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ABSESpy: An agent-based modeling framework for social-ecological systems

Shuang Song [1], **Shuai Wang** [1¶], **Chentai Jiao** [1], **and Elías José Mantilla Ibarra**[2]

1 Faculty of Geographical Science, Beijing Normal University. 100875, Beijing, China. **2** USFQ Data Hub, Universidad San Francisco de Quito. Diego de Robles s/n y Pampite. Quito, Ecuador. ¶ Corresponding author

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Summary

ABSESpy is a novel agent-based modeling (ABM) framework that facilitates socio-ecological systems (SES) research. It serves as an extension package of Mesa, the most popular ABM framework, and further enhances agents' interactions with other components, especially grid-like spaces. With a configuration file for managing parameters and an improved data Input/Output system, ABSESpy's modularity and low-coupling design enable elegant maintenance of large modeling projects. In addition, ABSESpy includes a schedule that aligns models' tick with the calendar time. These innovations position ABSESpy as a valuable tool in fostering more ABMs for real-world SES issues. Its ultimate aim is to become the go-to choice for ABM when working with a human-involved changing world.

Statement of need

Social-ecological systems (SES) are integrated concepts recognizing the complex and interdependent dynamics between human societies and ecological systems (Folke et al., 2010). SES consists of decision-making actors (i.e., agents representing people, communities, organizations, and environmental components) capable of following heterogeneous objectives (i.e., agents) (Levin et al., 2013). As such, SES has specific needs for research support from agent-based modeling (ABM).

However, since few models can effectively represent the real-world SES problem, the potential of ABMs has yet to be fully realized in SES research (Schulze et al., 2017). One reason is the variability of actors' interaction with each other or geographic spaces, including learning, decision-making, and contagion across social networks (Reyers et al., 2018). Another reason is the complexity of managing data, parameters, and social and natural processes (Davidson et al., 2024), which makes it hard to maintain large projects. Therefore, facilitating SES research with ABM requires novel tools (Schlüter et al., 2023) to implement the interactions between actors and real-world-like natural processes with manageability and reproducibility.

The popular programming language Python is among the first choices for scientists who care about ABM, and Mesa (Kazil et al., 2020) is the most widely used implementation framework. It remains extensible for different domains while providing the core functionality of ABM. Therefore, customizing Mesa by enhancing real-world representation could be a good start for specializing in SES research. It includes expressing decision-making actors' interactions, social-ecological networks, calendar time, raster data, and extensible sub-systems. To this end, ABSESpy is a Mesa package and an advanced framework that fills gaps in SES modeling with these features.

Design structures

ABSESpy's low-coupling design enables the implementation of maintainable projects by separating the human and natural subsystems within SESs (Figure 1). While the human subsystem manages actors (i.e., agents) and their interactions, the natural submodule typically handles how actors live in, move through, and interact with grid-like patch layers. This architecture also supports adding specialized submodules in each subsystem to represent varying processes with modularity.

ABSESpy includes the default schedule, data collector, and batch runner utilities, available as a `Mesa` package but with enhanced functionality. It also introduces a calendar-like time driver and supports configuration management using YAML configuration files. In addition, the packages `Xarray` (Hoyer & Hamman, 2017) and `Mesa-Geo` (Wang et al., 2022) are embedded to implement an Input/Output driver for different geographic datasets (`.tif`, `.nc`, `.json`, `.shp`, and others). The design focuses on two core improvements: (1) handling actors and their interactions and (2) enhancing the reality and manageability of ABMs.

