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Exploring system dynamics of complex societal issues through socio-scientific models

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Research on socio-scientific issues (SSI) has revealed that it is critical for learners to develop a systematic understanding of the underlying issue. In this paper, we explore how modeling can facilitate students' systems thinking in the context of SSI. Building on evidence from prior research in promoting systems thinking skills through modeling in scientific contexts, we hypothesize that a similar modeling approach could effectively foster students' systematic understanding of complex societal issues. In particular, we investigate the affordances of socio-scientific models in promoting students' systems thinking in the context of COVID-19. We examine learners' experiences and reflections concerning three unique epistemic features of socio-scientific models, (1) knowledge representation, (2) knowledge justification, and (3) systems thinking. The findings of this study demonstrate that, due to the epistemic differences from traditional scientific modeling approach, engaging learners in developing socio-scientific models presents unique opportunities and challenges for SSI teaching and learning. It provides evidence that, socio-scientific models can serve as not only an effective but also an equitable tool for addressing this issue.

KEYWORDS

socio-scientific issues (SSI), modeling, systems thinking, epistemology, science education

Introduction

In the 21st century, we are confronted with a myriad of complex societal issues such as climate change that are multifaceted and lack universally agreed-upon solutions. These issues not only impact our day-to-day lives but also have long-lasting effects on the environment and society. As educators, we need to prepare future generations to navigate and respond to these complex issues as responsible citizens (De Boer, 2000). Ideally, students should develop the skills necessary to critically evaluate scientific information, understand the social and ethical implications of scientific advancements, and engage in informed decision-making. However, science standards worldwide often fall short in promoting or achieving the full measure of these aims (Feinstein and Kirchgasler, 2015). A primary focus on canonical scientific knowledge and practices fails to address the need for learners to grapple with the real-world complexities that accompany complex societal issues.

Over the past two decades, researchers have explored socio-scientific issues (SSI), complex societal issues with connections to science knowledge, as meaningful learning contexts to promote scientific literacy (Sadler, 2009). Research on SSI has revealed that a significant challenge for learners is to appreciate the complexity of the systems associated with these issues (Sadler et al., 2007; Zeidler, 2014). It is essential for learners to develop a systematic understanding of the issue, considering both scientific and social dimensions (e.g., cultural, political, economic, and ethical factors) and the system dynamics within and between dimensions for informed decision-making (Ke et al., 2021).

The notion of systems thinking is not new to science education (Yoon et al., 2018). Systems thinking entails the ability to recognize patterns, interconnections, and feedback loops within complex systems, as well as the capacity to predict how alterations in one part of the system might impact the whole (Hmelo et al., 2000). Systems thinking is an important skill in STEM education that learners need to master to engage in scientific and engineering practices (Yoon, 2008). Prior research has found that engaging students in modeling practice can promote their systems thinking skills (Stratford et al., 1998; Hmelo-Silver et al., 2007; Dickes and Sengupta, 2013; Nguyen and Santagata, 2021). By engaging students in the creation, revision, and manipulation of models representing complex natural systems, they are expected to develop an understanding of the underlying structure and dynamics of the system through examination of the relationships and interactions among various components (Bielik et al., 2022).

It is important to note that prior research on system models has predominantly focused on exploring systems thinking within the context of science disciplines. Nevertheless, there are significant differences between systems from a science perspective and those involving social components. Therefore, it is critical to consider unique attributes of systems that involve science and social dimensions when teaching systems thinking in the context of SSI, as they differ markedly from systems exclusively defined by science.

In this paper, we explore how modeling can facilitate students' systems thinking about complex societal issues. Building on evidence from prior research in promoting systems thinking skills through modeling in scientific contexts, we hypothesize that a similar modeling approach could effectively foster students' systematic understanding of complex societal issues. In our previous work, we introduced socio-scientific models that incorporates social factors and address the learning needs of students making sense of SSI (Ke et al., 2021). Here, we advance this work and further investigate the affordances of socio-scientific models in promoting students' systems thinking in the context of SSI. Specifically, we examine learners' experiences and reflections concerning the unique features of socio-scientific models that distinguish them from scientific models.

From the outset, we aim to clarify the terms used in this paper related to model categorization, given the lack of consensus in the field. A model can be classified into various types depending on the criteria used. For instance, a NetLogo (Wilensky, 1999) simulation on predator–prey relationships could be viewed as a computational model (vs. a diagrammatic model), a system model (vs. a mechanistic model), a scientific model (vs. a socio-scientific model), or an agent-based model (vs. a system dynamics model). Thus, it is crucial to explicitly define how we categorize models.

Aligned with our prior work, we categorize models into two broad categories: scientific models and socio-scientific models (Ke et al., 2021). This distinction is important because most models familiar to the science education and learning sciences community are scientific models. However, socio-scientific models, which consider social dimensions, are vital when reasoning about complex societal issues. We further categorize models based on their primary epistemic goals, for either scientific or socio-scientific models. For example, scientific models can be mechanistic models, system models, or data models, among others (Ke et al., 2021). In contrast, work on socio-scientific models is still emerging, and further categorization has not been attempted. The socio-scientific models used in our work have a primary epistemic goal of understanding complex issues from a systems perspective, making them system models within the broader socio-scientific model category.

Given the topic on systems thinking and modeling in this collected issue, we focus on system models in the scientific model category and system models in the socio-scientific model category in this paper. Hereafter, we use "system models" to refer to scientific system models and "socio-scientific model" to refer to socio-scientific system models, as the term "system model" in the literature typically refers to scientific system models.

