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Using Participatory System Dynamics Modeling to Address Complex Conservation Problems: Tiger Farming as a Case Study

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Conservation practitioners routinely work within complex social-ecological systems to address threats facing biodiversity and to promote positive human-wildlife interactions. Inadequate understanding of the direct and indirect, short- and long-term consequences of decision making within these dynamic systems can lead to misdiagnosed problems and interventions with perverse outcomes, exacerbating conflict. Participatory system dynamics (SD) modeling is a process that encourages stakeholder engagement, synthesizes research and knowledge, increases trust and consensus and improves transdisciplinary collaboration to solve these complex types of problems. Tiger conservation exemplifies a set of interventions in a complex social-ecological system. Wild tigers remain severely threatened by various factors, including habitat constraints, human-wildlife conflict, and persistent consumer demand for their body parts. Opinions differ on whether commercial captive tiger facilities reduce or increase the threat from poaching for trade, resulting in policy conflict among diverse stakeholder groups. This paper explains how we are working with international conservation partners in a virtual environment to utilize a participatory SD modeling approach with the goal of better understanding and promoting coexistence of humans and wild tigers. We highlight a step-by-step process that others might use to apply participatory SD modeling to address similar conservation challenges, building trust and consensus among diverse partners to reduce conflict and improve the efficacy of conservation interventions.

Keywords: human-wildlife conflict, systems thinking, wildlife trade, wildlife farming, participatory modeling

INTRODUCTION

To navigate complex social-ecological systems and promote coexistence with wildlife, researchers and practitioners must focus on knowledge generation while increasing access to and use of information that already exists. Inadequate understanding of systems can lead to misdiagnosed problems and unintended outcomes (Larrosa et al., 2016). These misdiagnoses often create or exacerbate human-wildlife conflict (Hübschle, 2017). Conflict mitigation interventions typically focus on tangible disputes (e.g., livestock depredation and retaliatory killings, illegal poaching) without addressing root causes of problems such as inequitable social relationships and processes (Madden and McQuinn, 2014; Baynham-Herd et al., 2018). While a wealth of information about

these social relationships and processes exists, this knowledge often remains on the periphery of decision-making that impacts wildlife management (Bennett et al., 2017). Interventions that neglect to consider social and political context, such as a singular "war on poachers" are therefore unlikely to succeed. In fact, such interventions may inadvertently fuel social-cultural tensions and subsequent conservation-related conflict (Brashares et al., 2014; Challender and MacMillan, 2014). Efforts to reduce human-wildlife conflict, especially for controversial carnivore species like tigers, rarely address these issues (Krafte Holland et al., 2018).

Madden and McQuinn (2014) argue that "conservation efforts would benefit from improved capacity and resources for understanding and transforming the complex drivers of deep-rooted social conflicts impacting wildlife conservation and management actions" (p. 104). Numerous scholars have made a strong case that biodiversity conservation is ultimately a social and political process (Brechin et al., 2002; Lele et al., 2010; Montgomery et al., 2020). Yet, despite a growing body of research focused on the social component of social-ecological systems (Ban et al., 2013), including systems with carnivore species such as tigers (Torri, 2011; Struebig et al., 2018), efforts to apply this research by re-conceptualizing and adapting conventional conservation approaches have been slow (Bennett et al., 2017). As recognition of these challenges grows, the key ingredients for change are already present. Leveraging them might simply require a shift toward systems-level thinking and adaptation.

TOWARD A SYSTEMS APPROACH

Conservation practitioners often acknowledge the complexity of the systems in which they operate, which span a wide array of habitats, stakeholder groups, communities, sectors, and political boundaries. Most adapt and respond to these systems, altering interventions based on data and experience to better achieve their goals. Yet dynamic social-ecological systems make it very difficult to grasp the long-term implications of management actions due to delays between cause and effect (Kim and Senge, 1994). Implementation itself may also change the nature of the problem, influencing the success of the solution (Game et al., 2014; Larrosa et al., 2016). New tools and approaches are needed to advance understanding of systems and build capacity for action (Mahajan et al., 2019).

To advance understanding of systems, researchers have employed modeling approaches such as bayesian belief networks (Bennett et al., 2021), agent-based modeling, social network analysis, and system dynamics (Frerichs et al., 2016). There are also approaches that focus more on planning to help managers improve decision making and outcomes, such as structured decision making (Gregory et al., 2012) and the Conservation Standards (CMP, 2020). For example, use of the Conservation Standards provides a number of benefits, including identifying potential interventions, clarifying theories of change and increasing collaboration; however, it does not explicitly incorporate system behavior such as feedbacks, non-linear behavior or the consequences of time delays. With such a diversity of tools that could be used for understanding complex

systems (Voinov et al., 2018), it can be difficult for managers to know where to start.

The field of System Dynamics (SD) began in the early 1960s to better understand complex human and industrial dynamics (Forrester, 1971). Today, SD is used to inform decision making and policy in fields such as business (Ford, 1997; Sterman, 2000), health (Frerichs et al., 2016; Currie et al., 2018), social work (Trani et al., 2016; Appel et al., 2019; Fowler et al., 2019), and agriculture and natural resource management (Ford, 1999; Stave, 2010; Turner et al., 2016; Kopainsky et al., 2017). It has even been applied to species such as sage grouse (Beall and Zeoli, 2008), African penguins (Weller et al., 2014) and grizzly and spectacled bears (Faust et al., 2004).

