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Purpose, processes, partnerships, and products: four Ps to advance participatory socio-environmental modeling

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Abstract. Including stakeholders in environmental model building and analysis is an increasingly popular approach to understanding ecological change. This is because stakeholders often hold valuable knowledge about socio-environmental dynamics and collaborative forms of modeling produce important boundary objects used to collectively reason about environmental problems. Although the number of participatory modeling (PM) case studies and the number of researchers adopting these approaches has grown in recent years, the lack of standardized reporting and limited reproducibility have prevented PM's establishment and advancement as a cohesive field of study. We suggest a four-dimensional framework (4P) that includes reporting on dimensions of (1) the Purpose for selecting a PM approach (the *why*); (2) the Process by which the public was involved in model building or evaluation (the *how*); (3) the Partnerships formed (the *who*); and (4) the Products that resulted from these efforts (the *what*). We highlight four case studies that use common PM software-based approaches (fuzzy cognitive mapping, agent-based modeling, system dynamics, and participatory geospatial modeling) to understand human–environment interactions and the consequences of ecological changes, including bushmeat hunting in Tanzania and Cameroon, agricultural production and deforestation in Zambia, and groundwater management in India. We demonstrate how standardizing communication about PM case studies can lead to innovation and new insights about model-based reasoning in support of ecological policy development. We suggest that our 4P framework and reporting approach provides a way for new hypotheses to be identified and tested in the growing field of PM.

Key words: *agent-based modeling; collaborative modeling; fuzzy cognitive mapping; learning; participatory GIS; participatory modeling; public participation; stakeholder collaboration; system dynamics.*

Introduction

The popularity of participatory modeling (PM) has grown considerably in recent years. It is widely

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acknowledged that the broad inclusion of stakeholders, or who is affected by decisions and actions (Reed et al. 2009) and different scientific perspectives are required to improve our understanding of socioecological systems and current environmental problems. As Voinov and Bousquet (2010:1268) point out, "hardly any environmental assessment or modeling effort today can be presented without some kind of reference to stakeholders and their involvement in the process." Major objectives that drive PM are (1) to increase and share knowledge and understanding of a system and its dynamics under various conditions (Zellner 2008, Lynam et al. 2010) and (2) to identify and examine solutions to a given problem (Simon and Etienne 2010, Zellner and Campbell 2015). Currently, a wide range of stakeholder-centered modeling programs and practices exist, which all aim to provide collective decision support and facilitation in participatory planning contexts. Although the modeling tools and software that are available have increased, some critics have cautioned that diversity of modeling practices does not necessarily indicate diversity in function, as new stakeholder modeling programs are often prone to duplication of effort (Jones et al. 2009, Gray et al. 2015).

Recent reviews of modeling processes and tools have highlighted that community learning, by way of structured knowledge sharing, is the most significant benefit of including stakeholders in modeling (Voinov and Bousquet 2010). However, considerably less attention has been paid to how this structured learning is taken into account in terms of research or defining what decision-making outcomes should be expected (Zellner et al. 2012, Radinsky et al. 2016). As the number of case study applications continues to grow, comprehensive reviews and post-audits of how and when specific approaches or software tools are appropriate will be required if the field is expected to mature. As computational and cyber-enabled participatory approaches become more routine, with growing advances in "crowdsourcing" technology (Gray et al. 2017, Voinov et al. 2016), there are also questions about what conceptual, procedural, and technological designs need to be developed for effective stakeholder participation, enhanced public understanding of socio-environmental dynamics, and clearer recognition of how such understanding connects to environmental and social improvements (e.g., Bourget et al. 2013).

4P Framework for Participatory Modeling

To address these issues, we propose the 4P framework to help design and assess all cases of PM building on recent frameworks identified in the literature that integrate the costs, benefits, and practice of participatory processes (Stern and Dietz 2008, Seidl 2015), reviews of tools and uses of PM (Voinov and Bousquet 2010, Voinov et al. 2016) and recent comparative approaches to assessing the quality and processes associated with the variable application of PM (Hassenforder et al. 2015). Therefore the four Ps cover the following dimensions important both to participatory processes and to modeling practices commonly encountered in PM case studies including: (1) the Purpose for selecting a PM approach (the *why*); (2) the Process by which the public was involved in model building, or evaluation (the *how*); (3) the Partnerships that formed around different parts of the process (the *who*); and (4) the Products resulting from these efforts (the *what)* (Table 1). We illustrate the application of this framework by assessing four PM case studies in Cameroon, Tanzania, Zambia, and India, showing how this reporting approach may help standardize knowledge in the field, and facilitate systematic comparisons among cases and techniques to support reproducibility and hypothesis testing, and thus lead to innovation. Our call for standardization parallels others in a range of modeling fields, particularly in ecology (e.g., the Overview, Design concepts, and Details [ODD] protocol suggested by Grimm et al. [2006] for agent-based modeling).

Purpose

There are two dimensions related to model purpose: (1) to identify why stakeholders are included in the modeling process and (2) to identify the purpose of

Table 1. The 4P framework suggests questions to be asked when participatory modeling (PM) case studies are designed and reported and the types of information that should be included.

Parameter	Question to be addressed	Dimension reported
Purpose	Why was the PM approach selected?	1. Providing justification for why PM is used 2. Defining the issue and the purpose of the model
Processes	How were stakeholders involved?	1. Defining the characteristics of the interaction between the participants and the model. 2. Describing the level of participation. 3. Defining the relationship between the PM and a decision-making process.
Partnership	Who participated and why?	1. Defining model, data, and process ownership. 2. Describing the criteria for inclusion of participants. 3. Describing the steps participants are involved in.
Product	What was produced by the modeling process?	1. Defining characteristics of the PM tool produced. 2. Defining the social outcomes of the process. 3. Defining the policy, management, or scientific insights.

creating the model and what problem the model seeks to address. In other words, why "participatory" and why "modeling"? This information helps to establish the boundaries of the model and the goals of the process. Describing these dimensions in a PM context is similar to other processes such as structured decision making that explicitly define decision-making objectives, address sources of uncertainty, and outline legal and public preferences for the decision context (e.g., Starfield 1997, Runge 2011, Gregory et al. 2012).

