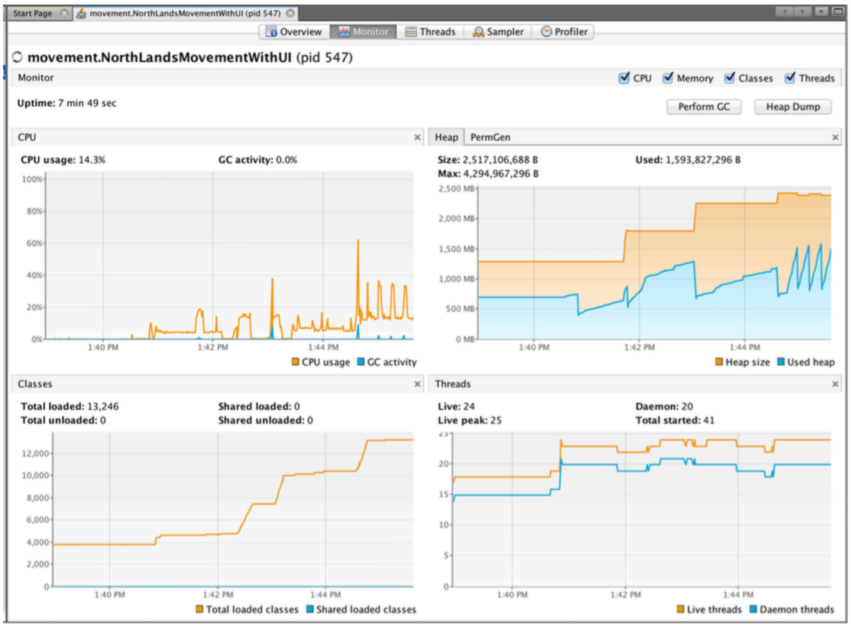

Fig. 3. Use of selected resources in NorthLands-Movement showing activity of CPU, memory, classes, and threads at run-time. Note the general increase in activity, consistent with increasing historical population in Canada during the 1900s epoch.

2.4 Validation

Validation procedures include several types (the more the better) of pattern-matching between simulated data and empirical data, such as time-series, histograms, and geospatial patterns, among others. The following is an illustrative summary of specific validation procedures used for NorthLands:

Time-series Figure 4 shows a screenshot of the model's GUI (Graphic User Interfase) with various results of a sample validation test, including time-series matching (lower right). The map of Canada shows a dynamic population distribution generated by the model (grey-blue dotted areas generally along relatively southern latitudes) and time-series on urban (blue) and rural (red) populations, demonstrating long-term urbanization that is consistent with historical records (Statistics Canada). This time-series passed when NorthLands correctly matched the crossover in the year 1911.

Histograms NorthLands also produced several matches between simulated data from the model and historical social data. For example, simulated results on the emergent household wealth distribution for Canada was successfully matched to the lognormal distribution obtained from Canada Statistics official records.

Geospatial patterns A variety of geospatial distribution patterns from NorthLands model runs were tested against empirical spatial distributions. For example, in one extreme run conducted by setting an annual increase in the mean of temperature to $\Delta T = +1$ degree per year, the emergent migratory pattern produced a clear re-settlement pattern of population density extending from the southeastern shore of Hudson Bay in Ontario in the south, to the Manitoba shore, and north to the Boothia Penninsula in Nunavut in the northern latitudes, rather than a simple uniform movement to the north across all of Canada, regardless of terrain effects (which would have yielded an invalid result). This included a series of east-west population concentrations (correctly)caused by several major river basins (the Severn, Nelson, Churchill, Kazan, Thelon, and Back river basins, among others) along the western shore of Hudson Bay and further north to the Gulf of Boothia.

2.5 Analysis

Thus far NorthLands has been subject to preliminary analyses (i.e., V&V only), with a view toward preparing the model to answer the main research questions in section 1.1. Scenario analyses will constitute a major thrust, to better understand the complex dynamics of coupled human-artificial-natural systems in the Boreal and Arctic regions.