While not suitable in all cases, SD offers a number of strengths in helping to understand the dynamic behavior of complex systems and test assumptions of different actions and policies with a focus on solving problems (Forrester, 1994; Sterman, 2000). SD traditionally uses two main modeling types: qualitative causal loop diagrams (CLDs) and quantitative simulation models. CLD's identify relationships and feedback mechanisms between elements. Simulation models incorporate the elements of a CLD into a stock-flow structure, where stocks represent what is accumulating in a system (e.g., number of tigers) and flows represent rates of change (e.g., birth or death rate). Structural (e.g. connections between elements) as well as numerical data are incorporated into simulation models to generate endogenous behavior over time under changing conditions and policy interventions. While not meant for predicting or forecasting, simulation models make it easier to explore the potential implications of changing conditions and selected policy interventions on system behavior (Sterman, 2000). SD simulation models run quickly and do not require high computing power; the approach is also particularly useful in environments where quantitative data is scarce and integration of qualitative data (e.g. expert opinion) could be used to address knowledge gaps (Luna-Reyes and Andersen, 2003; Gallagher et al., 2020).

SD is ideally used in participatory planning processes where it can support the negotiation of a shared understanding of a dynamic problem (Vennix, 1999). It facilitates exchange of ideas among participants (Sedlacko et al., 2014) and effectively integrates existing scientific research with local knowledge (Beall and Zeoli, 2008; Stave, 2010; Rouwette et al., 2016). Co-creating SD models necessitates turning implicit into explicit knowledge, so that participants are learning from each other and the model itself (Kopainsky et al., 2017). This also encourages participant ownership of the model and greater support of outputs to address the problem. Model creation can provide a laboratory for a group to examine policies and to visualize potential impacts of actions over time (Forrester, 1994; Sterman, 2000). This is an especially important benefit when working with endangered species or sensitive environments, where physical experiments are not always possible (Sterman et al., 2013; Turner, 2020). In addition to insights from the model, the model building process can increase the social capital of a group (Davies et al., 2015), strengthen relationships and improve communication (Beall and Zeoli, 2008; Stave, 2010). Although

there are several terms used for conducting SD modeling with stakeholders, we use the term participatory SD modeling in this paper.

Despite calls to increase the overall use of models in decision making, resistance may persist for several reasons. Primary concerns include lack of transparency regarding model-building and outputs and weak communication between modelers and practitioners (Addison et al., 2013). Participatory SD modeling offers several advantages since models are designed to be built with stakeholders, using the language of people working on the chosen problem. The visual nature of the modeling software is more accessible to a lay audience, and easy-to-use interfaces help minimize technical barriers between modelers and the modeling groups (Sterman, 1994). Although the value of participatory SD is well-documented (Rouwette et al., 2011; Scott et al., 2016b; Andersen et al., 2017), adoption of this approach to address complex conservation problems has been slow. The time required of participants in the short term (Stave et al., 2019) and the need for a competent modeler and facilitator to coordinate the process (Andersen et al., 1997) are major barriers to adoption. More research and guidance are needed to help conservation practitioners explore the potential value of the participatory SD modeling approach.

This paper explores how a participatory SD modeling process can be used to address a particularly complex problem: conservation of wild tigers.

CONSERVATION CONTEXT: IMPACTS OF TIGER FARMING ON WILD TIGER POPULATIONS

Approximately 3,900 tigers remain in the wild worldwide (World Wildlife Fund, 2021), and they are found in <7% of their original global range (Dinerstein et al., 2007). Wild tiger populations are found in up to 13 countries: Bangladesh, Bhutan, Cambodia, China, India, Indonesia, Lao PDR, Malaysia, Myanmar, Nepal, Russia, and Thailand (Goodrich et al., 2015), although this list includes several countries where wild tiger may be functionally extinct (EIA, 2017; Rasphone et al., 2019). The continued survival of tigers depends on a complex set of ecological, economic, and social factors across local and global scales. Because tigers need sufficient lands to roam where they can find adequate prey and live largely undisturbed by people, some experts believe that conservation efforts should focus on law enforcement and protection of habitat and corridors in and around key protected areas (Walston et al., 2010). In areas where tiger conservation succeeds and numbers grow, tigers increasingly come into conflict with growing rural human populations, threatening people and their livestock and potentially increasing revenge killings (Carter et al., 2014; Struebig et al., 2018).

In addition to the interrelated processes of human encroachment, habitat and prey loss, and human-tiger conflict, a persistent consumer market for tiger parts and products economically incentivizes poaching and makes the conservation of wild tigers even more challenging (Wong, 2016). In fact, there is growing consensus that the most urgent threat to wild tigers is poaching (Dinerstein et al., 2007; Chapron et al., 2008). International consumer demand for tiger parts (bones, hides, teeth, etc.) constitutes a major potential threat to wild tigers (Goodrich et al., 2015). Tiger parts are valued across Asia for their perceived health benefits and may confer status and wealth (Goodrich et al., 2015; EIA, 2017). As the species becomes rarer, illegal harvesting and trade in body parts are likely to increase alongside rising market values.

Reduction of the threat of poaching is difficult because tiger poaching crosses multiple countries with different cultures, laws, and policies, and it is influenced by complicated market behaviors (e.g., consumer demand for tiger parts) amidst a growing human population (Sharma et al., 2014). A feedback loop of inter-related increasing scarcity and rising prices can lead to a phenomenon termed the anthropogenic allee effect (Courchamp et al., 2006), which can drive a species to extinction or keep a population low. Under these conditions, drawing attention to the rarity of the species through a demand-reduction program can have the perverse effect of stimulating poaching (Courchamp et al., 2006; Hall et al., 2008). Poaching also appears to have a non-linear relationship with tiger survival, indicating that there are thresholds where even steady rates of poaching could suddenly cause an extinction risk to a tiger population (Kenney et al., 1995). Adding complexity, the tiger trade also potentially threatens other big cats around the world, as body parts from other species such as lions are being traded in the tiger parts market (Williams, 2015; Williams et al., 2017; Villalva and Moracho, 2019; Coals et al., 2020). To mitigate poaching, some have suggested that market demand for tiger products should be supplied from captive sources (Jiang et al., 2007), but this proposal is contested (Gratwicke et al., 2008).

