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A Conceptual Agent-Based Model of Farming Households' Vulnerability to Winter Storms

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Abstract

Vulnerability assessments are implemented to identify regions and groups at risk and factors that need to be addressed to reduce vulnerability. Existing assessments have allowed multidimensional factors to be examined in various settings and adopted complex models to simulate human-environment-weather interactions. However, these models are far less accessible than traditional models due to model abstraction and there has been limited research detailing a formalized way to simulate the interactions between rural households and external changes in response to a specific extreme weather event. To supplement applied efforts in vulnerability assessments and address the challenge in communicating agent-based models, this study proposes an integrated framework to examine dynamically winter storm vulnerability in farming communities and follows an elaborate protocol ODD (Overview, Design concepts, and Details) + 2D (Decision + Data) to present details of model data structure.

Keywords

vulnerability dynamics, agent-based model, ODD, winter storms, farming communities

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1 INTRODUCTION

The term "vulnerability" was introduced in the first assessment report of the Intergovernmental Panel on Climate Change (IPCC) and described as " a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity." (Watson and Albritton 2001; IPCC 1990). Since then, researchers have made significant progress in the characterization of vulnerability components (i.e. exposure, sensitivity, adaptive capacity) (Polsky et al. 2007; Adger 2006; Smit and Wandel 2006; Ford and Smit 2004). Building on these theoretical bases, research became focused on developing integrated models to quantify or predict vulnerability in different contexts (Clark et al. 1998; Nasiri et al. 2019; Owusu et al. 2016). In these existing indicator- and location-based vulnerability assessments, vulnerable groups and communities are often merged into a larger unit. It is acknowledged that these top-down approaches often fail to investigate the process through which adaptation measures are undertaken regarding specific climate conditions and local constraints (Smit and Wandel 2006; Windfeld et al. 2019). Hence, bottom-up approaches, such as agent-based models, emerged to assess the vulnerability at the individual or household scales (Hailegiorgis et al. 2018; Krömker et al. 2008; Acosta-Michlik and Espaldon 2008).

Agent-based models can mimic emergent behaviors by simulating how individuals interact with each other and adapt to changing conditions in a community. They are widely adopted in numerous studies to represent the dynamic and complex human-environment systems. Acosta-Michlik and Espaldon (2008) integrated indicator-based, profile-based, and agent-based approaches to identify vulnerable regions, construct farmer typologies, and simulate the adaptive behavior of local people to global environmental change. These approaches significantly shifted the foci of vulnerability assessment from general indices to diversified adapting agents (Klein and Patt 2012). However, agent-based models dealing with climate vulnerability and adaptation are still far less accessible than traditional analytical models to those who are less experienced in computer science, due to relatively ambiguous and incomplete model descriptions (Grimm et al. 2006). To reduce the model abstraction and supplement the applied efforts in agent-based modeling of vulnerability dynamics, this study proposes an integrated framework for assessing vulnerability dynamics and provides a sample application of ODD (Overview, Design concepts, and Details) + 2D (Decision + Data) to contribute to the skeletal understanding of agent-based assessment for vulnerability to extreme weather events.

2 THE CONCEPTUAL MODEL OF VULNERABILITY DYNAMICS AND THE ODD+2D PROTOCOL

Vulnerability indicates the extent to which people and their assets and activities can suffer damage when a hazard occurs (Bouwer 2019). Addressing the inequity that affects the vulnerability, has become relevant for building resilience, especially in a world with increasing globalization and changing climate. Many studies have focused on identifying generic or distinctive factors that differentiate vulnerability but often left room for discussion of subtle indicators that drive decision processes and consequences. For example, a county-level vulnerability map fails to delineate the precise boundaries for farming communities where groups (e.g., Amish) tend to make decisions on coping strategies based on their belief. The characteristics of the environment, the values, aims, knowledge, and characteristics of social groups that change over time and space, have an impact on the individual or collective vulnerability (Kroemker and Mosler 2002). The dynamic aspect of vulnerability has been recognized as key to identifying vulnerability variables and has raised studies on framing the networks of driving forces and the associated psychological manifestations that shape the vulnerability patterns.

There is no universal framework for process-based/dynamic vulnerability assessment, while efforts to conceptualize vulnerability variables and processes integrating agent-based modeling have made headway (Acosta-Michlik and Espaldon 2008; Pons-Pons et al. 2012; Sobiech 2012; Terti et al. 2015). These studies have brought in novelties and advanced the methodological standard for agent-based approaches to assessing vulnerability to climate change. Despite focusing on different issues and contexts, existing frameworks have common modules describing the external natural processes and internal cognitive processes. For example, the agent attributes in Sobiech (2012) and the individual status in Terti et al. (2015) were both concerned with social capital/network and assets/socio-economic dependencies that influence human behavior. Compared with Sobiech (2012), where the interactions of various components were depicted at the agent, environment, and system level, Terti et al. (2015) grouped the variables to the exposure, sensitivity, and coping capacity. Both models showed a lack of explicit descriptions and grounded assumptions for the decision-making process, which plays an important role in representing the adapting motivations and actions associated with environmental and social appraisal as well as individual uncertainties. This is also a well-recognized shortcoming of the ODD (Overview, Design Concepts, and Details) protocol—a standard procedure of describing agent-based models (Grimm et al. 2006; Müller et al. 2013).