In the following sections, we first briefly review relevant prior work in the areas of modeling, systems thinking, and SSI. We then highlight three major differences between socio-scientific models and system models. Next, we present an exploratory study of college students' engagement in socio-scientific modeling in the context of COVID-19. We conclude the paper by discussing implications of using socio-scientific models in classroom instruction.

Background

Scientific models and system thinking

In science, models play a crucial role in developing knowledge and theories that guide scientific inquiry and evidence-based reasoning (Nersessian, 2008). Models are simplified representations that visualize, describe, explain, and predict real-world phenomena or systems. Modeling is an epistemic practice that involves creating, revising, testing, and evaluating models. In K-12 science classroom, models and modeling are increasingly emphasized as effective pedagogical tools to help learners gain valuable insights into the practices and norms of scientists' work (Lehrer and Schauble, 2006; Windschitl et al., 2008; Schwarz et al., 2009; Manz, 2012; Krist et al., 2019; Ke and Schwarz, 2021). With appropriate instructional support, learners are able to develop and use models to make sense of underlying mechanisms and relationships within the natural world.

Models can take a variety of forms, including drawings, physical objects, computer simulations, mathematical equations, and more—each serving a unique purpose and providing insights into the underlying phenomena or systems (Schwarz et al., 2009). In our previous work, we argue that instead of focusing on their forms, it is useful to distinguish models based on their epistemic goals (Ke et al., 2021). This approach acknowledges the intrinsic link between the nature of model and its intended purpose in the process of scientific inquiry.

A common type of models in K-12 science education is system models that describe the constituent components and their interactions within a system (National Research Council, 2012). The primary epistemic goals of a system model are to understand the organization and predict the behaviors of the system (Assaraf and Orion, 2009; Bielik et al., 2022). Models can be particularly valuable in understanding and predicting behaviors of complex systems, such as ecosystems and cellular networks. A complex system comprises interacting components at multiple interacting levels (Wilensky and Resnick, 1999), and its aggregate nature cannot be easily predicted by merely examining the individual components in isolation. Prior research on science education has revealed that models are effective sensemaking tools for learners, helping them recognize two important features that characterize complex systems: causality and emergence (Yoon and Hmelo-Silver, 2017).

A complex system can have multiple causal factors that occur at different levels. Simple causal relationships often cannot account for the complex causality inherent in complex systems. Therefore, students often miss the connectedness and complex causal relationships within the system (Perkins and Grotzer, 2000). Hmelo-Silver and Pfeffer (2004) argued that a structure-behavior-function (SBF) model could help learners construct explanatory mechanisms about complex systems. They found that experts' behavioral and functional understanding served as a "deep principle" to organize their knowledge of complex systems. In contrast, novices like middle school students tended to focus only on the structure of a system. In a proof-of-concept study, Liu and Hmelo-Silver (2009) demonstrated that the SBF model could promote complex systems understanding, especially with respect to non-salient function and behaviors.

Emergence, another central concept of complex systems, is challenging for students to understand (Jacobson, 2001). This difficulty arises because emergent behaviors are often counterintuitive in nature and require thinking beyond the simple cause-and-effect relationships students are familiar with (e.g., feedback loops). Understanding emergence also calls for thinking at multiple levels, such as micro (individual), meso (clusters), and macro (the entire system). To address this challenge, Wilensky and his colleagues have extensively researched student learning about complex systems within computer-based multi-agent modeling environments such as NetLogo. NetLogo provides an interactive graphical environment that allows learners to visualize system components, explore their interactions, and observe emergent patterns in real-time. It supports the representation and analysis of multiple levels of a complex system, enabling students to explore connections between individual components and emergent system behaviors (Wilensky and Reisman, 2006).

Many complex systems can be viewed as causal, emergent, or both, depending on the levels of the systems being examined (Hmelo-Silver and Azevedo, 2006). This dual nature highlights the importance of understanding both the causal relationships and emergent properties inherent in complex systems. Regardless of the perspective, a modeling approach has been demonstrated to effectively support learners in developing system thinking skills that might otherwise be difficult to acquire.

Socio-scientific models and systems thinking about SSI

Socio-scientific issues, such as climate change, can be viewed as complex social systems, as they encompass multiple components that span both scientific and social dimensions (Ke et al., 2020). These components interact at different levels, ranging from individual (e.g., personal choices and behaviors) to community (e.g., community-shared values and practices) and societal scales (e.g., national policies and economic systems). The interconnectedness of these components across different levels creates a dynamic, complex system that demands a comprehensive understanding of the underlying causal relationships and emergent properties. By considering SSI as complex social systems, learners can better grasp the multifaceted nature of the issues and make informed decisions on the issues (Sadler et al., 2007).

Previous research on SSI has indicated that students often struggle to fully appreciate the complexity of the issues from a systems perspective (Hogan, 2002; Sadler et al., 2007). Instead of recognizing the multidimensional nature of SSI under study, students tend to pose relatively simple solution to SSI indicative of simple causal reasoning. They also find it challenging to take into account the social aspects of the issue. In fact, many teachers either feel uncomfortable about incorporating social dimensions into their teaching or are unsure of how to do so effectively (Tidemand and Nielsen, 2017; Hancock et al., 2019; Friedrichsen et al., 2021; Ke et al., 2023). Given the demonstrated success of modeling approaches to promote systems thinking across various scientific disciplines, it is worth exploring how the use of models could similarly enhance students' systems thinking about SSI.

A growing body of literature has begun to explore the integration of modeling and SSI (Evagorou and Puig-Mauriz, 2017; Zangori et al., 2017). For example, in our previous work, we found that high school students, with appropriate instructional and curriculum supports, developed robust scientific understanding about carbon cycling and climate change through modeling (Zangori et al., 2017). However, much of the research in the area, including our prior work, focuses on using scientific models to promote student understanding of scientific knowledge within the context of SSI, rather than using models to foster students' systems thinking about SSI.