Why participatory?.—The field of PM lies at the intersection of participatory approaches to planning, computational modeling, and environmental modeling. Ostensibly, the inclusion of stakeholders provides some unique insight that would otherwise not be available with models constructed by traditional (i.e., scientific) experts alone. From a modeler's perspective, in a PM approach, stakeholder participation may be justified by the need to (1) understand the values and beliefs different stakeholder groups hold in relation to the problem and how modeling can support new understanding (Voinov and Gaddis 2008, Jones et al. 2016); (2) understand how different stakeholder groups believe the system operates and how explicit knowledge representation can support articulation of differences and similarities (Gray et al. 2012); (3) support ethical or normative dimensions of planning and decision making, acknowledging that stakeholders should have a right to participate in decision-making processes that impact them (Stec and Casey-Lefkowitz 2000, National Research Council 2008); (4) understand the social and environmental implications of projected policy or behavioral changes, and for collective visioning (e.g., scenario planning; Zellner and Campbell 2015); (5) support mutual recognition of perceptions and articulate several points of view among participants (such knowledge sharing in a neutral space can reduce power asymmetries and overreliance on technical or scientific experts [Barnaud et al. 2013, Hoch et al. 2015]); (6) develop models that are applicable to stakeholders decision-making context (Henly-Shepard et al. 2015)

From the perspective of the stakeholder participants, the purpose of the PM exercise is typically to gain insight into a problem they care about, so as to better inform individual or collective decision making, or to (1) ensure that their knowledge, needs, and interests are included in social or environmental assessments; (2) better understand a socio-environmental situation; (3) make sure "incorrect" modeled answers are avoided, the models take into consideration key factors that might be overlooked, or key factors that not capable of being modeled are acknowledged; (4) to have a voice and control over the future of the socio-environmental systems they depend on.

These many purposes are not exclusive to one another, but formulating the goals explicitly can provide justification on the unique contribution of a particular PM approach, including the social, political, or scientific benefits that stakeholder involvement brings to the practice of environmental modeling. However, it is important to note that the perspective of adopting a participatory approach may differ among participants, and therefore the expectations of the group should also be included.

Why modeling?.—At its core, PM includes the strengths and weaknesses entailed with creating abstractions of complex reality. Understanding the purpose of a modeling effort helps identify why some aspects of reality are included and others are not (Grimm et al. 2006). Usually, this is determined both by social considerations and by the intrinsic constraints of the modeling approach. Reporting why the model is being developed, and what decision context the model seeks to address, is important. While other standardized modeling reporting approaches have indicated that such information is often provided in background information, a clear, concise, and structured description provides important context for what to expect in model-building processes, including the gathering of empirical or conceptual data and the role of the model in the decision-making context. Most important is that models be used, not as an end in themselves, but rather for decision support through reasoning to thereby improve the societal and environmental outcomes of the decisions ultimately made (Addison et al. 2013).

Processes

PM is inherently an interdisciplinary endeavor seeking to integrate different perspectives, or at times disciplinary understanding, about a problem space into one or multiple shared understandings via the construction of external representations. As such, the processes associated with PM and in our framework align with basic typologies previously identified in the field of interdiscinplinarity, including the scope of interdisciplinarity (i.e., *what* is integrated); the type of interdisciplinary interaction (i.e., *how* it is done); and the type of goals (i.e., *why* interdisciplinarity takes place) (see Huutoniemi et al. 2010). When applied to the processes associated with PM, we therefore suggest the reporting of how and who interacts with each other and the model constructed and report on (1) the interaction between the participants and the model, (2) the level of participation, and (3) the relationship between PM and a decision-making process.

A wide range of PM approaches and tools has been described. For example, Voinov et al. (2016) articulate multiple ways in which individuals, communities, or specific stakeholder groups can interact with model representations or simulations, and also with the gathering of data and model inputs. While the number of modeling studies that are specifically designed around varying degrees of public participation is increasing, the tradeoffs of different kinds of model tools (affordances and constraints) are not well understood. Some studies compare different approaches in specific contexts, e.g., incorporating community values and preferences into natural resource management (Lynam et al. 2007), identifying the general role of participatory system dynamics modeling in landscape planning (Sandker et al. 2010), and examining participatory approaches to resilience assessment in social-ecological systems (Gray et al. 2015). Nevertheless, generalizations about how the participatory process is influenced by tool selection, and vice versa, remains limited.

Previous research has attempted to typify the different ways in which stakeholders can be involved in PM, most often drawing from the public participation in environmental decision-making literature (see Stern and Dietz 2008). For example, drawing from Arnstein's ladder of public participation (Arnstein 1969), Jonsson et al. (2007) suggest that participation can take three main forms: (1) using the model as a boundary object for communication and a way to provide the public with information; (2) using the public as consultants to identify their priorities; or (3) using the public as part of the modeling team, where they are actively involved in model construction. Similarly, drawing on literature that addresses participatory processes (Siebenhüner and Barth 2005, Blackstock et al. 2007), Jones et al. (2009) suggest that PM processes can take three forms: a *normative function*, where the process of evaluating models increases the legitimacy of a decision-making process; a *substantive function*, which provides the synthesis of knowledge from different sources, including from empirical sources, stakeholder sources, and other expert sources; and an *instrumental function* that supports building collaborative relationships between modelers and the public thought to assist with implementation and reducing conflict.

These typologies are developed based on identifying public participation in a spectrum ranging from no involvement in the modeling process to full engagement and ownership. While it has its merits, thinking about public participation as a linear progression may marginalize differences between decision-making contexts, and may inadvertently place higher value on more local and direct forms of participation with a goal of community empowerment. This is not always the goal of PM (see *System dynamics: Sustainable intensification of livelihoods and landscapes in Zambia*). Indeed, there are inherent trade-offs between the degree of possible stakeholder involvement and the complexity of the modeling required (Gray et al. 2015). For example, some qualitative forms of modeling, such as visioning exercises or qualitative or semi-quantitative concept mapping, may provide high degrees of ownership because they are largely constructed based on stakeholder knowledge and require little training and facilitation. However, the post-hoc analytical capabilities and future use of the constructed models may be limited (Gray et al. 2015). Conversely, while more computationally involved approaches like system dynamics models or agent-based models (ABM) may be informed by stakeholders' priorities, parameterized based on stakeholder knowledge/behavior, and used collaboratively to refine collective thinking about the structure and functioning of a complex system (Zellner et al. 2012, Zellner and Campbell 2015), the technical skills and time required in these approaches may present barriers to public ownership, the degree of model transparency, and understanding of model assumptions. Further, the time required for such approaches may not align with the decision timeline of stakeholders or other managers. PM processes, both the selection of the modeling tools and the type of social interaction around them, should therefore be designed based on the problem to be addressed, the type of conceptual or empirical data required to support model-building, and the type of partnership that researchers, decision-makers, and stakeholders have established.

In addition to questions about how different modeling approaches influence PM process, how (and who) facilitates model building is also important. Effective facilitation can structure participation in such a way that everyone has equal opportunity to play their part in the process. For example, some audiences can fully participate in building an ABM through a large-group discussion with simple guiding questions from the facilitator. Other audiences using the same tool may need pairs or small group work to allow everyone's voices to be heard. Franco and Montibeller (2010) outline the particular competencies needed by a model-based facilitator in discerning these needs, which include active listening, chart-writing, managing group and power dynamics, and reaching closure with the appropriate modeling tool. Moreover, it has been suggested that facilitation should go beyond just one meeting and facilitators should consider issues related to timing, power and oppression, regulations, and model sequencing throughout the entire PM engagement process (Robinson 2005). Effective and non-biased facilitation can make the difference between a modeling approach appropriately capturing the full benefit of local expertise, or not, in a particular context and modelers should be aware of these group dynamics prior to initiating PM practices with stakeholders.