The original ODD (Overview, Design concepts, and Details) protocol was first published in 2006 and had been used in more than 50 publications in the few years before the authors updated the protocol with improved clarification (Grimm et al. 2006 2010). Using the "ODD" documentation standard composed of a set of guiding questions, ecologists and social scientists have established the agent-based models to study land-use change and resource management considering the social and environmental processes and have documented relevant elements (Polhill et al. 2007; Van Oel et al. 2019). While this protocol facilitates model communication and comparison, realizing an agent-based model is still demanding and faces these main challenges:

- Linking theories and empirical data to schedule the decision-making processes;
- Formulating real-world feedback mechanisms and assigning accurate parameters.

To address these challenges, Müller et al. (2013) proposed an ODD+D (Decision) protocol with rearranged design concepts to emphasize the human decision-making process. Building on this extension, Laatabi et al. (2018) introduced data mapping in ODD+2D (ODD+Decision+Data) to detail the linkages between data and model. Figure 1 presents the elements of the original ODD protocol and its extensions. The ODD+D reorganizes design concepts and introduced the "Individual Decision Making" that summarizes the conceptual background of the decision model. New aspects for input data description are added in the ODD+2D emphasizing the graphical views of data.

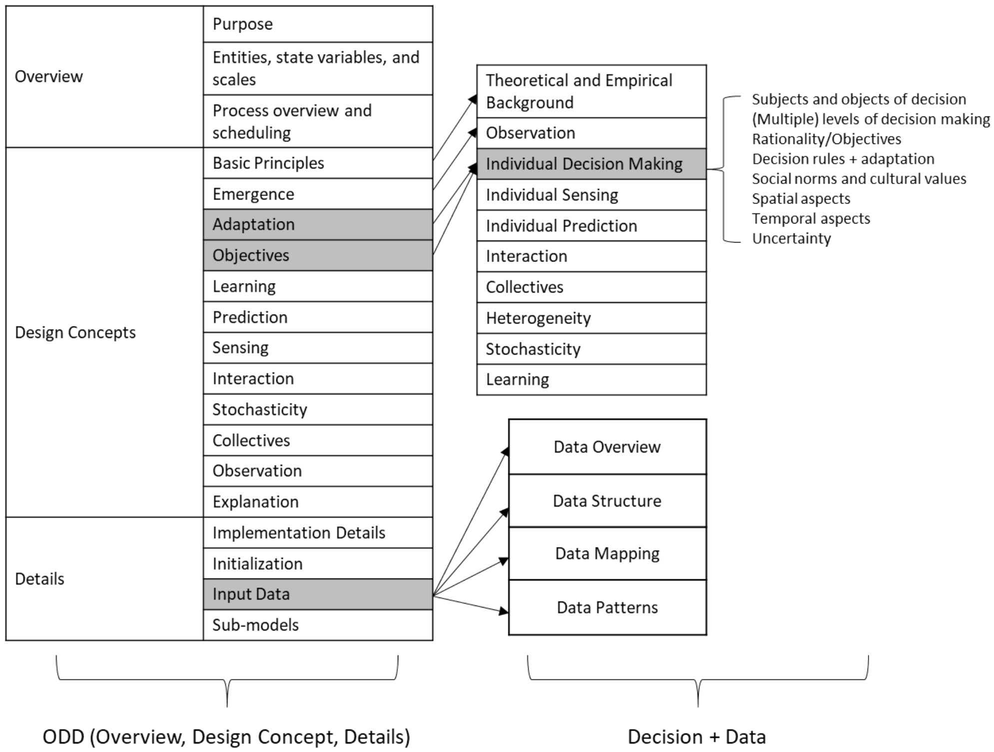

Figure 1. The ODD+2D (ODD+Decision + Data) protocol for describing the decision process and the relationships between data elements and model components. Reproduced based on (Laatabi et al. 2018; Müller et al. 2013).

Focusing on the architecture of the ODD+2D, this study reorganizes the dynamic vulnerability components (Sobiech 2012; Terti et al. 2015) and provides details of the decision process and data for a sample application focused on the vulnerability to winter storms in farming communities in Washington County – the best-known Amish settlement in Iowa.