As of 2017, at least 7,000 tigers were estimated to be held in captive facilities (hereafter "tiger farms") across Asia, catering to growing demands for various products ranging from tiger body parts and derivatives to live tigers used for tourist attractions (EIA, 2017). The global captive tiger population is larger, with ~5,000 captive tigers in the United States alone (World Wildlife Fund, 2020). Many conservation organizations would like to see this practice end, but the potential impacts of closures of farming operations for species are not entirely clear or without risk (Kirkpatrick and Emerton, 2010; 't Sas-Rolfes, 2010). For the purpose of this study, we define a tiger farm as "a facility that keeps or breeds tigers in captivity with an intent (or reasonable probability) of supplying or directly engaging in the commercial trade in tigers or tiger products, be they body parts or derivatives. The application of this definition is not limited by the stated purpose of such facilities."

As Asian economies grow, so might consumer demand for wildlife products such as skins and bones of tigers (Linkie et al., 2018). In one case, researchers found that nearly half (43%) of survey respondents in China (one of the largest consumer markets) had consumed a product that contained tiger parts (Gratwicke et al., 2008). There is uncertainty over the preference consumers may have for wild vs. farmed tiger products (Coals et al., 2020; Hinsley and 't Sas-Rolfes, 2020), with wild tigers possibly being prized more for their power and strength (EIA, 2017). Stronger preferences for wild vs. farmed animal parts have

been reported for other species, such as bears farmed for bear bile (Dutton et al., 2011), but these preferences are dynamic and can shift based on access and availabilty (Davis et al., 2021; Rizzolo, 2021). This uncertainty raises questions about the relationship between tiger farms and demand for tiger parts and products (Song and Yao, 2021).

The challenge of enforcing global wildlife trade under the Convention on International Trade in Endangered Species (CITES) (Challender et al., 2015), combined with limited capacity to combat poachers, has led to some researchers to support limited tiger farming (Abbott and van Kooten, 2011). The argument for legalized tiger farming proposes that increasing the supply of parts will suppress the market price of illegally harvested tiger products (Abbott and van Kooten, 2011). While the demand for tiger parts would persist, diminishing financial incentives for illegally harvesting wild tigers could deter poaching. Based on this hypothesis, some scientists have advocated for humane, renewable harvest and legal trade of other endangered wildlife species facing similar predicaments—such as African rhinos (Biggs et al., 2013).

Conversely, many argue that farming tigers and facilitating the use of their parts for a consumer market fuels market demand and complicates enforcement efforts to reduce wild tiger poaching (Gratwicke et al., 2008; EIA, 2017). According to this argument, the presumed benefits of legal supply might be undermined by imperfections in the tiger parts market, including dominance of a small number of producers controlling prices, the luxury status of tiger parts, and the relatively high expense of farming tigers (Kirkpatrick and Emerton, 2010). Legal markets for farmed tiger products might also lead to greater social acceptability of the product, thereby suppressing a stigma effect considered necessary to prevent unsustainable demand levels (Fischer, 2004; Rizzolo, 2021).

Considering the growth in tiger farms and potential demand for tiger parts globally, many scientists and conservation managers are seeking to better understand the impacts of tiger farming on wild tiger populations. The complex dynamics surrounding tiger farms highlight the need for holistic, systems-based approaches to understand their full impact on wild tiger conservation (Rizzolo, 2021). Understanding complex systems such as those impacting tiger conservation efforts is exceptionally difficult (de Vos et al., 2019), but remains a global priority in conservation science. Participatory SD modeling offers a unique opportunity to understand the problems related to tiger farms and to evaluate the efficacy of proposed interventions.

Below, we describe the development and implementation of a participatory SD modeling process designed to explore the impact of tiger farming on wild tiger populations.

APPLYING THE PARTICIPATORY SYSTEM DYNAMICS MODELING PROCESS

There is a tendency when applying SD modeling to focus on what is perceived to be the final product: the model itself. Although the model can be an important decision-making tool, it is often not the most valuable outcome. The process itself is
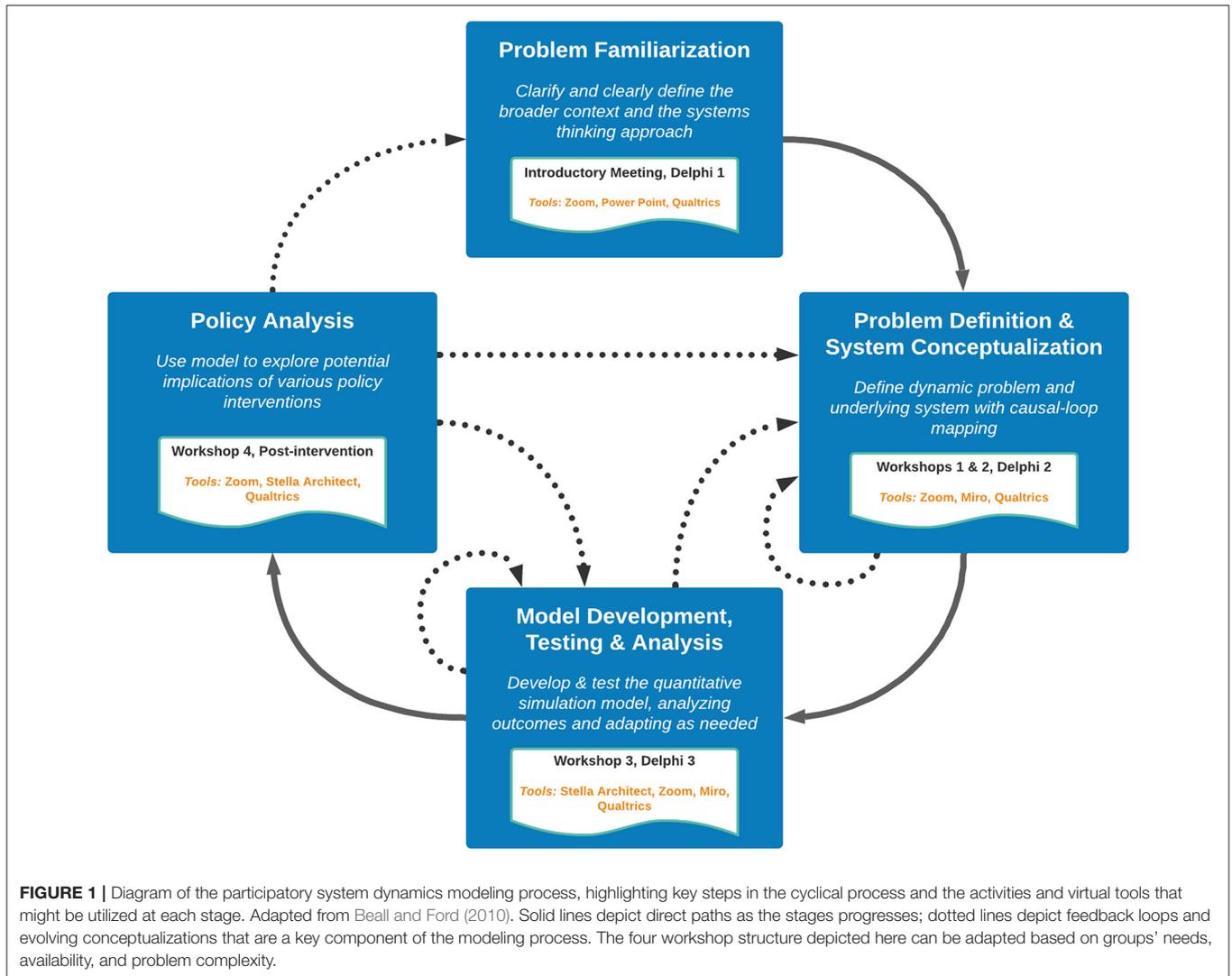
what creates an opportunity for conflict transformation (Madden and McQuinn, 2014). In the following sections, we discuss the primary steps in a participatory SD process and describe how we are currently applying them to improve understanding of the impact of tiger farming. Because our model building efforts are ongoing, the outcomes are not yet known and some aspects of our participatory approach continue to evolve. However, we have already learned multiple lessons that could help to inform participatory SD modeling in other contexts. Using tiger farming as a case study, the framework outlined in this paper illustrates how similar participatory SD approaches might be designed and implemented to build knowledge, trust and consensus among conservation partners with the goal of improving future conservation interventions.