Because of the fundamental aim of PM, to provide decision support and facilitation in participatory planning contexts, we argue that to understand and evaluate PM efforts it is key to report *both* the interaction among the participants around modeling, *and* the relationship between the PM process and the decision context. Indeed, such modeling process and engagement steps have been suggested (Voinov and Bousquet 2010, Voinov et al. 2016), building on previous generic models (Alkan-Olsson et al. 2011, Evers et al. 2012). However, these remain largely idealized design features and there is currently little information about how applicable or common these guidelines are in the real world, or how resources, time, and other constraints may influence PM.

Partnerships

In relation to the nature of partnerships that are formed by modelers, other researchers, decision-makers, stakeholders, and/or the public, of particular interest are (1) who is involved in the partnership and who is considered an expert and in what domain; (2) how the partnership was formed and the criteria for inclusion; and (3) at what steps of the modeling and/or decision-making processes include different groups of experts (e.g., local, scientific, etc.).

A number of approaches exist for stakeholder and expert identification and selection (Davis and Wagner 2003). Some of these approaches are more top down, in that who is included is largely determined by the modelers or managers who organize the process. In other approaches, stakeholders themselves help shape the list of participants that are included. In addition, the selection for inclusion can be influenced by existing social networks, as well as the policy and research contexts in which these partnerships are formed. Ultimately, the methods used to identify and involve participants will shape a number of aspects of the PM process, and therefore modelers should be aware of the range of options available, and the trade-offs of each.

Understanding motivations for participation and the partnerships that emerge is critical. It is therefore important to know how stakeholders and researchers expect to benefit from collaborative modeling partnerships. For example, researchers benefit by being able to publish on outcome of the PM process and contribute to the scientific knowledge of modeling in general. They may also obtain new insights from the capture of stakeholder knowledge, or they may appreciate contributing to the resolution of a particular problem. The pace of PM progress, however, may inhibit scientist involvement: working with stakeholders requires patience and a major time commitment to foster necessary relationships. Scientific merit systems to obtain tenure, promotions, or funding grants do not generally consider the time it takes to establish effective participatory methods, or the need to adapt study designs based on stakeholder feedback.

On their part, community participants may seek tangible benefits from PM, from resolution of a problem to financial/social benefits (Hobbs and Meier 2012), including scientific support for decision making. Communities may initially expect PM will result in near-immediate returns, but the PM process may take significantly more time than expected. Community participants may also face engagement fatigue, particularly when multiple projects are undertaken simultaneously or sequentially with a community (Curtis et al. 2014). Additionally, it may be difficult to engage a large working group iteratively over time as a model is developed, calibrated, and tested.

Given the potentially different aims of scientists, decision-makers and community members, the nature of partnerships and identifying the expected benefits that are expected need to be detailed and made explicit at the beginning of the relationship. Trust and credibility are important aspects of the partnership, and therefore clear communication is necessary throughout the partnership. Expectations and communication methods should be reported with detailed conversations between scientists and stakeholders and also after completion of the process when the model or research outputs are reported. Necessary information includes the composition of partnership(s), taking into account participant anonymity as needed, which may improve understanding of some sensitive environmental problems (see Nyaki et al. 2014), as well as scientist and stakeholder incentives to participate. Other key factors may also need to be reported, such as funding sources, research program associations, academic disciplines involved, and connections to real world policy processes, networks, and institutional systems. These are all important for understanding and evaluating PM efforts across different case studies in order maintain high quality and ethical research.

Products

Regardless of the modeling approach used, the outcomes that emerge from a PM process can be identified as (1) model-based products (e.g., maps, system structure, univariate or multivariate scenario output); (2) social outcomes (e.g., individual learning, social learning, social capital, conflict resolution); and/or (3) policy, management, or scientific knowledge (e.g., briefs, reports, or the development of policy options) that capitalize on model-based insights. For each of these product types, it is useful to differentiate between outcomes that relate to a specific place or context (e.g., maps, scenario outputs, and learning) and outcomes of general, or more transferable, character (e.g., model structures, modeling types, PM design features, procedures and insight into model-based reasoning, and data visualizations). These products should be compared to the initial purpose of the modeling activity to determine if the goals of PM were achieved.

While explicit reporting of products other than the models remains sparse in the literature, some researchers have begun to report on additional outcomes, including the number of "decision variables" and "decision criteria" in the model, how framing influences outcomes (Stirling 2006) as well as the degree of stakeholder frustration (Stave 2010). Social outcomes that have been reported include advances in individual insight, interest in and understanding of model structure, policy agreement, increases in group communication, increased engagement, and social learning (Stave 2010, Zellner et al. 2012, Hoch et al. 2015, Gray et al. 2017).

Another important outcome of PM is individual and collective learning and a level of systems thinking that can aid both knowledge synthesis (e.g., scientific and local expertise) and decision making (e.g., the development of policies or selection of management objectives). Understanding the impacts of social and environmental change and their implications for decision making requires systematic reasoning about systems (Maani and Maharaj 2001). Complex systems in particular are dynamic and multi-leveled, have emergent properties, and are the reason why the most pressing social and environmental problems persist (e.g., Grotzer and Perkins 2000, Zellner and Campbell 2015). There is extensive complex-systems-learning literature that shows how models may encourage expert and novice users to move from static to dynamic thinking (Leischow and Milstein 2006). Additionally, the practice of model-building encourages the user to explicitly formalize relationships, processes, and assumptions derived from both data and experience, which can help identify gaps in knowledge (Zellner 2008). Furthermore, modeling helps users to work through plausible mechanisms and outcomes, focusing on the proximate causes and consequences of environmental problems (Jordan et al. 2014, Gray et al. 2017), thus supporting discourse and the decision-making process, and helping to overcome some of the cognitive limitations (see Glynn et al. 2017) that complex problems present (Sterman 2008). Also, in some types of modeling the stakeholders are encouraged to substantiate their qualitative ideas and mental models with data (Gray et al. 2017). Finally, the act of modeling can be a venue for users to develop confidence and agency in the process (Jordan et al. 2016), which is critical for future participation. By building the systems thinking capacity of participants, model-based reasoning provides the foundation for multiple social outcomes in addition to the model that is produced. These dimensions are rarely captured when case studies are summarized in the literature.