3 DESCRIBING WINTER STORM VULNERABILITY IN IOWA'S FARMING REGIONS WITH ODD+2D

Winter storms are the second-most frequent catastrophe in the Midwest and tend to create non-negligible impacts on farming communities that highly rely on climatic-sensitive resources and activities. Iowa, one of the Midwestern states, has a strong agricultural foundation and experienced more frequent winter storm events over the last decade. In farming regions, severe winter storms such as unending snowfall, strong wind, and extremely low temperatures can lead to structural damage, animal losses, and a decrease in milk production (Bunting 2019; Knutson 1949). These on-farm losses are unevenly distributed across farmlands and vary from group to group due to spatial-temporal and behavioral variability. A starting point of quantifying the winter storm vulnerability is to consider storm loss as the proxy vulnerability prediction. This paper presents a conceptual framework in an attempt to unpack some of the boxes in previously developed frameworks, with emphasis on the human behavior/decision-making element.

At first, the Structured Decision Making (SDM) approach—a guiding tool in the environmental management decision process—and the constituent decision-making elements (i.e. objectives, alternative decision, decision influence) (Conroy and Peterson 2013) are introduced to assist in identifying the decision problem and schedule the decision process. Figure 2 describes decisions made in response to the changing Entity State, which is some measurable conditions of households or environments. The fulfillment of response Objective depends on the influence of decisions on the Entity State. In this assessment, the decision maker's objective is to minimize the loss from winter storms through adaptation actions (Figure 2). Farmers from different settings, at different event phases, take actions based on their socioeconomic characteristics and the externalities of the environment. These management response decisions are important determinants of the state of storm impacts as well as the objective values. For example, the ready access to machinery and technology would increase livestock farmer's capacity to mitigate winter storm impacts at close-to-event and during-event phases (Figure 3).

Secondly, this study uses methods and language provided in the ODD+2D to describe the links between data and the model. This paper addresses the elements "Purpose", "Entities, state variables and scales", "Process overview and scheduling", "Design concepts", and "Details-Input data" to illustrate how to model aggregated storm loss pattern at the community level, resulting from diverse farmers' coping behaviors, weather conditions, and social and environmental attributes at the farmland scale.

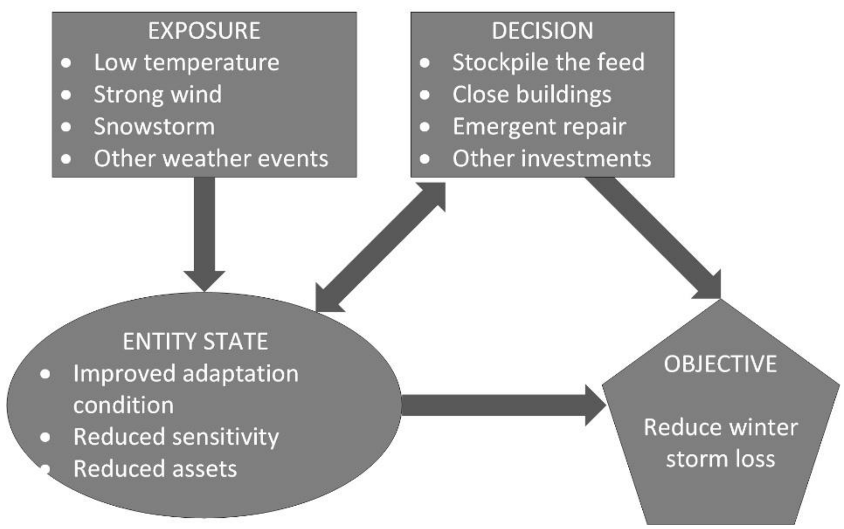

Figure 2. Schematic of household decision making for winter storm adaptation. Adapted from the SDM decision diagram of resource decision problems (Conroy and Peterson 2013).