Like any complex system, this process is not linear. At each step new information is learned and the identified problem may change, along with system components. **Figure 1** depicts our participatory SD process in action (adapted from Beall and Ford, 2010). Key steps in **Figure 1** are described in more detail below. Our process draws from many earlier examples of participatory modeling (Vennix et al., 1990; Sterman, 2000; Beall and Zeoli, 2008; Beall and Ford, 2010; Stave, 2010; Hovmand et al., 2012; Homer, 2019; Wilkerson et al., 2020), synthesizing and adapting these based on participant feedback and study context.

Setup and Design

The first step in a participatory SD project involves ensuring the right people are involved and that the process is tailored to match the scope of the problem. To develop a robust understanding of a complex problem, participants should bring diverse perspectives, knowledge, and expertise. This includes people who may not agree about a problem, its causes, or potential solutions. It is also important consider who is making policy and management decisions and involve these key actors in the process, if possible. This helps generate a model that is comprehensive, valuable to the individuals participating, and supported by leaders. Who participates also depends on the scope of the project (i.e., relevant geographic area, number of organizations or communities involved) and whether the model building will be done in person or virtually. There are benefits to convening in-person, however virtual platforms (e.g., Zoom) can engage more voices across a wider geographic area at a lower cost (Wilkerson et al., 2020). For either setting, group (or sub-group) size should be structured to make sure everyone can participate fully. Other factors to consider when designing the process include the experience level of facilitators and modelers, funding, and time available for both participants and facilitators/modelers.

Our tiger project was initiated by one organization (an international conservation NGO) starting in 2019, but the desire for diverse perspectives led to the creation of a four-person advisory group, each from varying backgrounds, perspectives, and organizations. This advisory group co-created the process with the research team, then selected and invited the rest of the participants. Throughout 2020, we devoted significant time to building understanding of the project within the advisory group and building trust

FIGURE 1 | Diagram of the participatory system dynamics modeling process, highlighting key steps in the cyclical process and the activities and virtual tools that might be utilized at each stage. Adapted from Beall and Ford (2010). Solid lines depict direct paths as the stages progresses; dotted lines depict feedback loops and evolving conceptualizations that are a key component of the modeling process. The four workshop structure depicted here can be adapted based on groups' needs, availability, and problem complexity.

among group members. Extensive conversations helped us reach consensus about which participants to invite, ensuring diverse perspectives regarding the costs and benefits of tiger farms while maintaining manageable group size for coordination purposes. To date, our participants include over 50 people spread across conservation NGOs (32 people from 20 different organizations), governmental or intergovernmental institutions (four people), research organizations or institutions (20 people), consultants (five people), and law enforcement (four people) (with participants able to identify multiple sectors). Participants live across Europe, Asia, North America and Africa. Expertise varies among participants, with self-reported knowledge being highest in wildlife trade (76% participants), law-enforcement and anti-poaching (40%), tiger farming in Asia (38%), and farming of non-tiger species (30%). Less than 20% of participants reported high confidence in systems thinking or participatory modeling, demonstrating that this process was relatively novel for most of these conservation practitioners.

Given the global network of experts involved, the costs and logistics made in-person meetings prohibitive (with challenges accentuated by the COVID-19 pandemic); thus, we made an early choice to adopt a completely virtual process. To operate in a virtual environment, the research team needed to learn new tools to be utilized at different stages (**Figure 1**). Recognizing not everyone could (or would) be interested in participating directly in the participatory modeling itself, we created two main groups: a modeling group (including the advisory group) and a consultation group (**Table 1**). To incorporate information from such a large group into the model and to support consensus building among the entire group in a virtual format, we decided to integrate a modified Delphi process into participatory SD modeling. The Delphi technique has been widely used for consensus building about topics ranging from program planning to policy development (Hsu and Sandford, 2007). It utilizes rounds of anonymous questionnaires to explore assumptions, illuminate diverse views, develop a range of possible alternatives, and to educate respondents about complex aspects of a topic.