Application of the 4P Framework

To demonstrate how such formalized reporting can increase understanding and support innovation and reproducibility across PM application and tools, we use the 4P framework to describe the purpose, process, partnerships, and products in four diverse case studies, each using different modeling approaches, including fuzzy cognitive mapping (FCM), agent-based modeling (ABM), system dynamics modeling, and participatory geographic information system (P-GIS) (Table 2). References to software packages and data files for projects are *available online* .[18]

Fuzzy cognitive mapping: Wildlife conservation and bushmeat hunting in Tanzania

Purpose.—The purpose of this PM study was to understand the social and ecological drivers of the zebra and wildebeest bushmeat trade from the perspectives of Tanzanian bushmeat hunters, bushmeat sellers, and bushmeat consumers who reside in communities adjacent to an international protected area, the Serengeti National Park. Although several conservation programs have been initiated by international nongovernment organizations (NGOs) and government agencies to decrease illegal hunting in the area (Nyaki et al. 2014), the variable success of these programs prompted park officials and researchers to compare assumptions about the drivers of the bushmeat trade between current conservation policies and community-based perspectives. The purpose of the study was to identify structural characteristics of the issue based on local knowledge, including the identification of specific social and ecological variables comprising the system and networked relationships between these variables. Fuzzy cognitive mapping (FCM) was used because the approach is flexible and can be undertaken with little formalized training and minimal instruction. FCM was also used to standardize community-based models via concept mapping so that the perceived dynamics of the bushmeat trade could be compared across groups and also compared to policy assumptions. The study was largely exploratory and meant to inform conservation policies in the region with park managers and NGO partners.

Process.—The process of model-building was led by an independent local facilitator who lived in a nearby community. Nine workshops were held with 127 individuals over a 2-month period. The number of attendees at each workshop ranged from 9 to 27. Workshops lasted from 4 to 6 h each. During workshops, the modeling activity began with introducing participants to the method with an unrelated example FCM. Participants then brainstormed about concepts that were related to zebra and wildebeest hunting and the relationships (either positive or negative) and degrees of influence (high, medium, or low) between the variables were defined. Identification of concepts was unstandardized (see Gray et al. 2014), with the exception of the three concepts of hunting, and wildebeest and zebra populations.

Partnership.—Participation in the project was advertised through a local NGO. Participants were domain experts who were nominated by a larger group of community residents. Participants were not paid for their participation; instead, the research team motivated participation by explaining that the effort was designed to capture and communicate the community perspective to protected area managers and NGOs in charge of conservation programs in the region. Stakeholders were enthusiastic about being able to articulate a model that was intended to inform future policies. Furthermore, because the modeling activity included no personal identifying information from any individual who participated, stakeholders freely provided information without fear of retribution for illegal hunting, which has been identified as an issue in household surveys used to collect data on bushmeat hunting (Nuno et al. 2013). After models from each group were collected, workshop participants discussed new bushmeat management policies (Gray et al. 2015), but the research team took ownership over the models to compare them for recurring concepts to be communicated to park officials, NGOs, and academic audiences in a peer-reviewed manuscript (see Nyaki et al. 2014 and Gray et al. 2015) and other reports but

[18] https://www.participatorymodeling.org/projects

TABLE 2. 4P Framework applied to PM case studies.

Factor	FCM in Tanzania	ABM in Cameroon	System dynamics in Zambia	P-GIS in India
Purpose				
Why participatory	collect local knowledge	collect local knowledge; raise local awareness of hunting sustainability; support community-based hunting management	collect local knowledge to parameterize the model	inform and empower local decision-making
Why model	understand social and ecological drivers of the bushmeat trade; compare with current policy assumptions	assess the impact of traditional bushmeat hunting on game survival; collectively explore the effects of protected areas or no hunting periods	test alternative hypotheses about how USAID's investments may/not counteract each other	identify causes of groundwater shortage and solutions to address it
Processes				
Participants model interaction	local facilitator; nine workshops over 2 months; concepts mostly unstandardized	three steps with increasingly realistic models	researchers facilitated four workshops over 14 months; two workshops created CLDs; one workshop parameterized model; one demonstrated model and solicited policy ideas	researcher/local facilitated series of meetings; sketched area over time; transect walks with GPS/GIS units; GIS maps discussed in focus groups; plans made to improve system
Level of participation	helped construct model; substantive function	helped construct model; substantive function	helped construct and interpret model; substantive function	helped collect data and construct model; model used as artifact; normative, substantive, and instrumental functions
Model decision relationship	compare to existing policy assumptions	testing community-based hunting rules	testing policy scenarios	testing water usage scenarios
Partnerships				
Model/process ownership	research team owned	copy given to the villagers; however ability to modify model stays with research team	copy given to USAID; however ability to modify model stays with research team	participant owned; shared only the results with outsiders
Participant selection process	advertised through local NGO; larger group of residents selected participants; no paid incentives	any villager was welcome to workshop; 65 male hunters were monitored	USAID recruited stakeholders; all participants were professionals	researchers selected stratified sample; local school children helped with transect walks and GIS maps
Products				
The PM tool	nine group FCMs	one ABM	one SD model	one simplified water accounting and cropping model; several GIS maps of wells and crops, one for each decade since the 1970s
Model use and sharing	model not shared	participants started brainstorming management scenarios based on model	copy given to USAID with a brief training; policy scenarios tested two peer-reviewed articles	tested policy scenarios; chose policy; used model to monitor policy implementation one conference presentation
Social outcomes	participants enjoyed it	participants enjoyed it; critical thinking and learning group problem solving	stakeholders expressed appreciation	social learning about system's drivers; implemented and monitored policy plans
Policy/ management insights	cultural factors and confusing hunting rules were key drivers; system more complex than assumed.	from skepticism about risk of extinction, to acknowledgement of overhunting problem; community-based rules	conservation agriculture does not promote landscape-scale forest conservation	need to limit groundwater exploitation

Note: CLD, causal loop diagram.

the information was not shared back with the stakeholders who constructed the model given funding and travel resource constraints.

Products.—Nine FCM-based models of the bushmeat trade were produced in the effort, one from each of the workshops held in the area. These models included, on average, 36 variables and 90 connections, and identified the drivers of the issue and the most central variables using network centrality metrics. In terms of social outputs, the research team and park officials learned that the drivers and central variables involved in the bushmeat trade were more complex than the assumptions that underlie current conservation policies in the region (see, for example, Fig. 1). Locally relevant results indicated that cultural factors and confusing legal hunting policies contributed significantly to the bushmeat trade, in addition to known factors such as income generation and food security. Other conclusions more generally applicable to PM contexts included the finding that an anonymous knowledge sharing and modeling approach may generate more detailed data about illicit behaviors in sensitive conservation contexts such as the bushmeat trade.