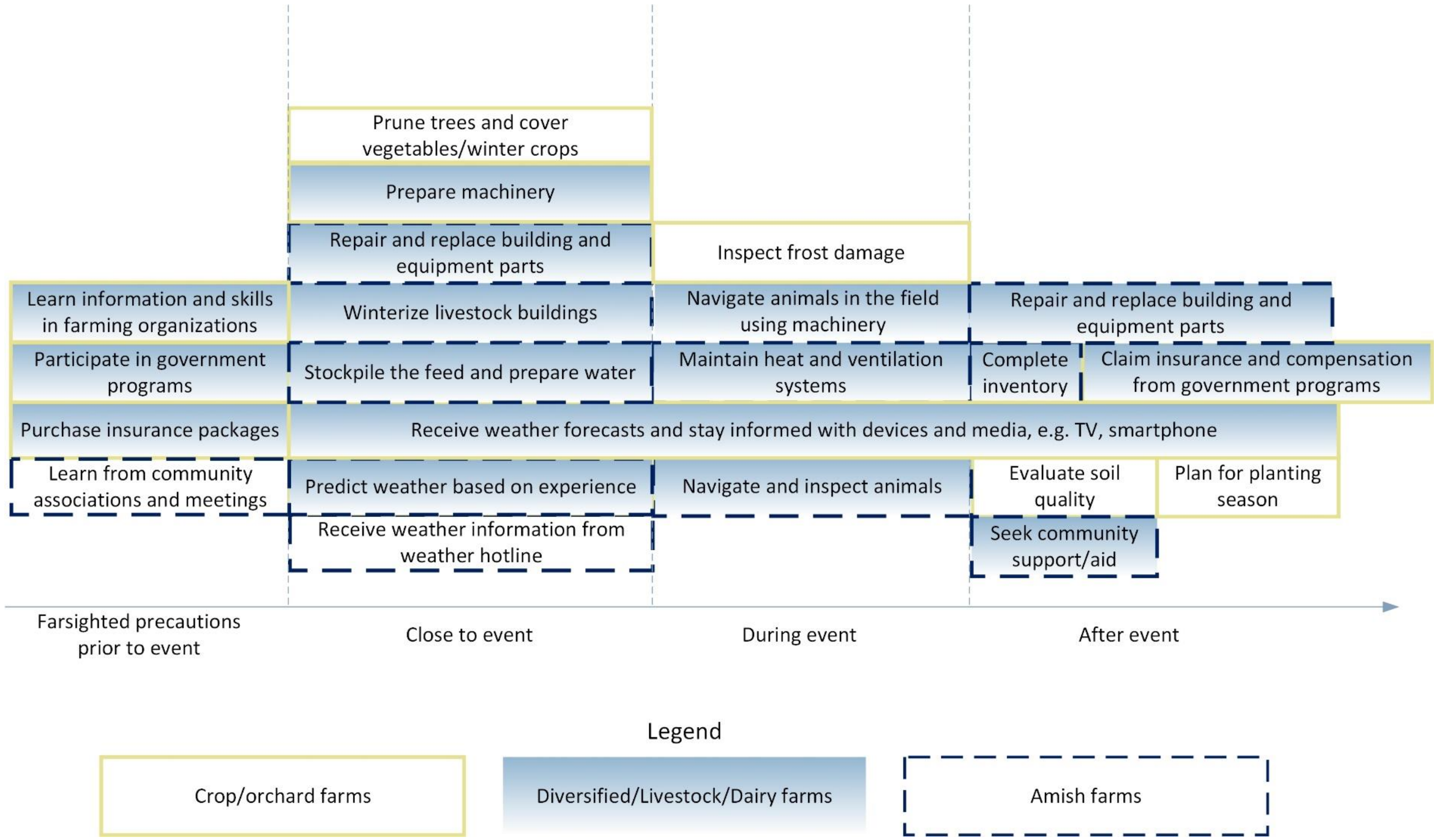

Figure 3. Adaptation measures during different winter storm phases.

The purpose of this model is to demonstrate:

i) the spatiotemporal pattern of farmer decision-making for winter storm response;

ii) the response costs and total winter storm losses.

An overview of this conceptual ABM is given in Figure 4. This model provides a basis for empirical assessment for rural winter storm vulnerability by linking vulnerability components (exposure, sensitivity, and adaptive capacity) and agent concepts. There are various variables identified to influence the exposure and sensitivity at the environment level and the adaptive capacity at the agent level. Household behaviors under varying internal and external conditions are determined by the level of need satisfaction and the uncertainty a person faces concerning taking actions. The collective actions of households result in the pattern of winter storm loss at the community level.

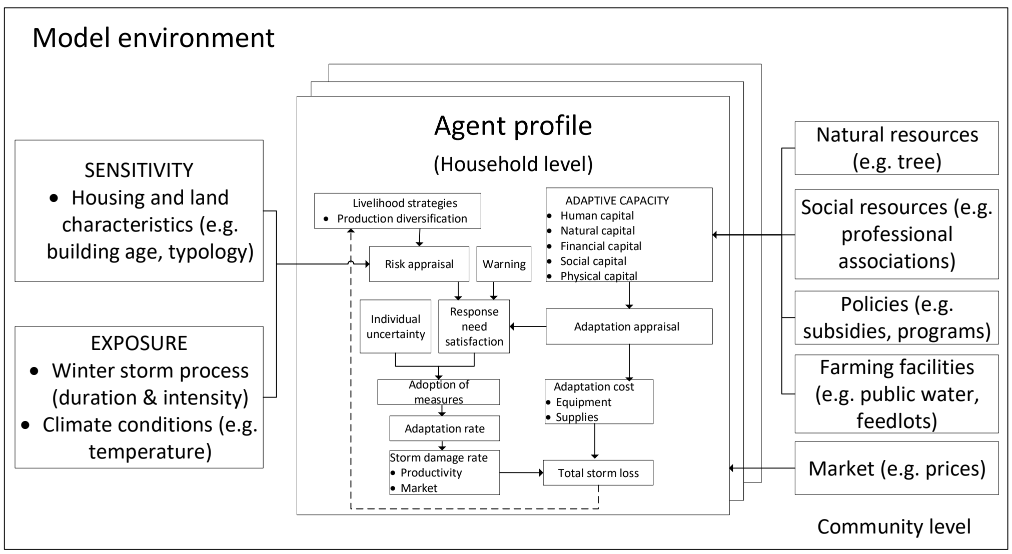

Figure 4. Integrated framework of an agent-based model for winter storm response/loss simulation.