TABLE 1 | Roles and responsibilities for different stakeholder groups engaged in the participatory system dynamics (SD) modeling process designed to improve wild tiger conservation.

Group	Roles	Important considerations
Research team (2–5 people)	Small group of senior and junior system dynamists who lead model building and facilitation effort; assistance in managing workshops provided by additional researchers.	Modelers and facilitators must act (as much as possible) as honest brokers in facilitating the group process. Modelers are adept at their practice, but they are not subject matter experts (and may be perceived as objective, third-party mediators). Ideally, the modeler and facilitator are separate people.
Advisory Group (3–5 people)	Small, diverse group of experts who co-lead the process with the research team and join the Modeling Group for all modeling workshops.	Members of this group should bring different perspectives to the table. In addition to advising the research team, this group plays the critical role of identifying and inviting appropriate participants for other groups.
Modeling Group (up to 20 people)	Group of experts who, along with the Advisory Group, build the model with the Research team.	Participants should be chosen from different organizations, geographies, and sectors (law enforcement, ecology, wildlife trade, etc.). Ideal candidates have interest, sufficient time, and willingness to collaborate constructively through differences. Group size should be limited to keep workshops manageable, and may be split to facilitate scheduling across multiple international time zones.
Consultation Group (20 or more people)	Additional experts who are invited to contribute to the model through questionnaires and information gathering exercises throughout the process.	Participants include all experts whose input is relevant and important to include. Considerations for selecting individuals for this group might include expertise, organizational affiliation, and time available to devote to the project.

Similar group structure could be used in other participatory SD modeling efforts.

After each round, respondents review summarized responses and highlight areas of disagreement (Hsu and Sandford, 2007), as well as additional questions informed by the modeling (Vennix et al., 1990).

Introduction and Problem Familiarization

Since many participants may not be familiar with systems thinking or the participatory SD process, it is critical to provide a road map to illustrate where the modeling process is going. This overview should include a basic review of systems concepts, such as the definition of a system and the concepts of reinforcing and balancing feedback loops and stocks (what is accumulating or declining) and flows (the rate of change). The introduction should also lay out the modeling process timeline, and show examples of what a model looks like to give participants an idea of where the process will end up. Example models should be relevant to participants, but unrelated to the conservation problem being tackled (Beall and Zeoli, 2008). Finally, it is important to get the group talking about the problem they want to address and to begin working toward defining that problem. The amount of time or focus this takes depends on the particular group, the nature of the problem, and how much clarity and agreement already exists.

The first step in our modeling process was an introductory meeting with all participants following official invitations. The meeting covered the history of the project, introductions, and an overview of the overall process. Basic systems concepts were introduced through real-world hypothetical examples. We used the iceberg model (Senge, 1990) to show that observable events,

the tip of the iceberg, are part of larger patterns of change caused by unobservable relationships between elements in a system (also called "system structure"). These are further created and shaped by mental models at the bottom of the iceberg. Changing system structure and mental models produce long term change (Senge, 1990). A demonstration of a simple working dynamic simulation model provided participants with a vision of the end result of their efforts. The meeting ended with a group brainstorm around the broader issue of tiger conservation and the greatest concerns related to tiger farming (**Figure 1**, Problem Familiarization). The most important problems participants identified fell into the following major categories:

- Demand for tiger parts and products (or understanding drivers of demand)
- Lack of understanding the connections between wild tigers and tiger farms
- Market dynamics (price, supply of parts, diversity of products and consumers, etc.)
- Consumer behavior change
- Trade and criminality
- Governance and regulation
- Law enforcement

Setting expectations for participants about the importance of integrating diverse perspectives, including those of potential adversaries, was a key element of the first few meetings. We focused on creating an atmosphere of trying to understand the problem and not to debate specific positions.

Problem Definition and System Conceptualization

Modeling a system without a boundary or a clear focus would produce a model that was unnecessarily, and maybe impossibly, complex and impractical (Sterman, 2000). For this reason, the next step in the modeling process is defining the dynamic problem the group wants to address. A dynamic problem is composed of multiple variables that are changing over time (Homer, 2019), such as a declining wild tiger population, increasing demand for tiger products, and increasing tiger farms. Getting clarity on the problem can be one of the most challenging parts of the process, and may be revisited multiple times as knowledge increases (Mashayekhi and Ghili, 2012). Once the problem has been defined, then the system surrounding that problem can be conceptualized. A qualitative model known as a causal-loop diagram (CLD) is iteratively built based on expert judgment and opinion, followed by reflection about the problem and the system elements. The CLD is later used as the foundation of the simulation model. Approaches to eliciting this initial model vary, but efforts such as Scriptapedia (Hovmand et al., 2012) and the Online System Dynamics Collaborative (https://onlinesd.w.uib.no/) provide tested facilitation scripts to get started.

We are using a combination of questionnaires (that include an adapted Delphi process) and small group workshops to develop consensus around the problem and system components. We began with a pre-modeling survey that contained two open-ended questions focused on understanding the potential impacts of tiger farms on the illegal tiger trade and tiger conservation: (1) what is the most important problem to address within this system? and (2) what factors are contributing to this problem? Answers to these initial questions were summarized and used to inform discussions in the introductory meeting with the modeling group (See introduction and problem familiarization above).