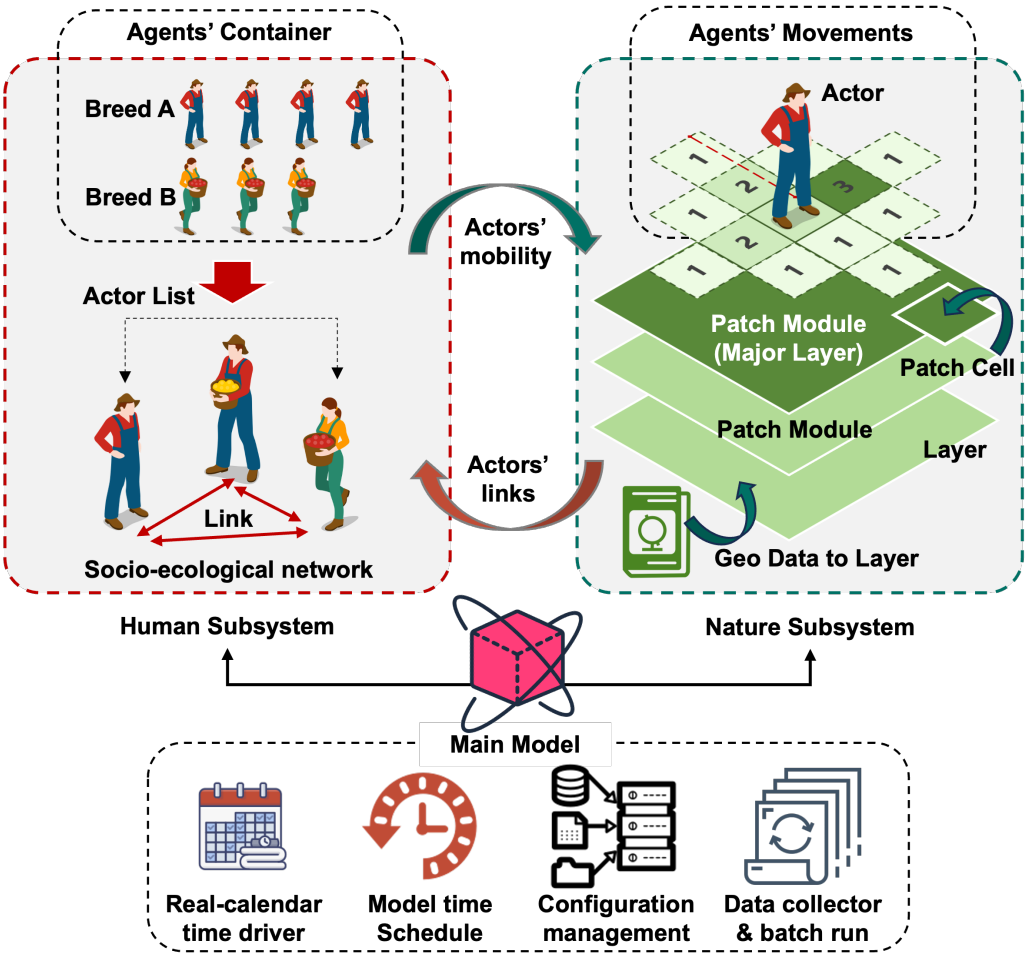

Figure 1: Diagram of the designed structures and included utilities of `ABSESpy`.

Handling actors and their interactions

Under the context of SES, `ABSESpy` conceptualizes "agents" as `Actors` managed within a global `ActorsContainer` which can be manipulated in batches through any `ActorsList`. Users can also query, select, or apply a function to a subset of actors by `ActorsList`. Furthermore, whenever users link some `Actors` with others or some `PatchCells`, `Networkx` can automatically

convert these linkages into a graph. Thus, it enables actors to interact through social networks or implement a social-ecological network analysis.

Since ABSESpy recognizes the centrality of human behavior in SES studies, it also provides a standard workflow based on a popular theoretical framework for decision-making (Figure 2) (Beckage et al., 2022; Schlüter et al., 2017). The following main steps can be implemented seamlessly when working with ABSESpy:

1. **Perceptions**: An `Actor` holds perceptions of natural and human subsystems by observing global/environmental variables (cognition) or learning from links with others (contagion). ABSESpy helps users dynamically define an expression to update perceptions as `Actors`' attributes.
2. **Decision-making**: `Actors` evaluate potential options to determine how to act in the current situation. ABSESpy includes utilities for pre-defined options, thus enabling auto-triggering actions by passing an evaluating function.
3. **Response**: Some actions may lead to feedback towards human or natural subsystems as a response. Besides many available actions, such as spatial relocation and setting attributes, ABSESpy also includes tools to avoid the feedback that causes a nested loop.