3.1 Entities, State Variables, And Scales

This element defines variables including behavioral attributes and model parameters that characterize a physical or social property of an agent (Grimm et al. 2010). Farming households are represented by agents at the local level. The modeling environment consists of communities with varying weather conditions. The ZIP Code Tabulation Areas (ZCTAs) are approximate area representations of these communities for which weather conditions are calculated daily. Despite the multiple factors included in the general conceptual model to influence storm loss patterns, this simplified empirical model only considers the impact of the most significant factors. State variables that are related to agents and their decisions include farm location and sub-components of sensitivity, exposure, and adaptive capacity. The community is characterized by social and environmental attributes: community extent, farmland extent, a list for patch and total storm losses, numbers of households in the community, tree distance, facility density, and building age. State variables describing weather conditions include temperature variation, daily temperature, mean temperature. The spatial extent covers all ZCTAs of Washington County. One time step represents one day and the simulations would run for the winter months (Dec, Jan, Feb) of a specified year.

3.2 Process Overview and Scheduling

Agent, community, and weather conditions are built into this model and they follow a sequential procedure: winter storms taking place on land parcels, household updating profiles, analyzing coping responses, allocating resources, and the community updating storm losses. During each time step, weather conditions update winter storm scenarios and temperature statistics. The households set up with different profiles follow different adaptation appraisal processes to cope with winter storms based on the risk appraisal components: warning received, sensitivity, exposure, and adaptive capacity. In addition to capturing how these interactions lead to storm loss at the household level, this model is also designed to summarize the losses of communities. At the end of the decision-making process, the model totalizes the household losses and updates the list of community loss. This allows for the comparison of storm losses at the household level, regional vulnerability, and coping capacity at the community level.

3.3 Design Concepts

Theoretical and empirical background. This model is proposed to assess the vulnerability of farming communities to winter storms at the household and community level. The vulnerability is measured at the storm loss, as the vulnerability is typically expressed as the mean loss (or the full distribution of losses) for a given intensity of the hazard (Bouwer 2019). Using storm loss to indicate vulnerability makes the vulnerability quantifiable and measurable. This model is established based on the Structured Decision Making (SDM) and the previous vulnerability assessment frameworks. As the exposure may lie outside the coping range, or may exceed the adaptive capacity of the community (Smit and Wandel 2006), households are assumed to be unable to continue adaptation once the cost exceeds a threshold. The winter storm characteristics and the vulnerability paths were drawn from previous interview results, backing up this model with an empirical foundation.

Individual decision making. Agents seek to increase the success of reducing storm loss as the objective by taking actions that maximize the utility. The utility is measured by reduced damage rate associated with the affordability of response cost. Although the adaptation process and corresponding cost are considered, there are no detailed ranking criteria used for alternative actions in the current simplified model. Household coping efforts are decided by comparing adaptation costs with coping capacity. When threshold (adaptive capacity) is activated there is no action, which can also be a choice in decision-making (Conroy and Peterson 2013). The household decision process also involves the consideration of whether to take precautions. These household behavioral traits are determined by the attributes indicating the vulnerability to winter storms. Figure 5 shows an example of the household's response-loss process during winter storms.

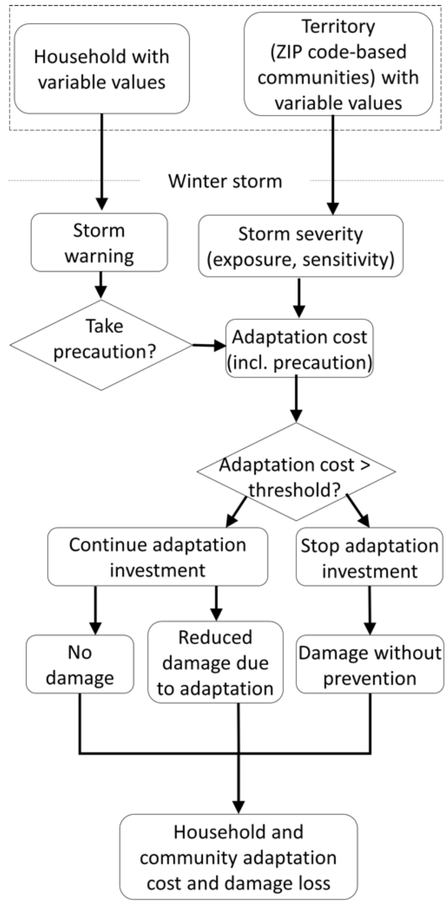

Figure 5. Hypothetical agents' winter storm response-loss process.