After collecting and synthesizing this information, we hosted a longer workshop to begin the collaborative system conceptualization process. We did this with variable elicitation and behavior over time exercises adapted to the *Miro* online platform (https://miro.com) in Workshop #1. Participant-defined variables, along with relevant behavior over time graphs describing how variables have shifted in the past and predicting how they might shift in the future, were then worked into a CLD. The CLD was modified to include key stocks and flows important in the quantitative model (**Figure 2**) (Homer, 2019). The model was further developed in Workshop #2. Examples of key components of this model include: farmed tiger populations and farm capacity, connections between farmed tiger mortality and sales of products, consumer demand for products and factors that influence demand, and wild tiger population dynamics. Between workshops, the modeling team worked to refine the model and incorporate additional input through one-on-one conversations. When this paper was written, our modeling effort remained in this stage. The following sections outline next steps that could be taken in this, or any other, participatory SD modeling process.

Model Development, Testing and Analysis

Once the initial qualitative CLD is developed around the problem, it is transferred to SD modeling software for creation of a dynamic simulation model. Popular software programs used for this purpose include *Stella* (https://www.iseesystems.com/store/products/) or *Vensim* (https://vensim.com). With this transition, additional questions as well as gaps in logic and knowledge become apparent, and changes to the problem definition or system components are common. Developing, testing and analyzing the quantitative simulation model happens through frequent dialogue between the research team and participants in the modeling group. As the modeler creates the model, they seek input and approval from the modeling group to refine overall system structure and to ensure necessary data are included. Data may include peer reviewed literature, public or private datasets, and local or expert knowledge. Not every relationship and variable within the system of interest will be captured by the simulation model. The focus of SD model building is to build as simple an explanation for the underlying historic behavior as possible. It is impossible to capture all relationships, but this is often unnecessary for understanding the major endogenous influences of problem behavior. As the model is being built, and before it is finalized, it should go through rigorous testing including structure and parameter confirmation, extreme condition testing, and sensitivity analysis (Forrester, 1980; Sterman, 2000).

For this study, we are using *Stella Architect* software for the simulation model and complementing this with *Miro* as a collaborative space for model development. Once the qualitative CLD is sufficiently complete in the previous step, the draft simulation model will be created in *Stella* (see simplified example in **Figure 3**). This model will be built sector by sector, starting with tigers in farms, then demand (and purchasing) of wild and farmed products, and finally linking to poaching of wild tigers. The model draft goes through a model review exercise (https://en.wikibooks.org/wiki/Scriptapedia/Model_Review), after which it is further refined by the modeler. After initial system structure has been determined, the second-round questionnaire using the Delphi process will ask stakeholders to review summarized feedback from round one and the logical integrity of the model, provide input into model parameters, and share additional relevant data sources. Information collected will then be summarized, shared with participants (in Workshop #3 and through another round of Delphi questionnaires in analysis of policy interventions) and used to revise the initial model presented in Workshop #3. In addition to these activities, one-on-one meetings will take place between the modeler and participants to answer questions as they arise.

Analysis of Policy Interventions

One of the primary benefits of an SD model is that it can be used as an experimental platform to explore and evaluate the potential implications of policy interventions (Stave, 2010; Sterman et al., 2013; Turner, 2020). Once the model has been validated and can approximate historical behavior, policy interventions can be added and a more user-friendly interface can be built to
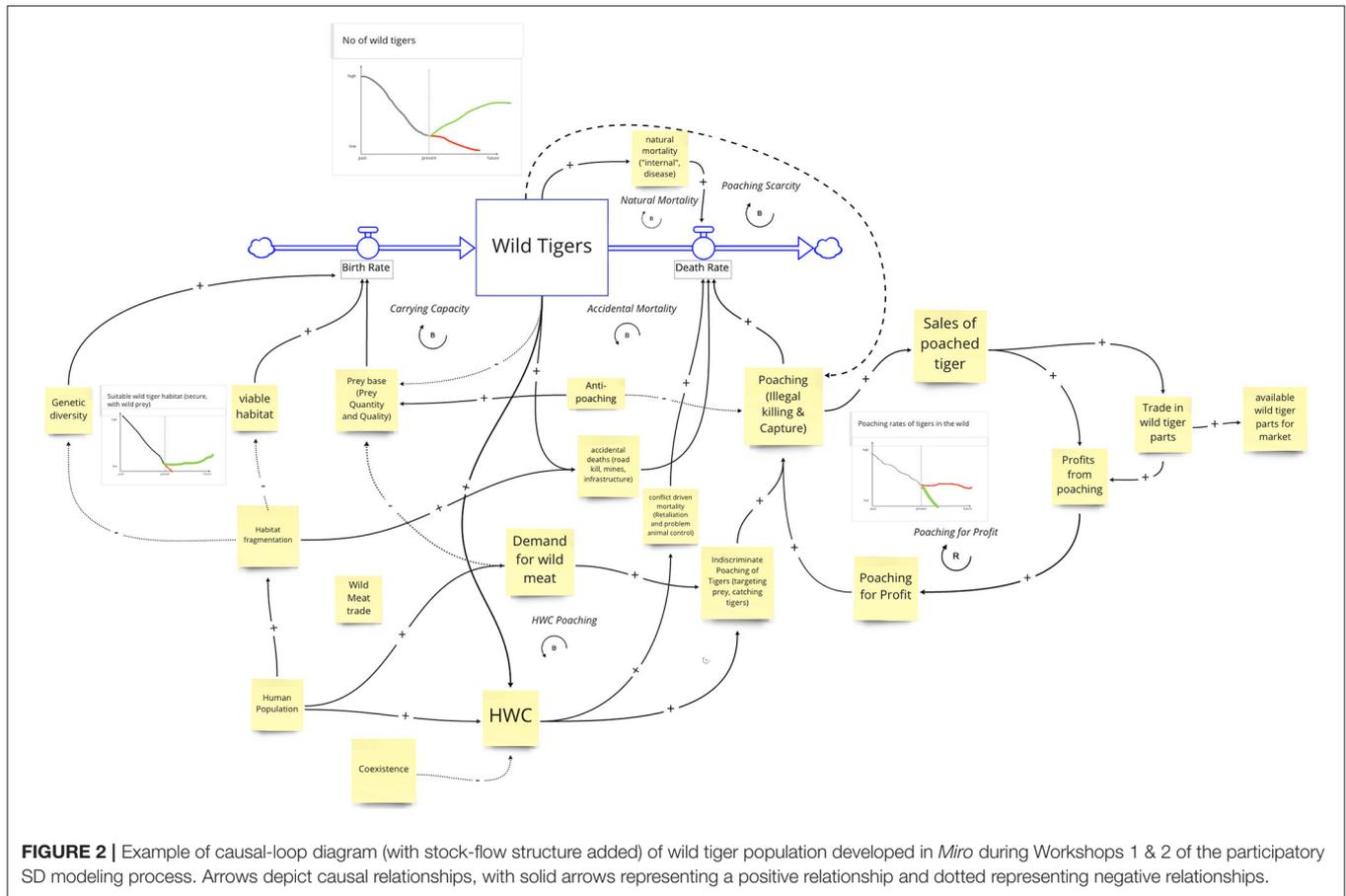
FIGURE 2 | Example of causal-loop diagram (with stock-flow structure added) of wild tiger population developed in *Miro* during Workshops 1 & 2 of the participatory SD modeling process. Arrows depict causal relationships, with solid arrows representing a positive relationship and dotted representing negative relationships.