Agent-based modeling: Interactive simulations to codesign with villagers an agent-based model of bushmeat hunting in Cameroon

Purpose.—A companion modeling process (Barreteau et al. 2003) was conducted to assess the impacts of hunting activities in the region of the Korup National Park (southwest Cameroon). Bushmeat hunting in African tropical forests is an essential survival means for rural populations. At the same time, the hunting, which is primarily done using snare traps, is relatively unselective, affects many different wildlife species, and consequently negatively impacts biodiversity.

Computational models of socio-environmental systems can use concepts, terms of relationship that are not meaningful to the local stakeholders whose behavior is being modeled (Sterling et al., *unpublished manuscript*). Furthermore, regional population dynamics models used to determine sustainable hunting pressures may not include information meaningful to resource users at the local scale. Yet, for the same general level of hunting pressure, the system "hunter–animal–hunting territory" can be sustainable or not depending on the spatial and temporal distribution of hunting and of hunted individuals (Van Vliet and Nasi 2008). Therefore this study adopted PM to develop spatially explicit individual-based models to investigate the sustainability of bushmeat hunting parameterized using information from a combination of stakeholders and scientific experts.

An agent-based model (ABM) was co-designed and used with local populations to raise their awareness about the sustainability of bushmeat hunting activities. It focuses on the population of blue duikers (*Cephalophus monticola*), a common game antelope in Cameroon, considered as an important bioindicator species. The purpose of designing and using an ABM with villagers

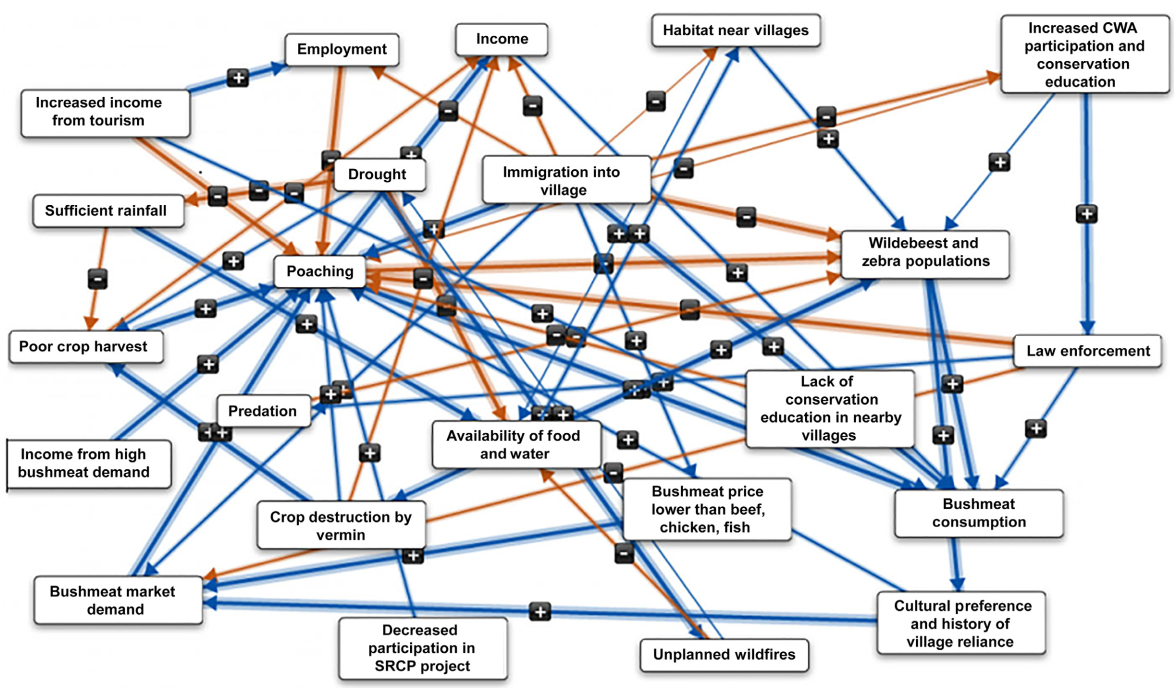


Fig. 1. Example cognitive map of the bushmeat trade and its drivers, produced at a workshop. "CWA" stands for "Community Wildlife Area" and SRCP is an NGO conservation program. Blue lines/arrows with + signs indicate a positive relationship; red lines/arrows with – signs indicate a negative relationship. [Color figure can be viewed at wileyonlinelibrary.com]

was to turn the question of bushmeat hunting sustainability into a matter of common concern at a sub-regional scale (a group of seven villages) and to stimulate villagers to engage in community-based hunting management. General objectives were to promote non-judgmental, non-directive public discussion and reflection, and to collectively envision possible management options for the sustainability of blue duikers hunting. The specific objective of the PM workshops was to share information on the biology and behavior of blue duikers in a non-hunted habitat; the potential impact of snare-trap hunting on the blue duiker population; the elicitation and specification of hunting practices through collective discussions during the presentation of the computer simulation model; the feasibility and potential impact of different hunting management rules.

Process: A step-by-step interactive design of the ABM.— Village meetings were structured in three successive steps. During the first step, an abstract representation of a village surrounded by a portion of forest was co-designed by directly manipulating the computer interface displaying a spatial grid. The model used the Cormas software (*available online*),[19] which enables various types of interactions with users (see Bommel et al. 2015). Then, knowledge about the life-cycle and behavior of blue duikers was shared through the demonstration of the individual-based population dynamics module of the ABM (previously constructed by biologists on the project). This first step was meant to illustrate a basic model to the villagers and to progressively engage them in further collaborative and interactive design, particularly for the development of the hunting module in the second step of the meetings. This second step elicited snare-trapping practices through interactive simulations, and calibrated the hunting module by setting a value for the probability of a blue duiker being caught by a snare trap. In a third step, a more realistic version of the ABM was introduced. The seven villages included in the process were located in the GIS-based spatial representation, and the number of "hunter" agents for each village in the ABM was set according to the results of a survey. The demonstration of this more realistic version triggered discussion about possible management scenarios. The modeling results of those scenarios, obtained with a final version of the ABM, were discussed during later village meetings (Fig. 2).

Partnership.—The project's team was mainly composed of a wildlife biologist from the University of Dschang (Cameroon; who also played the role of facilitator), and an ABM modeler from Cirad (France). They constructed the first version of the individual-based module for the blue duikers. A total of 187 hunters were identified in the study area and 65 (35%) of them were monitored for hunting behaviors. While farming remains the main activity, hunting is performed by male villagers (from 15 to 60 yr old) mainly during the wet season: on average a trapper sets around 100 snares.

Three workshops were organized in three villages: Abat, Mgbegati, and Bakut. Four other communities were also involved in the three workshops. Any villager interested in attending the workshop was welcome. Participants were from 60 to 80 people and demographically diverse (male hunters, but also women, children, and the elderly). The three workshops all started in early afternoon and lasted over three hours. Just before and just after the interactive demonstration of the ABM, a total of 42 participants (most of them belonging to the group of 65 hunters whose activity was previously monitored) were asked a short list of questions, to assess the effects of attending the workshops.