Learning. This model does not consider the potential of adaptive trait change. However, it is worth discussing the learning process of households and its associated impact on livelihood strategy transitions. For example, household memories in the storm loss from livestock commodities may lead to production diversification or agricultural practice changes.

Sensing. This model includes warning frequency as the variable the households are assumed to sense. Social influence is not negligible in many decision processes while sensing through social networks is not included in the current model.

Prediction. The farmer's decision process does not involve any predictions in this assessment.

Interaction. The storm losses are updated and interacted at the community and household levels. There is an interaction between the changing weather and the storm severity received by the household.

Collectives. Households are assumed to form networks that affect social capital. These dynamic aggregations are generated by counting the number of households within the community.

Heterogeneity. This agent-based model is expected to be applied in farming communities with heterogeneity in storm coping traits and geographical distribution. For

example, communities with and without Amish concentrations may receive different storm damage patterns due to different coping capacities.
Stochasticity. The pattern of settlements is drawn from empirical distributions to include spatial heterogeneity. The damage rate and the chances of receiving storm warnings are simply assigned as ratios and probabilities. They can be derived based on the ground survey for information on household warning management and storm inventory.
Observation. Observations include a graphical display of metrics capturing the characteristics of adaptation cost, storm loss, and multiple measures generated during the modeling, such as the sensitivity, exposure, and adaptive capacity. Another possible observation is dynamic visual elements displaying the real-time storm loss. The emergent property of this model is household decisions on adopting adaptation measures. The decision of households with different socio-economic backgrounds and locational attributes can jointly affect total winter storm loss.

3.4 Details – Input Data

3.4.1 Data Overview

This study requires government agricultural statistics (e.g., farmland size, farm operations) and a survey to gather information about household attributes (e.g., building age, animal sale, warning management). Land cover is required to extract the farmland and tree cover in the study area. The farmland layer, farm operation number, and farmland size are used to generate the location of the household agent. Other attribute values are synthesized based on the survey data. To determine the winter storm occurrence and to calculate the exposure, daily temperature data is used and available on PRISM.

3.4.2 Data Structure

Table 1 describes the data that is related to household, community, and weather conditions of agent entities. The proposed data attributes are listed in Table 1.

Table 1 Data table of agent entities.

Abbr.	Type	Attribute	Description
		Household	
cid_h	Geometry	Location	Household location identifier
land_size	Continous	Farmland size	Household farmland size
animal	Continous	Animal sale	Total sale from livestock commodities
severity	Continous	Severity	Household storm severity calculated based on exposure and sensitivity
exposure	Continous	Exposure	Household storm exposure calculated based on temperature deviation and storm probability
sensitivity	Continous	Sensitivity	Household storm sensitivity determined by building age and animal sale

resp_cost	Continous	Response cost	Investment for taking actions
cost_threshold	Continous	Cost threshold	The equivalent of adaptive capacity
dmg_r	Continous	Damage rate	The rate of damage caused by events on livestock and building
w_fc	Continous	Warning frequency	The frequency of receiving storm warning derived from survey data
		Human capital	
hh_ size	Discrete	Labor	Household size derived from survey data
edu	Continous	Education	Year of education of farm manager
		Financial capital	
income	Continous	Farm-related income	Household income earned by operating farm-related business
		Natural capital	
windbreak	Discrete	Proximity to windbreaks	The level of the distance to tree cover from spatial analysis
		Physical capital	
acc_fac	Continous	Access to farming facilities	The density of farming facilities from spatial analysis
		Social capital	
membership	Binary	Membership	Membership with professional organizations
nbr	Discrete	Proximity to neighbors	The number of households within the community
loss	Continuous	Total loss	Final total storm loss output
		Community	
cid_c	Geometry	Spatial extent	The extent of selected communities specified by ZIP code
StormOccur	Binary	Storm occurrence	Boolean variable for storm occurrence
num_h	Discrete	Initial numbers of households	The number of farm operations within the extent
dis_tree	Geometry	Tree cover distance	Euclidean distance to tree cover
dens_fac	Geometry	Facility density	The density of facilities around each cell within the extent
bld_age	Continuous	Building age	The age of the oldest housing units

list_c	Text	Household total loss list	List of households and their losses
farmland	Geometry	Farmland	The layer of farmland distributed within the extent
		Weather conditions	
temp	Continuous	Daily temperature	Input daily temperature
temp_var	Continuous	Temperature variation	The level of changes in daily mean temperature
temp_mean	Continuous	Mean temperature	Mean temperature of the modeling period as the reference temperature

3.4.3 Data Mapping

Figure 6 shows how the listed data attributes can be translated into model entity variables through a set of defined functions: Aggregation, Population synthesis, and Dependence.