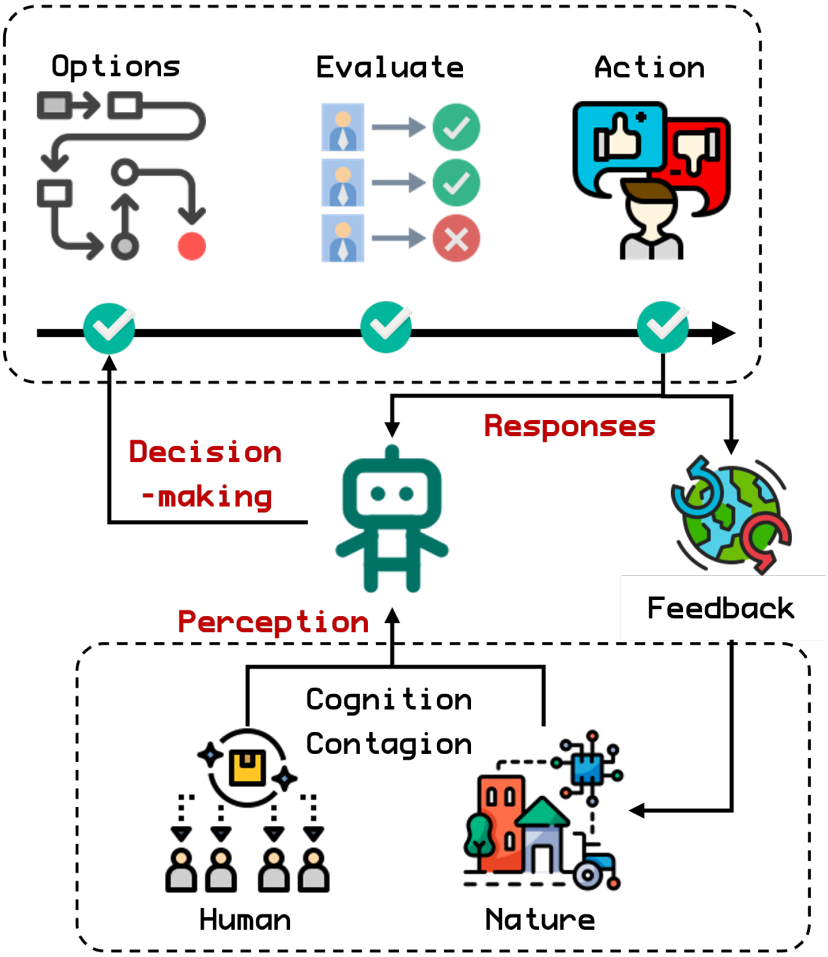

Figure 2: Decision-making workflow for simulating human behavior.

Enhancing the reality and manageability of ABMs

To enhance reality, ABSESpy provides an innovative time control mechanism to bridge the gap between the association of ABM and real-world time (Figure 3). In addition to Mesa's standard

tick-based time advancement, users can implement calendar temporal modes to match the diverse scales of SES phenomena with ABSESpy. The model can represent time intervals from minutes to years by defining the calendar time for each simulation step. This flexibility is crucial when modeling real-world events like natural cycles or periodic human activities.

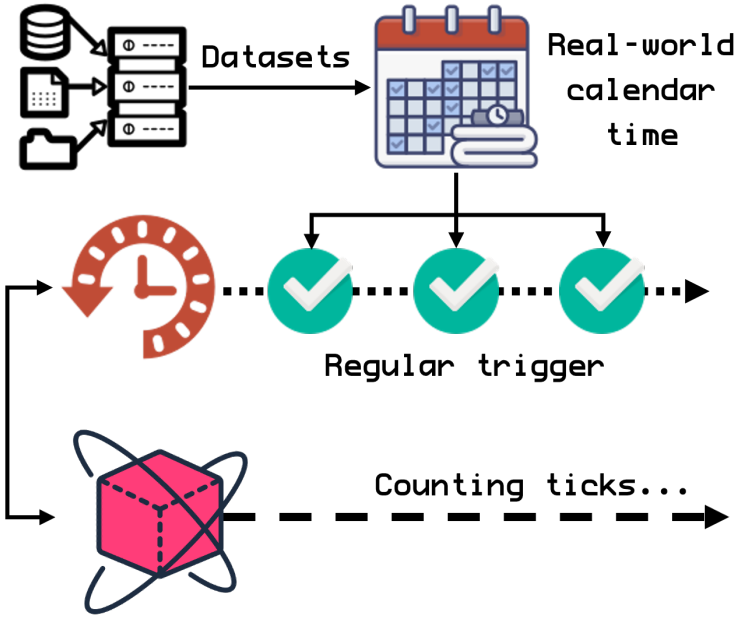

Figure 3: Calendar time module enhances real-world social-ecological system modeling approaches.

ABSESpy includes utilities for manageability purposes based on the above time control mechanism. The commonly used one is automatically importing and updating temporal time series datasets like monthly or daily weather. Users can also specify time conditions to apply or not apply any model method, such as customizing a "`get_up()`" method to `Actor` and only calling it at 8:00 am in a one-hour-per-step model. Finally, all parameters can be stored in YAML configuration files with readable expressions. For example, passing parameters `{"start": '2022-12-31', "end": '2024-01-01', "years": 1}` to the `time` module means the simulation starts at the end of 2022 and ends when the beginning of 2024 is reached. Since each step represents a year, the model only goes one step.

Positioning and comparison

By translating theoretical constructs into user-friendly, operational components, ABSESpy empowers researchers to bridge the gap between conceptual models and their tangible application in SES. As a specialized Mesa package for the emerging SES field, ABSESpy can take advantage of most of the benefits from the related projects (e.g., model visualization from Mesa and geo-data processing from Mesa-Geo). ABSESpy aims to become the go-to choice for ABM when working with a human-involved, changing world. This vision is similar to the existing ABCE (Taghawi-Nejad et al., 2017), which aims to provide an economic problem modeling framework (also a Mesa package), but it targets real-world SES problems.

Many open-source SES models are published on CoMSES (Janssen et al., 2008) and use NetLogo (Tisue & Wilensky, 2004) software. However, users might struggle to maintain its all-in-one structure when data Input/Output and parameters become extensive. The visible advantage of ABSESpy lies in its modularity and low-coupling design, which is suitable for large-scale SES modeling projects. It calls upon vast amounts of actual data for real-world problem modeling. With a separate configuration file, ABSESpy makes it easier to maintain a large project, allowing users to couple sub-modules and maximize Python's advantages as a "glue language." In

Python, another possible competitor is AgentPy (Foramitti, 2021), whose goal is a general ABM framework and is thus more concerned with agents (in other words, the "human" part). Due to more geographic data processing extensions like Mesa-Geo, ABSESpy allows users to handle grid-like spaces and calendar-like schedules more efficiently. Thus, facing real-world SES problems, building on ABSESpy will require less coding effort to simulate interactions between humans and nature.

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