3 Discussion

3.1 Current status of NorthLands

The NorthLands model currently consists of two federated modular components, called the Permafrost Model (NP-1) and the Movement Model (NM-4). Both consist of coupled human, artificial, and natural systems in the Boreal and Arctic regions, for answering research questions regarding human and social consequences under a range of climate change scenarios. The Governance Model (NG-0) is based on an extension of RebeLand 2.0, which implements the standard model of a polity. The federated model consisting of NP, NM, and NG component models, all three in MASON and GeoMASON with extensive GIS facilities, implements the ecological triad of coupled human, artificial, and natural systems.

3.2 Future research

The following developments are planned for the MASON NorthLands project:

1. Further validation of both extant models (NP-1 and NM-4), such as through additional time series analysis (e.g., computing Hurst parameters and other statistics of process complexity), distributions analysis (testing for power laws and other non-equilibrium distributions of extreme events), and other analyses of output data comparing with real data.

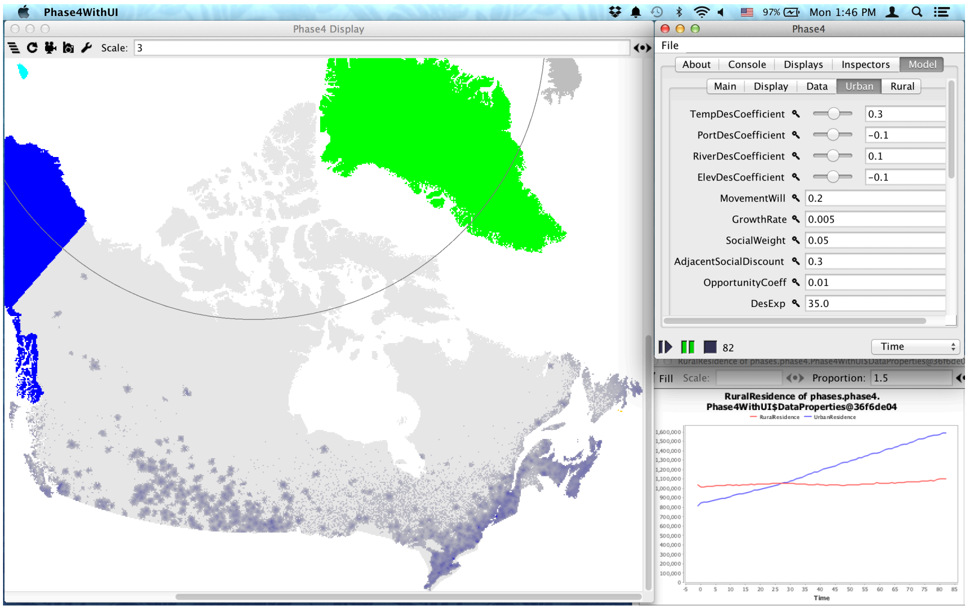

Fig. 4. Screenshot of NorthLand-Movement's GUI (Graphic User Interfase) showing the region of Canada with population distribution at time = 82 quarters = 10.5 years since initialization (corresponding to July 1, 1921), an example of parameters settings (upper right), and two output time series (lower right) measuring rural (red) and urban (blue) households. The time-series crossover is consistent with historical urbanization in Canada throughout the 1900s epoch modeled by the simulation.

2. Extending NM-4 to include other regions, such as Alaska, Scandinavia, and Russia, as already done for NP-1. Most necessary data are available, although additional data collection will likely be needed.
3. Coupling of NP and NM modules to simulate the permafrost thawing jointly with behavioral movement responses, as envisioned by the federated architecture. This is already underway, with promising initial results.
4. Creating a separate governance module for NorthLands (NG), adapting the policy institutions of an earlier model called RebelLand (Cioffi and Rouleau, 2010). This model will need to undergo proper verification and validation prior to analysis. At present, governance functions are implemented in the NM-4 component model, through national/central and local/provincial Gov-

ernment actors that produce policies that respond to and mitigate climate change effects on humans and communities.
5. Coupling of NP, NM, and NG models to achieve the final federated architecture comprising human, artificial and natural systems envisioned in the original design.