- **survey** – an operation of population synthesis used to generate agents for each community.
- **storm** – three variables (temp, temp_mean, and temp_var) being aggregated to build the Boolean state variable StormOccur.
- **exposure_transform** and **sensitivity_transform** – the process of aggregating attribute values to represent the sensitivity and exposure states of the household.
- **neighbor_transform** – uses the number of neighbors in the community to build a state variable representing a household's social capital.
- **risk_appraisal** – dependence of adaptation decisions on a household's estimated storm severity calculated from sensitivity and exposure.
- **adaptation_appraisal** – dependence of adaptation decisions on a household's estimated effectiveness of its adaptive measures for averting threats. It is a function of household attributes (e.g., income, education level, and household size) (Hailegiorgis et al. 2018).
- **precaution_investment** – dependence of farmer precaution behaviors on warning management.

3.4.4 Data Patterns

This section formalizes relations between the database and agents. The household survey data is required to derive demographic profiles of households and communities. Each household is assigned farmland based on household size from the survey, the initial number of households from agricultural statistics, and GIS data for farmland. The warning frequency is assigned to each household based on the frequency of receiving weather forecasts. The warning frequency and other socio-economic attributes such as building age and membership that may not be provided in other authoritative data sources need to be derived from surveys. The farmer's propensity to take precautions, continue coping investment, response costs, and damage rate are determined by the following data transformations:

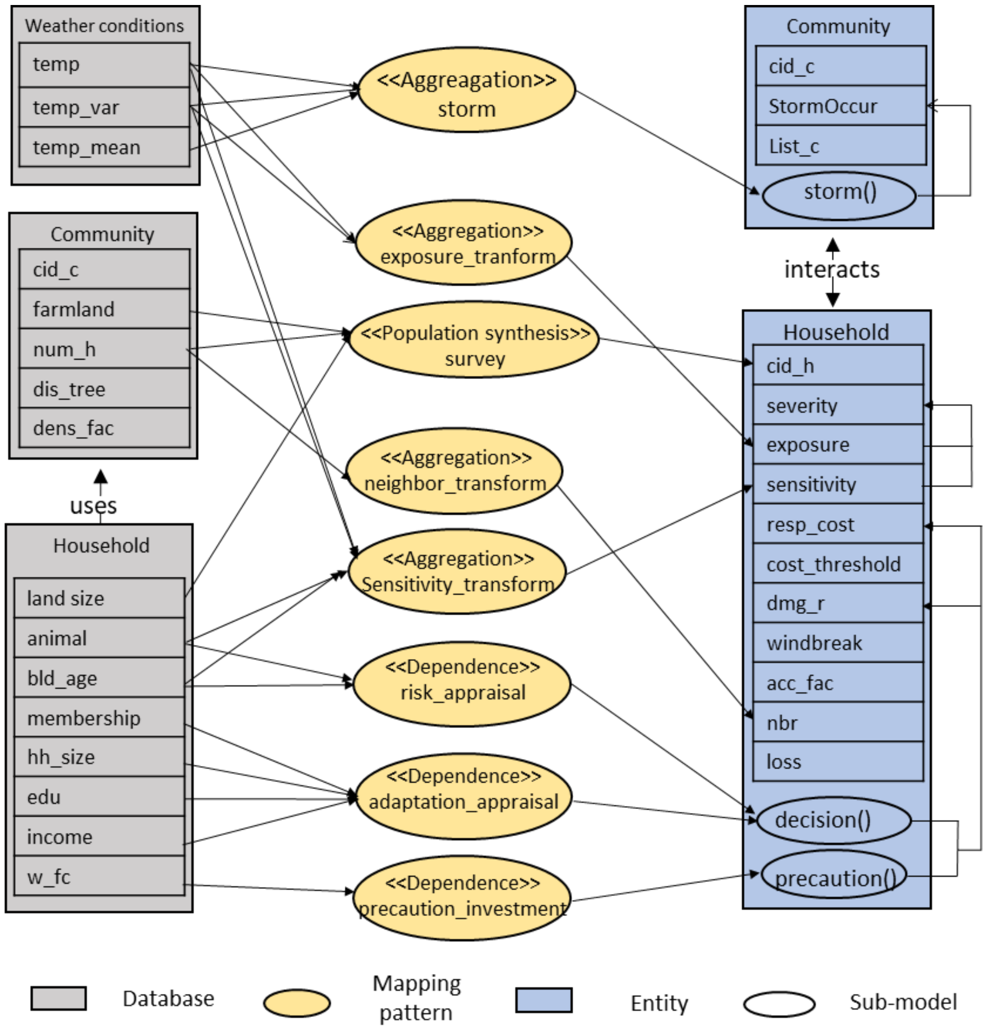

Figure 6. A map of the major links between data and agent-based model.