Products.—In the three workshops, the participants reacted positively. The reality and the magnitude of the overhunting problem were acknowledged by a large majority of participants. Before the workshops, 20 out of the 42 interviewed participants expressed skepticism about the risk of extinction of the blue duiker population in the region. After the workshops, this number fell to nine. Education and raising awareness were stressed by some other participants as being crucial. They argued that the population should be made aware of the long-term dangers of over-hunting and that youths should be better educated in agriculture, forest sciences, and biodiversity conservation. Survey measurements also indicated that a significant number of people experienced measurable learning gains about the biology and the ethology of the blue duiker; 15 people improved their understanding about the longevity of the species, and 11 people improved their understanding about its territoriality.

In terms of using the model, 37 out of the 42 interviewed participants declared that they enjoyed its demonstration, three found it difficult to follow and understand, and 36 felt that it was a fair representation of reality (Ngahane 2013). Thirty-seven interviewed participants volunteered to be involved in the next stages of the process. By the end of the first workshops, the participants had already started to discuss additional possible scenarios to be tested with the ABM. Three main management options were discussed, including (1) restriction of foreign hunters, (2) reducing the number of snares per hunter, and (3) the establishment of a reserve zone. Thus the primary output of the model provided a learning context for critical thinking and sparking creativity, and identifying and clarifying the impacts of potential solutions to a given problem.

In terms of general conclusions, there is still a gap from the post-model debriefing discussions to the formulation of decision-making outcomes. The level of abstraction required by explaining generalities is high for participants, who tend to focus on their peculiar situation. As an individual, it may be difficult to think in terms of behaviors representative of a group of individuals. The approach advocates for the early and interactive use of a

[19] http://cormas.cirad.fr

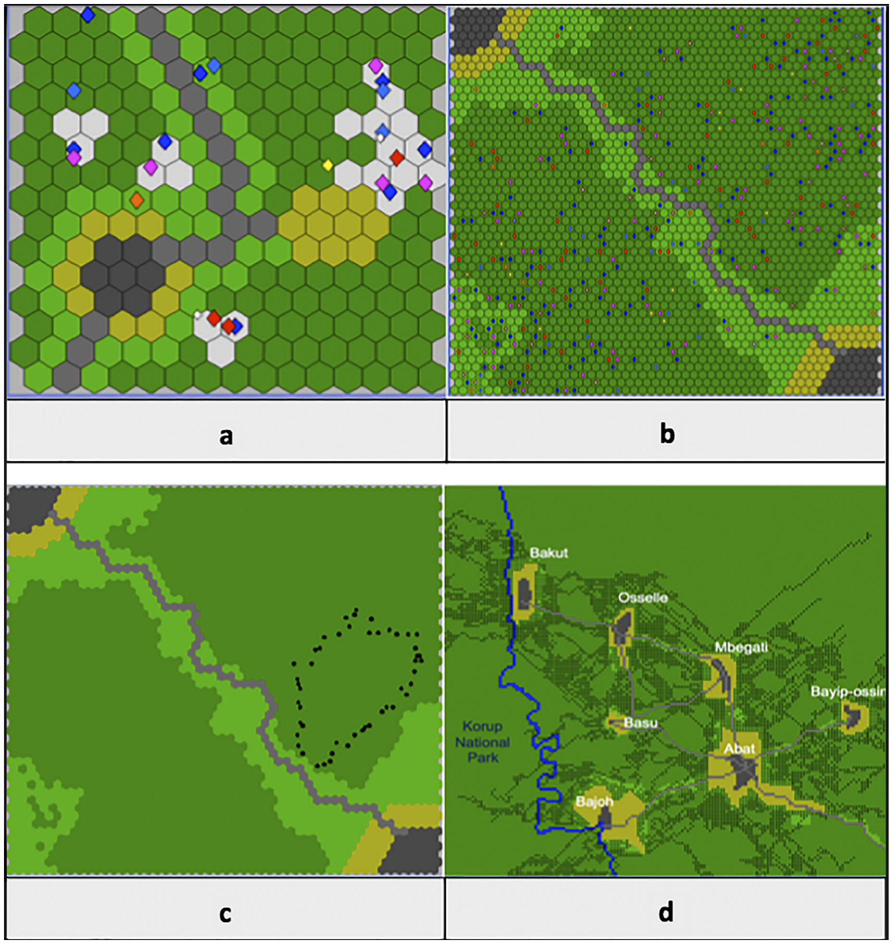


FIG. 2. The whole portion of space represented in the model was gradually expanded, from (a) 1.5 × 1.5 km^2 to (b and c) 5 × 5 km^2 in the second step, to (d) 16 × 18 km^2. In panel a, a schematic representation of a village crossed by a road and surrounded by agricultural fields in a forest, the various stages of antelope agents are displayed (gravid females in pink, females in red, males in dark blue). When a couple of adults have mated, they establish a 3-ha territory (three light gray cells) and exclude other adult antelopes from settling and reproducing there. (b) The spatial representation is zoomed out to display two villages connected by a road. In the forest, a population of antelope agents is created with a local density proportional to the distance to the nearest village. (c) Results of a trap-path set interactively by a participant. (d) An explicit representation of the seven villages and the northern periphery of the Korup National Park, Cameroon. [Color figure can be viewed at wileyonlinelibrary.com]

stylized scale model as an intermediate object to facilitate this activity with local stakeholders.

Further references are available in Le Page et al. (2015). The computer code and the full documentation (including ODD) are available from the CoMSES Net Computational Model Library.

System dynamics: Sustainable intensification of livelihoods and landscapes in Zambia

Purpose.—The United States Agency for International Development (USAID) is currently making investments in Zambia to foster progress in both conservation agriculture and biodiversity conservation. Conservation agriculture is a set of practices intended to benefit small farms and reduce their environmental impacts, typically through minimal tillage and agroforestry practices. USAID commissioned a research team, led by an ecological economist and a system dynamics modeler, to understand how both conservation objectives might support or counteract each other. For example, farms experiencing greater productivity through conservation agriculture might forego cutting down forested land, because their productivity is sufficient to their household needs. Alternatively, higher yields might provide motivation to expand their farms into critical wildlife habitats. USAID wanted to investigate these alternative hypotheses, and was interested in integrated program recommendations that might be supported by Zambian stakeholder partners. In this study, a system dynamics PM process was used to address these two objectives.