In other words, most of the modeling-in-the-context-of-SSI work that has been conducted thus far does not directly support learners in connecting science to their everyday lives, much like traditional science teaching approaches. It falsely assumes that students, once equipped with relevant scientific knowledge, can readily apply it to real-world problems. As such, in our recent work, we proposed a new type of modeling, socio-scientific models, to leverage students' prior experience and knowledge about the social dimensions of underlying issue as students develop models in the context of SSI (Ke et al., 2021). The goal was to encourage students to construct new knowledge about how these issues connect to their own lives. Socio-scientific models are similar to system models in that they both involve systems thinking. However, there are subtle yet important epistemic differences between the two due to the introduction of social elements. It is crucial to be aware of how these epistemic differences might affect SSI teaching and learning.

Epistemic differences between socio-scientific models and system models

Investigating the epistemic dimensions of modeling practices is essential for fostering meaningful science teaching and learning (Pluta et al., 2011; Berland et al., 2016; Ke and Schwarz, 2021). It sheds light on how learners construct, evaluate, and validate scientific knowledge through modeling. Likewise, it is important to understand how students generate and justify their knowledge around SSI using socio-scientific models. Socio-scientific models incorporate social components, which calls for a different set of epistemic knowledge compared to system models or other models in the disciplines of science. In this section, we highlight three epistemic aspects where socio-scientific models differ from systems models, (1) knowledge representation, (2) knowledge justification, and (3) systems thinking.

Knowledge representation

A key epistemic consideration for any type of model is determining the relevant components or variables to represent the underlying phenomena or systems. With system models, learners must consider epistemic questions such as, what are the system's boundary? Which components or variables are important for representing and simplifying the system under study? These questions apply regardless of the type of systems being examined. For socio-scientific models, learners need to ask similar epistemic questions. What scientific and social components are relevant and important for the issue I am investigating?

Incorporating social dimensions in socio-scientific models is not trivial. It fundamentally changes how learners perceive the legitimacy of knowledge in science classrooms. Socio-scientific models encourage learners to integrate components from various disciplines such as policy, economics, or sociology, based on their relevancy to the issue. For example, when modeling climate change, learners might consider the impact of government policies on carbon emissions or the economic implications of transitioning to renewable energy sources.

Contrasting with system models that primarily value scientific ideas and principles, socio-scientific models rely on learners' understanding of various subject areas. This interdisciplinary modeling approach allows learners to explore the connections between science and other domains within complex societal issues. Consequently, scientific knowledge is not treated in isolation; instead, it is constructed and represented in relation to knowledge from other social disciplines, promoting a more integrated understanding of the issue being studied.

As such, when developing socio-scientific models as opposed to system models, learners must expand their knowledge representation beyond purely scientific dimensions. Not only do they need to ask themselves, "What scientific components do I need to include in my model?" but also delve into social aspects, asking, "What social components are relevant for the issue? How do the scientific components relate to the social components?"

Knowledge justification

Another important epistemic aspect of modeling is knowledge justification, which involves evaluating the validity of the knowledge being represented in a model. How can one determine if a model is correct? In system models, learners are expected to use scientific evidence and reasoning to justify their choices of components, relationships, and structure. In contrast, when developing socio-scientific models, learners must also consider social factors, ethical and moral implications, and multiple perspectives from different stakeholders. Therefore, socio-scientific modeling requires learners to provide justifications based on a broader range of evidence that may also include personal experiences, narratives, and values.

Moreover, knowledge justification in modeling not only concerns what constitutes evidence but also involves determining the robustness of that evidence. In system models, the evidential criteria are predominantly focused on how well the model is grounded within empirical data, how well it aligns with established scientific principles and theories, and how accurate it predicts system behaviors under various conditions. However, in socio-scientific models, the evidential criteria are more complex. In addition to evaluating empirical evidence based on different methodological traditions (e.g., qualitative, quantitative), learners also need to take into account factors such as how well the evidence represents diverse perspectives and marginalized communities, whether the evidence aligns with generally accepted ethical standards and moral principles, and how relevant or applicable the evidence is to the specific issues under study.

Take the issue of water scarcity for an example. When constructing socio-scientific models, learners may need to rely on various types of evidence to justify their models. This can include quantitative data such as precipitation and groundwater levels, as well as qualitative data gathered from interviews with local residents and experts. Furthermore, learners may also need to consider the ethical implications of different water management strategies, such as water privatization, and assess their impacts on marginalized populations. The justification process requires learners to apply different evidential criteria based on the type of evidence used. Due to the diverse evidential criteria involved in socio-scientific models, it can be challenging for learners to navigate them without adequate instructional support. Prior research in science education has highlighted the role of uncertainty as a productive pedagogical construct to promote students' disciplinary understandings (Manz and Suárez, 2018; Chen et al., 2019). We argue that making explicit the uncertainty inherent in social sciences due to various evidential criteria used in socio-scientific models could likewise enhance learner's appreciation of the complexity of societal issues.

Systems thinking

One epistemic aspect specific to socio-scientific models is systems thinking from a broader social science perspective. The goal of this form of thinking is to understand complex societal issues by examining interrelationships, feedback loops, and emergent properties within social, economic, and political systems, where human behavior, values, and decision-making are crucial factors. Systems thinking in socio-scientific models differs from systems thinking in scientific disciplines due to the contrasting epistemic foundations. While scientific disciplines primarily emphasize objectivity, quantifiability, and replicability, social sciences prioritize diverse perspectives, qualitative data, and the complexities of human interactions within systems. So how might systems thinking look different in socio-scientific models?