- **precaution** –the propensity to take precautions depends on how many times the household receives weather information per day (warning frequency) (1).

$$\text{precaution} \begin{cases} \text{yes}, & \text{if w\_fc} > 1 \\ \text{no}, & \text{else} \end{cases} \tag{1}$$

- **severity** – the summation of exposure and sensitivity expressed in equation (2).

$$\text{severity} = \text{sensitivity} + \text{exposure} \tag{2}$$

- **decision** – how much should the household invest in taking measures calculate from the expression (3).

$$\text{adaptation cost} = \begin{cases} \text{severity}, & \text{when adaptation cost} \leq \text{cost\_threshold} \\ \text{cost\_threshold}, & \text{when adaptation cost} > \text{cost\_threshold} \end{cases} \tag{3}$$

- **dmg_r** – the property damage rate determined by a function of precaution and adaptation. Households unable to respond due to the lack of adaptive capacity are assigned a higher damage rate, leading to higher damage loss. When the adaptation cost threshold is not activated, the damage loss is proportionate to income.
- **resp_cost** – an aggregation of adaptation cost and precaution cost estimated using equation (4). The nominal results from equation (1) are interpreted and used to calculate the precaution cost which is proportional to the storm sensitivity with a constant of α.

$$\text{resp\_cost} = \text{adaptation cost} + \alpha * \text{sensitivity} \tag{4}$$

- **loss** – the total loss calculated from damaged property and response cost using the following expression (5):

$$\text{loss} = L_d + L_r = \text{income} * \text{dmg} + \text{resp\_cost} \tag{5}$$

4 DISCUSSION

Traditional approaches to evaluating future dimensions of vulnerability tend to aggregate local characteristics to the regional level, neglecting finer-scale climate experiences (Windfeld et al. 2019). To address the limitation of the aggregation of static indicators that cannot capture vulnerability dynamics, an agent-based model is therefore established to upscale household responses to the community level, as the multi-agent systems can serve as a bridge between farm-level and regional-level model analysis (Berger and Troost 2013). Current agent-based models dealing with adaptation are often hard to read and far less accessible than traditional analytical models due to relatively ambiguous and incomplete descriptions. It remains challenging to communicate clearly the theoretical background and assumptions of agent-based models (Grimm et al. 2006). Following the "ODD+2D" protocol, this paper hypothesizes the network of factors contributing to the household responses and vulnerability patterns. The simplified conceptual model addresses the communication challenge by detailing the decision-making process and data flows, facilitating the understanding of linkages between agents.

For simplicity, this model does not include all interacting variables, however, it eases modification and replication of the model structure in assessing the dynamics of response-loss processes under climate risks. It is hoped that agent-based models could be more accessible to researchers assessing complexities in climate adaptation but lacking an explicit or adjustable framework. Programming language can also be a key barrier to the generic entry of agent-based assessment. It would be helpful to develop a model package and share it with the user community.

This paper describes a simple downscaling method to statistically derive information and attributes for heterogenous patches and agents using data obtained from larger scales (e.g., land use, summary statistics), and involves an upscaling process to aggregate dynamically indicators at finer scales (e.g., sensitivity, coping capacity) to predict spatial changes at larger scales. This paper demonstrates a formalized way to manage and translate data obtained from various scales by addressing the downscaling and upscaling issues involved in complex models. Framing the decision-making process and mapping the data warehousing, need to be considered as necessary steps in preparing data and surveys, which are essential in initializing agent characteristics (Acosta-Michlik and Espaldon 2008; Van Oel et al. 2019).

5 CONCLUSION

This study presents a nested framework integrating agent concepts and vulnerability assessment methodologies and presented the first steps of establishing an agent-based model of vulnerability to winter storms. Rather than simply aggregating indicators at larger scales, this paper identifies specific flows of influence contributing to the upscaled patterns of winter storm vulnerability and developed graphical representation to facilitate understanding of agent relationships and ease model modification. There is still a need for theoretical and methodological advances for process-based vulnerability assessment and strategy analysis that not only capture the dynamics of global change but also represent community specificity. Agent-based models have proved vital in disaggregating upscaled patterns produced by static indicator-based assessment approaches. The ODD+2D provides a clear structure based on which modeler can modify agent-based models to suit other contexts. The data mapping serves as a visually compelling blueprint for data handling and model implementation. The transferability of this protocol remains to be further validated with more empirical models.

Before an agent-based model can be implemented, a well-planned ground survey for physical and socio-economical information is needed to generate realistic agent populations. Future research looks to develop a sample model concerning the interrelationships between adaptation behavior, changing weather and environmental realities at the temporal and spatial scales, and provide detailed sample data and model documentation, to make dynamic climate vulnerability assessments more accessible for research focused on climate adaptation.

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