Process.—Four stakeholder-modeling workshops, facilitated by the research team, were conducted sequentially in Zambia over the course of 14 months. The workshops were co-facilitated by the project lead (an economist with extensive personal and professional connections in Zambia), and by the lead modeler for the project. The research team consulted with key stakeholders as needed between workshops. A total of 50–60 people participated in at least one of the workshops, and five or six people participated in all of the workshops. The first two workshops were dedicated to stakeholder construction of a causal loop diagram (CLD) around the key problems they (or their organizations) dealt with at the environment–agriculture–livelihood nexus. The CLDs were synthesized into one overall diagram by the research team, which formed the basis for the system dynamics (SD) model (Fig. 3). The third stakeholder workshop took place after the SD model had been parameterized by the research team and could be simulated. Stakeholders gave feedback on the model structure and parameters, and the model was updated accordingly. After corrections were made, the model was demonstrated for key stakeholders who had been unable to attend the third workshop (e.g., a wildlife biologist and a traditional leader in charge of land allocation decisions), and their input was sought. The fourth workshop initiated construction of the semi-final version of the model (with an associated manual) and solicited ideas for scenario building and policy interventions from stakeholders that could be tested with the SD model. Minor corrections were made, and a copy of the model was available for interested stakeholders after a brief (3-h) training session.

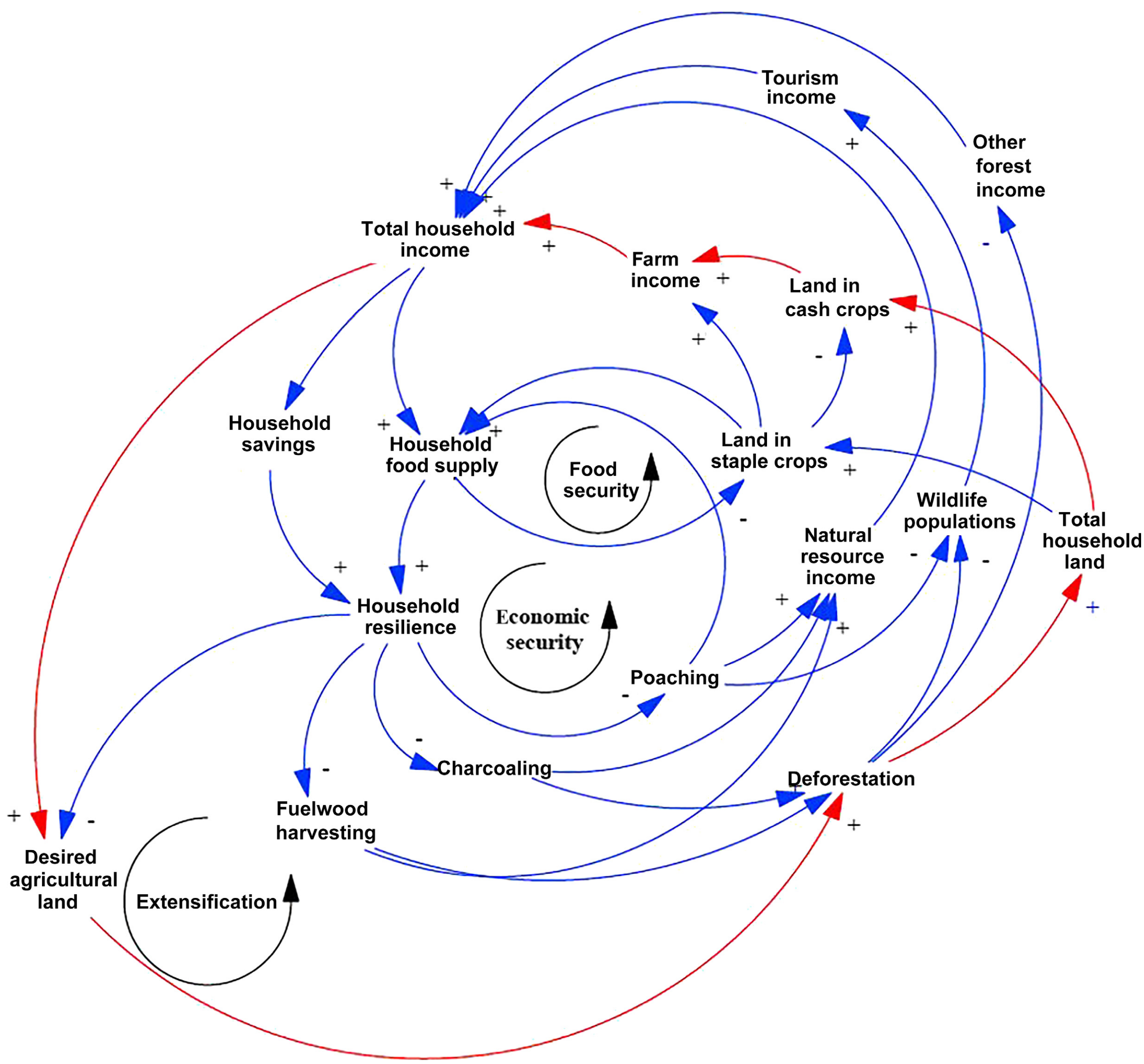


Fig. 3. Causal loop diagram generated by participants at the first workshop in Zambia. This diagram and others like it formed the basis of the system dynamics model. The plus signs indicate a direct relationship between variables, while the minus signs indicate an inverse relationship. Feedback loops (causal loops) are named and labeled with circular arrows. The extensification feedback loop (depicting how land use affects household income) consists of the red arrows; the food and economic security feedback loops are represented with blue arrows. [Color figure can be viewed at wileyonlinelibrary.com]

Partnership.—The convenor of the process was the USAID Zambia mission, which took charge of recruiting their in-country stakeholders to the workshops. Workshop participants included Zambian government officials, scientists, and representatives from the private sector, and from a wide range of international and local non-governmental organizations. Representatives from the Washington, D.C., USA office of USAID were also present at the first two workshops.

USAID Zambia's role as a convenor gave the participatory nature of the project significant weight. Many organizations and individuals whose work was funded or supported by the mission felt highly motivated to attend and participate. To the mission's credit, they actively sought representation from groups with opposing views; for example, one NGO promoted conservation agriculture in ecologically sensitive areas, while several others opposed this practice. All participants agreed that women were not well represented at the workshops, given their important role in charcoal production. The modeling team sought to address this by conducting interviews with female farmers and charcoal producers during the model-building phase of the project.

Products.—Products included

1. A report with policy recommendations for USAID. No evidence was found that conservation agriculture either promoted or impeded biodiversity conservation; instead, charcoal production is the major threat to forest habitat.
2. The SD model itself, a quantitative system dynamics model created on Vensim software (Vensim publisher: Ventana Systems, Inc), a copy of which was delivered to the USAID Zambia mission after a short training session in how to run different scenarios using the model.
3. Two peer-reviewed journal articles (in progress).