The levels in a socio-scientific model are often different from those in a system model due to the inclusion of social components and human involvement. Socio-scientific models often feature a multi-level structure, with personal, community, and societal levels. Different relationships can exist at each level, making it challenging to predict behaviors across them. The multi-level nature of systems in socio-scientific models is closely tied to values and priorities, which are essential factors in decision-making for SSI. For instance, when addressing air pollution, an individual may choose biking based on their personal values and priorities. However, this choice does not guarantee a community investment in bike lanes, as it also depends on community values and local resources. At the society level, governments might implement loose emission standards for vehicles to stimulate the economy, which prioritizes short-term economic gains over long term environmental and public health concerns.

Another area where socio-scientific models differ from systems models in terms of systems thinking is causality. While complex causality can be involved in system models, as noted above, causal relationships in socio-scientific models are often more nuanced. This is due to potential biases and assumptions held by researchers when interpreting causal relationships in social sciences, even when established through rigorous methods like experimental designs or advanced statistical techniques. Furthermore, causal relationships in social sciences can be highly context-dependent, varying across different populations, cultures, and time periods. Thus, it is essential to consider the specific context in which causal relationships are established.

In many instances, establishing causality is challenging, leading to a focus on correlation rather than causation. While correlations do not necessarily imply causation, they can still provide insights into how variables are connected and interact within the system. For instance, in the context of public health, there is often a correlation between socioeconomic status and overall health outcomes. Although it may not be possible to establish a causal relationship between these factors, understanding the correlation can help identify patterns and inform policy decisions. Additionally, recognizing correlation necessitates an understanding of uncertainty. Uncertainty refers to the degree of doubt in the relationships between the variables. By quantifying uncertainty, we can better understand the limitations of the correlation and make more informed decisions based on the available data.

An exploratory investigation

In the previous section, we examined three epistemic differences between socio-scientific models and system models from a conceptual standpoint. We argue that these differences can have important implications for SSI teaching and learning. To further this work, we conducted an exploratory study to investigate how learners respond to these three epistemic differences. We aimed to gain insights into the challenges and opportunities learners encounter while engaging in socio-scientific modeling activities. Specifically, we ask the research question: *How do learners develop a socio-scientific model on COVID-19 with respect to knowledge representation, knowledge justification, and systems thinking?*

The findings from this exploratory study will contribute to our understanding of how learners make sense of and coordinate both scientific and social components of the underlying issue within the context of socio-scientific models. Additionally, the findings will inform our design of socio-scientific modeling activities, making them more meaningful and accessible for learners. This study is exploratory because little research has been conducted on socio-scientific models and we focus specifically on learners' use of epistemic ideas represented in in socio-scientific models. Although the sample size is small, the goal is not to make generalized claims; instead, we aim to provide empirical evidence that illustrates what these epistemic ideas might look like in the context of socio-scientific models.

Research context and participants

This study investigated collaborative construction of socio-scientific models among six female college-age students at a large public research university in the southeastern United States. Participants were recruited through convenience sampling and consisted of three pairs: one consisting of an African American female (Tia, a psychology major) and a Latina (Clara, an English major), and two pairs of white high school graduates (Sally & Stephanie, Aria & Chloe). All pairs know each other well. The study took place on the university campus spring 2022 and it was not associated with any science-related coursework. The study design involved an initial 30-min session where the first author guided each pair in constructing a socio-scientific model on local river water quality, familiarizing them with the processes and norms (e.g., adding arrows to indicate the direction of causal relationships) involved. The participants were then asked to collaboratively develop a COVID-19 socio-scientific model on a whiteboard in approximately 20 min. During the process, the participants were encouraged to think aloud and to discuss with each other what to and not to include in their models. Upon completion, each student participated in a semi-structured interview, reflecting on their experiences in constructing the socio-scientific models.

Socio-scientific models

We selected COVID-19 as the focal issue for the socio-scientific models, assuming that participants would be familiar with both scientific and social dimensions of the issue. This choice was appropriate, as no instructional intervention about the focal issue was involved, and participants had no prior experience with socio-scientific models. As a result, we designed the initial session to familiarize participants with this type of model.

During the initial session, we provided scaffolds to support learners in the following aspects. We divided the process of creating socio-scientific models into two steps, (1) identifying key factors relevant to the system and (2) establishing relationships between these factors. When identifying key factors, we prompted learners to consider both scientific and social components. We illustrated that pesticides washing into a river, a scientific component, could be one factor affecting water quality. In turn, the water quality would influence the money spent cleaning the river, an economic component relevant to the issue. Figure 1 was one of the slides used during the initial session.

We then demonstrated that arrows could be used to represent causal relationships. We also informed learners that not all factors had obvious causal relationships; some factors might be closely correlated. To encourage learners to consider the system dynamics of the underlying issue, we introduced conventions of "+" and "-" signs to represent positive and negative causal/correlation relationships. For instance, a negative sign between pesticides washing into a river and water quality indicates that an increase in pesticide use will result in decreased water quality. This approach prompted learners to think about causal or correlational relationships in a semi-quantitative manner. After familiarizing the participants with the process and conventions, we asked them to identify factors and relationships they deemed significant for the issue of water quality on their own.