Further analysis of alternative scenarios will generate additional results, particularly as the final federated architecture approaches. An analogy to this might be similar to building the International Space Station (ISS), where increasingly complex experiments are enabled as the system is constructed.

3.3 Policy implications

Analysis of the final federated NorthLands model will provide novel insights with potential value for policy. Thus far main policy implications may be summarized as follows. First, policy-relevant analysis of issues such as those addressed by Northlands and the Joint Mason-Smithsonian Project on Climate Change and Society require intense and sustainable collaboration among scientists from multiple disciplines (social, engineering, and natural sciences), policy analysts willing and able to engage in substantive and methodological exchanges, and policy-makers grounded on evidence-based analysis. These are stringent requirements that are relatively rare in academic and policy circles.

Second, adding value to policy analyses through models such as NorthLands requires paying attention to elements of information that prove useful to analysts and policymakers, as opposed to basic science results that are not per se useful to policymakers (although they can still be informative). Policy analysis and policymakers require what are commonly called by analysts "actionable results," meaning information that has a significant probability of adding value for improving policy in some specific way. For example, information related to hazards, vulnerabilities, and potential disasters can be particularly useful for improving disaster mitigation, preparedness and response. This is even more so for the case of catastrophic disasters induced by climate change.

4 Summary

Climate change is an increasingly significant area of policy analysis, as the Earth system's seasonal weather patterns change, affecting humans, the built environment, and ecosystems. Current climate change is causing major biophysical effects in the Northern Hemisphere, especially in the Boreal and Arctic regions. Similar effects are also observed in high-elevation regions elsewhere in the world, such as in the Andean, Himalayan, and Alpine regions, among others. A recent special report by the Intergovernmental Panel on Climate Change (IPCC, 2013) identifies permafrost thawing and snow loading as significant specific hazards that are increasingly affecting human societies on multiple spatial, temporal, and risk-related scales.

The MASON NorthLands computational simulation model is motivated by both fundamental science questions and policy analysis needs. NorthLands is a “federated” geospatial agent-based model for analyzing alternative scenarios and deepen scientific understanding of aspects of climate change and emergent societal impacts in the Boreal and Arctic regions. Similar models are also feasible for other regions with significant human interest, such as urban areas in coastal regions or river basins fed by mountain sources. The study area of NorthLands corresponds approximately to the international and transnational indigenous membership of the Arctic Council, comprising approximately two dozen sovereignties and non-state actors.

NorthLands uses the MASON (Multi-Agent Simulation of Neighborhood and Networks) computational system, combined with extensive GIS data, and is part of broader efforts under the Mason-Smithsonian Joint Project on Climate Change and Social Impacts, funded by the Cyber-enabled Discoveries and Innovations (CDI) Program of the US National Science Foundation.

Preliminary analyses of the two initial models for permafrost thawing and human migratory movements focus on the probabilistic causal process relating ambient temperature increases (and variability) to social impacts, mediated by several biophysical effects of climate change on the built environment, as in a coupled human-artificial-natural system (CHANS). Initial results illustrate testable relationships among entities and variables in all three domains of the Boreal-Arctic coupled human-artificial-natural system: climate, built environment, and human societies on multiple scales (local, national, regional, international). This modeling project extends prior research that focused on other regions (Central Asia and East Africa, areas affected by different natural and anthropogenic hazards).

The final modeling architecture of NorthLands will enable better understanding of coupled human-artificial-natural dynamics in the Boreal-Arctic region through detailed scenario analyses previously not available to scientific researchers and policy stakeholders. Such novel insights will provide a basis for improving preparedness and response policies to mitigate climate-induced disasters.

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