help stakeholders interact with the model and discern the impacts of various policy options. An example demonstrating the potential of an SD simulation interface is the C-ROADS climate simulation model from Climate Interactive (Sterman et al., 2012; https://www.climateinteractive.org/tools/c-roads/). Stakeholders involved in the participatory SD process choose the policy interventions to be tested, in collaboration with the modeler.

For our case study, the ability to test potential implications of policies related to tiger farms is a main focus. Once the final draft of the model is ready for scrutiny, a final round in the Delphi process will create an opportunity for the full participant group to review summarized results earlier surveys, to provide input into key components and results of the model, and to suggest priority policy interventions. Input from the Delphi questionnaire will be summarized, reported back to the modeling group, and used to add policy interventions into the model. We anticipate this model could provide an opportunity to explore the potential implications of closing or phasing out tiger farms, or tightening restrictions to the trade or sale of tiger parts and products. Once policies and an interactive interface are added, Workshop #4 will give the modeling group an opportunity to test the model and explore the impacts of different scenarios. To mark the end of this stage and the whole process, a full-project presentation will

share SD model results with all participants and provide a forum for reflecting on the process and discussing next steps for policy and practice.

Evaluating the Process, Outputs and Outcomes

A key benefit of participatory SD modeling is its potential impacts on shared knowledge building and social outcomes such as trust, communication, and consensus (Rouwette et al., 2002). Evaluation is necessary to verify outcomes and gather feedback to improve further participatory modeling efforts. Participatory approaches to SD have been evaluated in many cases, generally yielding positive outcomes (Rouwette et al., 2002; Rouwette, 2011; Hovmand et al., 2012; Scott et al., 2016b; Stave et al., 2019). Yet, to determine if the process is achieving desired goals, both output and outcome evaluation are an essential part of any modeling effort.

We are integrating evaluation throughout our modeling process. Following recommendations by Scott et al. (2013) we are employing a pre-post survey model. We adapted survey protocols from literature evaluating other collaborative model-building processes (Rouwette et al., 2007; Scott et al., 2016a, 2017), and we are distributing questionnaires to all groups of participants using *Qualtrics XM* software (https://www.qualtrics.

FIGURE 3 | Hypothetical example of a stock-flow model of wild tiger population dynamics, developed using *Stella Architect* software.
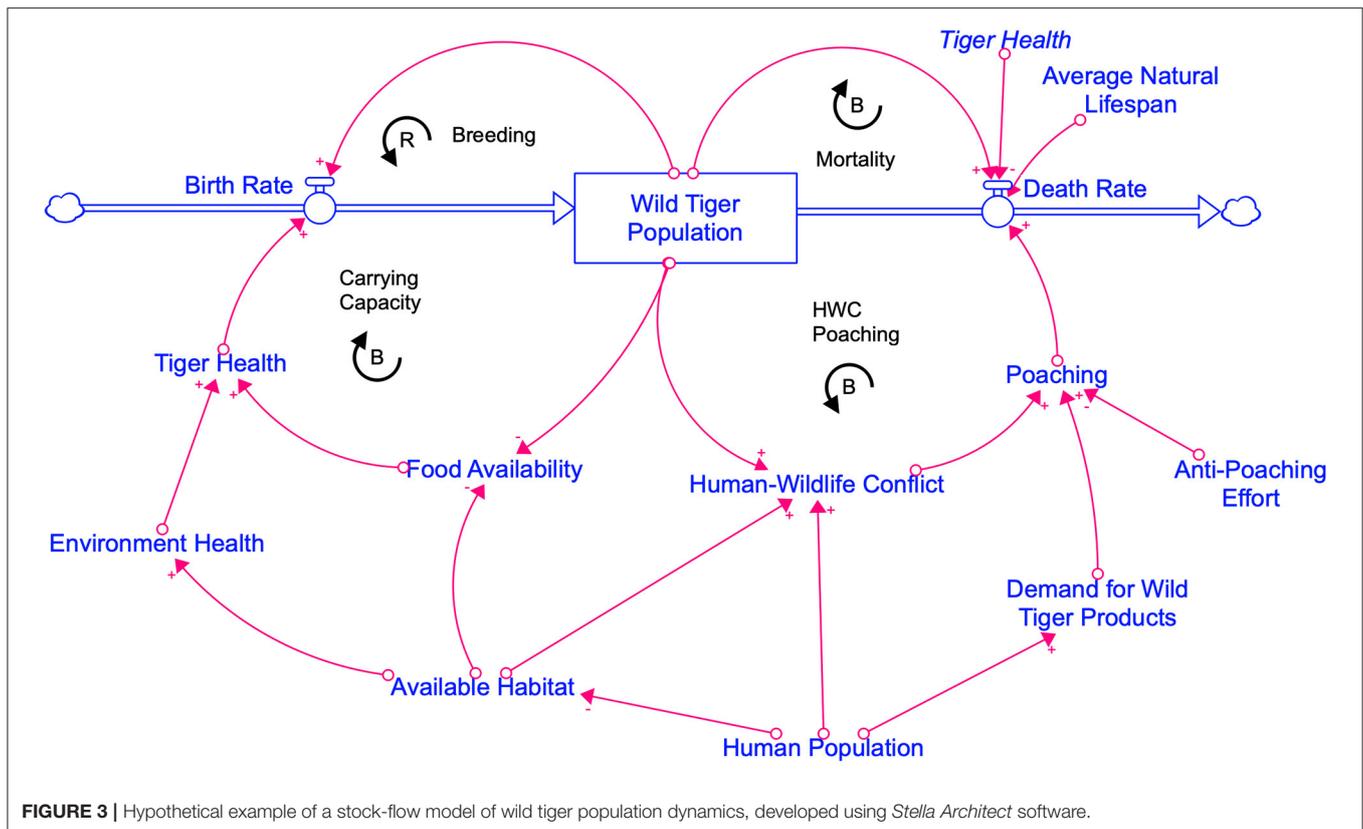
com/). The pre-intervention questionnaire, which doubled as the first round of the Delphi process, included questions about participants' areas of expertise, specific perspectives on tiger conservation and tiger farms, and previous experience with systems thinking (see **Supplemental survey instrument**). We also included questions designed to measure key process outcomes such as knowledge and understanding (Rouwette et al., 2016; Scott et al., 2016a), trust (Stern and Coleman, 2014; Basco-Carrera et al., 2017), and consensus and commitment among conservation practitioners (Rouwette, 2011; Scott et al., 2016b; Basco-Carrera et al., 2017). We aim to integrate a post-intervention questionnaire that allows the research team to measure changes in responses from the beginning to the end of the modeling process. This final questionnaire will include additional questions to gather feedback about understanding of the dynamics in the tiger conservation system (i.e., connections between wild tigers, demand for tiger parts and products, and tiger farming), the utility of the final model, and perspectives on how the process itself influenced perceived outcomes such as knowledge, trust, communication and consensus and commitment (i.e., the same outcomes addressed on the pre-intervention questionnaire). Multiple rounds of Delphi questionnaires integrated throughout the process will help us track the evolution of participants' thinking regarding the problem(s) and the complex system surrounding tiger conservation.