For the COVID-19 socio-scientific model, we gave participants the driving question, "how has COVID-19 impacted your life?" We encouraged participants to consider relevant factors that encompassed both scientific and social components. Additionally,

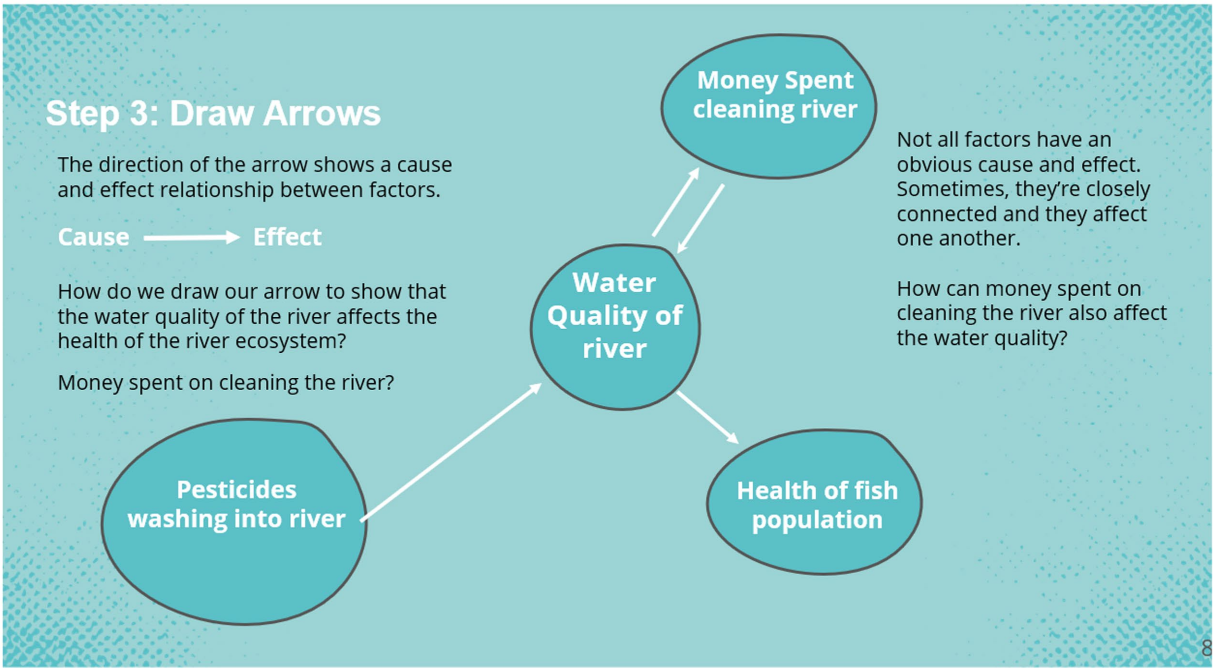

FIGURE 1
The slide used in the initial session to introduce socio-scientific models.

we provided participants with the component, COVID-19 infection rates, at the center of the whiteboard, allowing them to start creating the model with factors affected or were affected by COVID-19 infection rates.

Data sources and analysis

The primary data sources for this study were video recordings of participants working on their COVID-19 socio-scientific models and individual interviews. The video recordings captured the detailed process of creating socio-scientific models and the negotiation between pairs. The interviews focused on participants' reflections concerning the epistemic dimensions of the modeling process, as well as the perceived affordances and challenges of socio-scientific models. We selected these sources as they provided evidence of participants' epistemic ideas used during the socio-scientific modeling process. The video recordings offered in-the-moment data as participants were encouraged to think aloud. The interviews provided reflective data on students' epistemic ideas, allowing us to inquire about ideas not explicitly mentioned during the session. Both sources were transcribed for data analysis. We also used the socio-scientific models participants developed as supplementary evidence to inform and triangulate our analysis.

To address the research question, we compared and contrasted data among the three pairs concerning knowledge representation, knowledge justification, and systems thinking in the socio-scientific modeling activities. We used the constant comparative approach (Glaser and Strauss, 1967) to develop codes that were subsequently modified and aggregated into emergent themes. Given the small sample size and the exploratory nature of the study, we do not present the frequency of the emerging themes. Instead, in the following findings section, we highlight the patterns observed across the three pairs and trends that were unique to specific pairs.

Findings

Knowledge representation

Regarding knowledge representation, all three pairs incorporated various social factors into their COVID-19 models, including economic, educational, public health, and policy elements. For example, Tia and Clara from Pair 1 incorporated employment, mental health, international travel policies, and remote teaching into their model (see Figure 2).

Additionally, the interview data revealed that participants chose these social components because they were personal and relevant to them. For instance, Sally and Stephanie from Pair 2 incorporated virtual schooling into their model because they lived in the same area and had similar experiences with online learning. Likewise, Chloe from Pair 3 included lockdown, quarantine, and labor shortage in their model because she had recently contracted COVID-19 and her family's small business was significantly affected by labor shortages.

One interesting pattern we observed was that most factors identified by the participants were social components. Only Pair 3 included a few scientific components, such as vaccines and testing, and their potential impact on reducing COVID-19 infection rates. While it was possible that participants were more familiar with the social dimensions of COVID-19 (compared to other issues such as climate change), based on the data, we hypothesized that this pattern might be attributed to the

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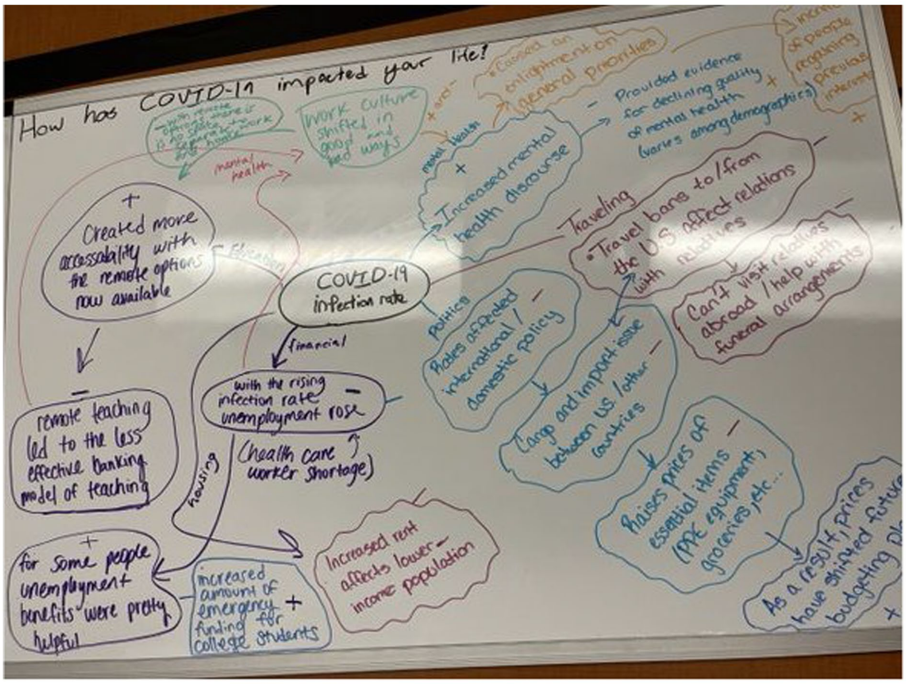

FIGURE 2
Tia and Clara's COVID-19 socio-scientific model.

participants' backgrounds. The excerpt below, from Clara's interview, reveals that they did not include scientific components mainly due to their humanities backgrounds. Instead, they chose to include social components that were relevant to them.

> I think if you would have asked two different people, maybe someone who was like in a science field, they would go into how the infection rate affects your health wise. But because Tia and I are kind of both into like humanities, we did focus. And we're both people of color. So, we both like wrote down ways that affected us and that's why, and our things are kind of unique to our experiences. (Clara, Pair 1)

Knowledge justification

Regarding knowledge justification, participants leveraged various sources of evidence to establish relationships within their models. Personal narratives emerged as the primary source upon which participants relied. As these narratives were based on their own experiences, participants felt it was legitimate to include them in the model. For instance, in Pair 1, Clara drew from her experience of losing a family member to justify a relationship between mortality rates and travel ban, and how these travel bans impacted people's lives and cultures.

> Clara: families had lost people, family members. I know that like particularly for –.
> Tia: So you want another one to be like mortality rates?
> Clara: Yeah, could you write that?
> Tia: Yeah, mortality, okay, what do you want to say about that?
> Clara: I know that I did have family members who passed away in other countries because, um - and you just - you are not able to - you are not able to, I do not know, travel.
> Tia: Oh, that could be another one, the traveling. There were like a lot of travel bans.
> Clara: When my uncle died, we were not able to go to Mexico, even his family were not even able to be with him.
> …
> (Towards the end of the session, when asked to explain the model)
> Clara: We tried to incorporate mortality rates into that because that is an immediate effect of the infection rates, sadly. Some of the biggest issues with not being able to travel is that you cannot directly help with funeral arrangements. And we know in certain cultures that's a really big deal, especially doing it properly.

Our findings revealed that, across all three pairs, participants were often uncertain about many of the relationships they identified in their models if they were not related to their personal experiences. Uncertainty was a common theme among the participants. As one participant reflected, "a challenge (of creating a socio-scientific model) would be the lack of credibility." Participants expressed a lack of confidence in the relationships, mainly because they had not conducted extensive research on the topic and might have only encountered the information through news sources or social media platforms like TikTok.

Furthermore, some of the uncertainty expressed by participants originated from the complex nature of epistemic knowledge in social sciences. For example, Chloe from Pair 3 described her struggle with establishing relationships in their model during her interview:

Like with lockdowns, we could not quite place like do we put it as a cause or an effect. I guess there's room for, subjectivity or opinions, kind of, just in like where everything is. And also, I do not know, I think you could argue some of these things are like they could be positive or negative, instead of just one or the other. (Chloe, Pair 3)

In the excerpt, Chloe mentioned the "subjectivity" involved in determining relationships among social components, stating, "just like where everything is." To her, the causal relationships were not apparent among some the components they had selected.

For the relationships in which participants felt confident, the primary epistemic criterion used by all participants was whether it made sense to them. For example, Stephanie from Pair 2 remarked, "We just kind of knew that, okay, these things are related. Like it makes sense. We only stuck with what made sense to us. So in our minds, it was right." Likewise, Aria from Pair 3 stated, "I just pictured in my brain, making sure it makes sense. And if it does not, then I try and find something different."

Systems thinking

Regarding system thinking, most participants noted that one of the affordances of socio-scientific models was their ability to help them see the connections among relevant components that they might otherwise not consider. The following quote from Tia's interview is representative of how participants perceived the advantage of socio-scientific models:

> If I hadn't seen it all put together like this, I wouldn't have been able to make the connections where these two things (work culture and public discourse) are connected to mental health, and now it's visually here so I can see that. (Tia, Pair 1)

Furthermore, with the scaffolds of positive and negative signs, all participants were able to reason, to varying degrees, about the systems dynamics of the underlying issue. For instance, Stephanie from Pair 2 explained their model (see Figure 3) during the session:

> Infection rates, we start with the basics, you know, social distancing, mask mandates, businesses closing down, and quarantine. And those led into bigger issues. So, quarantine led to mental illness because you're away from people, your mental health deteriorates. And then social distancing led to relationship impact, which was also connected to mental illness.