IMPLICATIONS FOR CONSERVATION PRACTICE

Conservation practitioners work in complex social-ecological systems to address threats facing biodiversity, reduce conflict, and promote positive human-wildlife interactions. Inadequate understanding of the direct and indirect, as well as short- and long-term, consequences of decision making within these dynamic systems can lead to misdiagnosed problems and interventions with perverse outcomes, exacerbating conflict (Larrosa et al., 2016; Hübschle, 2017). Participatory SD provides an opportunity to minimize these risks through building a more complete shared understanding of a problem and potential implications of interventions. This is achieved while increasing trust and reducing conflict among stakeholders working to tackle these wicked problems. Once created, a simulation model can also be used as an experimental platform that is almost impossible to replicate *in situ* with threatened ecosystems and endangered species.

The process we have outlined in this paper shows how conservation researchers and practitioners can design and implement participatory SD modeling to address a complex problem such as wild tiger conservation. Throughout our ongoing modeling process, we have confronted conflicting perspectives and worked toward shared understandings of the tiger farming problem and its consequences. Through iterative

meetings and conversations combining science with expert knowledge, we are building trust and fostering productive collaboration. As our simulation model progresses, it should yield insights regarding policy interventions that enhance the value of the process for participants. By strategically dissecting the social and political relationships that fuel many conservation conflicts (Madden and McQuinn, 2014), participatory SD processes like ours may be a key step on the path to sustainable coexistence between humans and tigers.

The participatory SD modeling process does not occur without challenges (Addison et al., 2013; Stave et al., 2019). It requires a large time commitment for both the research team and the modeling group. Our study, for example, will have taken multiple years from the initial advisory group meetings to development of the final policy model. The process at minimum requires a competent modeler and, ideally, a facilitator who has experience with systems modeling. Since participatory SD modeling is not common in the conservation world, there is a learning curve for participants to help them understand where the process is going and how to realize its value. Additionally, with a polarized topic such as tiger conservation, it is challenging to find diverse stakeholders willing to participate. Finally, while SD models provide insights that can help to guide management and policy, key decision makers must be willing and able to utilize these tools to initiate action. Strategies for addressing these potential barriers undoubtedly vary by context, but investments of time and resources into systems-based approaches could ultimately lead to long-term changes the way conservation efforts are conceptualized and carried out.

Despite challenges, enthusiasm with our effort to model the impacts of tiger farming on wild tiger conservation remains high. Some participants may not be able to engage in the whole process, but excitement has grown as conversations delve deeper into complex issues and the practical implications and potential policy impacts of the effort become more apparent. Our approach is showing how systems thinking and systems-based approaches can help to address the complex social, economic, political, and ecological problems that threaten the survival of wild tigers. Application of systems thinking could improve coexistence with other species where contentious policy choices are being critically evaluated, such as elephants (Mahajan et al., 2019), rhinos ('t Sas-Rolfes, 2016), and wild horses (BLM, 2020); it could also facilitate understanding of conservation issues that span multiple species and contexts, such as the substitutability of tiger and lion products across the farmed/wild nexus (Coals

et al., 2020; Rizzolo, 2021). Additionally, SD approaches create unique opportunities to explore the effects of different property rights or management regimes on wildlife (Wilson et al., 2016). Regardless of geography, focal species, or management context, participatory SD modeling could represent a valuable tool in a conservation practitioner's toolbox to address conflict and improve coexistence with wildlife around the world.

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 human participants were reviewed and approved by Institutional Review Board of North Carolina State University (IRB 21209). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcosc.2021.696615/full#supplementary-material

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