As evident in the excerpt, Stephanie was able to use a chain of reasoning to explain how an increase in infection rates could result in mental illness through intermediate factors such as quarantine and social distancing policies.

Another common pattern we observed was how participants considered factors and relationships at different levels: personal and family, community and specific groups of people, and national or international societal level. Interestingly, each pair seemed to have unique approaches. For pair 1, Tia and Clara, they started with the most personal and relevant factors, themselves and their family members, and they moved on to groups of people with whom they could resonate. Below is the excerpt from Tia's interview when asked about her strategy to create the model:

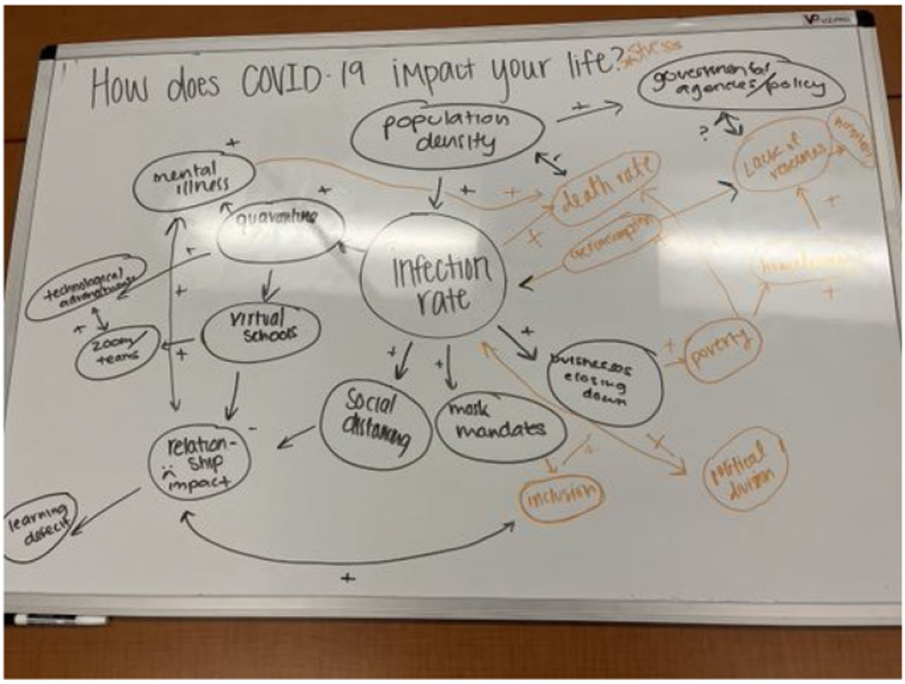

FIGURE 3
Sally and Stephanie's COVID-19 socio-scientific model.

> I went with the most important ways like the biggest impacts that it had. I started with myself and education, because that's just the biggest thing I have going on right now. And then, I went from like family members which is financial, which is the most important thing that my mom has going on. And then I went from there.
>
> I felt that we got really personal. We did reflect a lot on what affected us more. So, what affected other populations that we weren't familiar with? We had a lot to say about the housing and mental health, especially as college students who aren't from affluent neighborhoods or anything. So, we definitely had a lot to say about that, because it was more personal. (Tia, Pair 1)

In contrast, Aria and Chloe from Pair 3 took an opposite approach. While still drawing from their personal experiences, they were hesitant to include too many personal level components in the model. The excerpt below explains their rationale for emphasizing more on the societal level:

> I think, overall, we were listing like scientific explanations, and not as much personal. I guess I was able to think back to my time. But also, at the same time, we didn't list that many personal things, so I didn't see my experiences in it as much. I think we were listing more general, like the world, the impacts on society actually. (Aria, Pair 3)

It appeared that Aria and Chloe's focus on the societal level was because they believed it might be more "scientific." This also reflects that they might prefer a large sample size over personal experiences based on their evidential criteria.

Indeed, there seemed to be a tension between whether to focus more on the personal level or the larger societal level. What makes this complex is that different levels also involve different values and perspectives. For instance, Clara from Pair 1 made the following comment, highlighting the tension she felt when trying to make the model personal, while also wanting to account for various perspectives and experiences:

> It was difficult to decide whether it was a positive or a negative relationship. We can't really see it just from our perspective, as we mentioned earlier. It was kind of thinking outside of yourself, like, the unemployment that we mentioned, and the funding received for that. Well, for some families who are already making like maybe underneath what is deemed as the poverty line, that would have been a humongous help, because that's a grant that's more than what you've actually been working towards. But for other families, that probably just wasn't enough. So, it really depends on the situation. And we tried to not be biased, because we tried to make it personal. But at the same time, there are so many people in this world affected by the pandemic, and we really can't account for all of their perspectives and experiences just from our generalizations. (Clara, Pair 1)

For Clara, her struggle with the contextual nature of some of her claims highlights the epistemic difference between science and social sciences. It is likely that she was not very familiar with the context-based aspect of social sciences. Sally from Pair 2 shared the same sentiment, expressing that she could not speak for something that she had not personally experienced. She noted, "The things that were not as directly affecting me like poverty, I wasn't affected by poverty. My parents did not lose their jobs. I do not know. It felt like, I cannot really speak for this. But this is just like from outward looking in."

Discussion and implication

The findings of this study demonstrated that, due to the epistemic difference from traditional scientific modeling approach, engaging learners in developing socio-scientific models presents unique opportunities and challenges for learners for SSI teaching and learning. The inclusion of social elements enabled learners to leverage their personal experiences, values, and perspectives into the modeling process. At the same time, socio-scientific models can be challenging for learners. Being unfamiliar with certain epistemic traditions in social sciences hindered learners from fully realizing the potential of socio-scientific models and using them to make informed decisions on issues that mattered to them. In the following section, we discuss how socio-scientific modeling can promote diversity, equity, and inclusion in science classrooms and what additional supports are needed for socio-scientific modeling to be meaningful for learners. We conclude the section with suggestions for future research.

Socio-scientific models to promote diversity, equity, and inclusion

An important finding of the study was the critical role personal experiences or narratives play in the development of socio-scientific models. This was evident in all three epistemic aspects of the model-building process. During knowledge representation, most learners selected social components based on their personal experiences. In knowledge justification, the majority of learners used personal experiences as evidence to justify their model components. Regarding systems thinking, some learners preferred to start with components and relationships at the personal level and then progressed towards community and societal levels.

This emphasis on learners' personal experiences makes socio-scientific models a productive approach for promoting diversity, equity, and inclusion (Schwarz et al., 2022). Fundamentally, socio-scientific models disrupt the traditional notion of legitimate knowledge and embrace diverse voices and perspectives in science classrooms. By highlighting personal experiences, socio-scientific models empower learners from marginalized communities to contribute their unique perspectives and knowledge to classroom discourse, as exemplified in Tia and Clara's case. This approach can also enrich the learning experience for all learners by exposing them to a broader array of viewpoints and experiences.

From a systems thinking perspective, socio-scientific models can also promote science learning for social-justice. By exploring complex societal issues at the community level, students can gain a better understanding of the systemic factors contributing to structural inequalities affecting marginalized communities and work towards developing potential solutions. For instance, in their socio-scientific models, our participants identified historically marginalized individuals such as people living in poverty, immigrants with distant families, and those who lost their jobs. and how the pandemic disproportionally affected these groups. Focusing on social justice issues within the context of SSI can foster a more inclusive and equitable learning environment while also promoting empathy and civic engagement among students (Calabrese Barton et al., 2021; Rawson Lesnefsky et al., 2023).

Additional supports for socio-scientific modeling

The present study showed various challenges learners face as they engage in socio-scientific modeling. Additional supports are needed to further scaffold the modeling process and make it meaningful for all learners. One major challenge learners encountered was related to the epistemic traditions in social sciences. Participants from all three pairs were unfamiliar with, and therefore uncomfortable with the uncertainty involved in determining the relationships among social components and the tensions in balancing multiple perspectives at different systematic levels.

As such, learners need supports in navigating these epistemic ideas that may differ significantly from those they are accustomed to in science. For example, providing explicit instruction on how personal narratives, qualitative data, and different perspectives are valued in social sciences could be potentially helpful. In addition, learners would benefit from understanding how uncertainty or probability plays a role in our comprehension of correlational relationships, and how these relationships can be highly context specific.

Another significant challenge learners faced was a lack of sufficient evidence to justify their models. This, in part, contributed to the uncertainty learners experienced as they determined the relationships among components. Participants in this study had to primarily rely on their personal judgments to determine the validity of the relationships, considering whether they made sense to them or not. This justification process could lead learners to a false sense that everything was connected. Therefore, to help learners systematically understand the complexity of the underlying issue, more evidence is needed, either by encouraging learners to seek evidence on their own or providing them with a variety of evidence sources. By doing so, learners can have the opportunity to learn how to use and evaluate different types of evidence for knowledge justification in the context of socio-scientific models.

One limitation of the socio-scientific model described in this study is its paper-pencil format. Due to technological constraints, it primarily emphasizes the causality aspect of systems thinking, and limits attention to emergence as a feature of systems. To further support learners in understanding emergent outcomes, computational technologies, such as NetLogo, may be helpful. For example, in its current form, learners can reason about system dynamics in a semi-quantitative way as evident in our data, but it was challenging, if not impossible for them to predict system outcomes with high quantitative accuracy. However, with the support of computational tools, achieving more accurate predictions might be possible.

Direction for future research

Given initial results of this study, we suggest further exploration in the following three areas. First, additional empirical evidence should be gathered to demonstrate how using socio-scientific models can facilitate equitable learning opportunities for students, especially those from underrepresented populations, across a range of SSI topics. This is important as students may have diverse reactions to different SSI topics, and we need to figure out how to best leverage students' prior knowledge and experiences. Second, further research is needed to investigate how learners use different epistemic understandings and evidential criteria to develop socio-scientific models. This link between students' epistemic ideas and modeling practice is crucial for making instruction meaningful for all learners. Third, we need to learn more about how to adequately evaluate socio-scientific models. Given the distinct epistemic understandings and criteria used in socio-scientific models, a new framework needs to be developed to assess how well the socio-scientific models capture the system dynamics of the target complex issue, including both science and social dimensions.

Conclusion

As the world faces complex societal challenges, including the global pandemic, it is more critical than ever to prepare our future generations to be scientifically literate and responsible citizens. SSI teaching and learning have the potential to achieve this goal, yet many teachers find it challenging to address the social aspects of complex societal issues. This paper provides evidence that, socio-scientific models can serve as not only an effective but also an equitable tool for addressing this issue. The three epistemic features highlighted in this paper contributed new knowledge for fostering meaningful SSI-based instruction. By focusing on these features, science educators can better support learners in understanding the complexity of the underlying issues while empowering them to become informed citizens capable of tackling pressing societal issues.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by University of North Carolina at Chapel Hill. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

LK, EK, TS, and RL contributed to the conceptualization and design of the study. LK, EK, and RL collected, organized, and analyzed the data. LK wrote the first draft of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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