USAID expressed great interest in the PM approach, and there is possible follow up to use participatory system dynamics modeling in other countries. Stakeholder participants also gave feedback reflecting an appreciation for the process and an interest in learning from the different perspectives represented in the workshops.

Participatory GIS: Groundwater crisis and participatory water accounting in an Indian village

Purpose.—Several upland villages in India are suffering from acute groundwater depletion that has resulted in collapse of the agricultural economy and distress migration to urban areas. Farm owners and workers believe that it is due to a lack of rainfall and that nothing can be done. A PM study of an affected village was conducted to enable stakeholders to identify the true causes of their groundwater crisis and to devise specific sustainable solutions to their problem. Participatory GIS (P-GIS) was used to map the evolution of wells and farms, and their water and crop yields, over time. The maps helped stakeholders visualize and understand water accounting issues better and helped them build models.

Process.—One of the authors of the present paper had settled in the affected village and was the primary facilitator for the P-GIS effort (Kolagani and Ramu 2016). In total, 14 participatory water accounting and modeling exercises using GIS maps were carried out over two years. Initially, participatory mapping using a blackboard as a representation medium that stakeholders were comfortable with was conducted with 30 stakeholders, selected using stratified sampling from each category of farm stakeholders. Rough maps of wells and farms and their water and crop yields were created for different decades using stakeholder recollections. Transect walks were then done with some of the stakeholders to collect data about each well and farm using a mobile based global positioning system (GPS)/GIS application. Accurate location data, detailed questionnaire-based attribute data, audio interviews, and photographs were collected. Such walks to actual locations with groups of stakeholders were preferred to individual interviews as they made it easier for them to recollect and provide data and cross-verify it among themselves. Accurate GIS maps of wells and farms showing their evolution over time were prepared by some of the stakeholders using a custom Quantum GIS plug-in (Piotr Pociask, GIS Support sp. z o. o. see http://www.qgis.org/en/site/). These GIS maps were used during focus group discussions with stakeholders to carry out the participatory water accounting and modeling exercise. Again, individual interviews were less preferred to such group discussions to facilitate cross-validation and to improve trust in the resulting model. Recharge of groundwater aquifers due to rainfall, and discharge of water from wells to farms for crop irrigation, were calculated over time and a time-dependent model for groundwater use was built. Using this model, stakeholders planned, analyzed, and discussed alternative solutions, such as the linkage of well conduits into a village-wide grid for sharing/selling water, returning to traditional cropping patterns or traditions, etc. Various funding agencies were approached with some of these plans, and a few of them were implemented. Their implementation was regularly monitored by the stakeholders using P-GIS.

Partnership.—All farm owners and workers in the study village were invited to these exercises. Out of about 240 such households in the village, members of about 30 households participated in the exercises. Care was taken to ensure that households from all socioeconomic strata participated. This was not easy as members from lower strata tended to be diffident about participating as equals in these exercises with members from the middle and upper strata. The fact that the facilitator had a long-term association with them helped in these efforts. During transect walks for collecting data about wells and farms, farmers and farm workers provided information and guidance, while youth and school children from the households provided technical help in using the mobile-based GPS/GIS application. High school children participated in preparing GIS maps of wells and farms using a custom Quantum GIS plug-in.

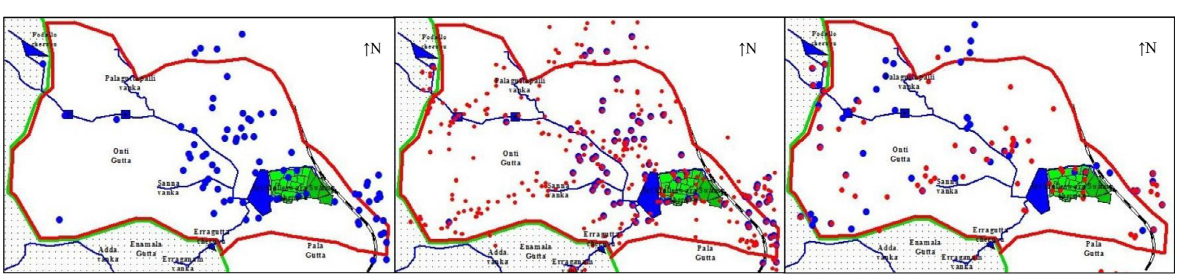
Products.—A simple numerical model was built, based on detailed calculations estimating groundwater recharge and well discharge, to help understand the causes responsible for the groundwater depletion. The participatory modeling helped stakeholders understand that reduced rainfall, which they do not have control over, was just one of the causes, and that a more important cause was their own over-exploitation of groundwater reserves (Fig. 4). This led to discussions about the need to limit water exploitation at sustainable levels, while seeking reasonable economic returns from agriculture. They used the model to analyze different scenarios such as linking well conduits into a village water network, and returning to traditional cropping patterns, with the objective of devising economically and ecologically sustainable plans. Some of these plans were implemented immediately, and others are being followed up with various funding agencies.

4P Framework Analysis for the Four Case Studies

The case studies presented here using the 4P framework provide insights into similarities and differences for the four projects, and can help draw some general conclusions about PM. For example, three of the four studies (Tanzania, Cameroon, and India) used PM to generate stakeholder discussions about potential policy options for resource conservation issues. While the Zambia case study did not use the PM process to foster policy discussions explicitly with stakeholders, the model results were used by funding agencies to reason about their agricultural development interventions. This was also the case in the Tanzania study. Thus, all PM applications, regardless of tools used or problems addressed, were used to collaboratively develop greater understanding of the complexity of a problem or issue. Some studies placed more emphasis on model-based reasoning with government agencies or NGOs active in the region, while others focused primarily on the model as a boundary object with stakeholders. All studies, however, focused on both to some degree and while three studies served the substantive function of integrating knowledge resources, only the India case study served a normative and instrumental function. Although model-based reasoning was at the center of all case studies presented here, only the Cameroon case study formally evaluated stakeholder learning through surveys and exit interviews. Indeed, although recent reviews have indicated that learning is a core benefit of PM (Voinov and Bousquet 2010), which is also supported by the studies presented here, formal evaluations of learning among researchers, managers, and stakeholders involved remains extremely limited (Gray et al. 2017).

Other similarities among the case studies include the number of core participants involved in the process, generally less than 50 but with total participants sometimes over 100. However, the number of participants was modulated by the frequency and extent of participation. Three of the case studies involved multiple interactions with stakeholders, and only two (Cameroon and India) had considerable repeated interactions with a smaller group of the same stakeholders. The degree and type of interactions between modelers and stakeholders is expected to influence the degree of learning and types of decision outcomes; understanding how the nature of participation influences social outcomes is an important area for future research. Finally, none of the three case studies, to date, evaluated the outcome of a specific policy decision engendered by the modeling and learning process after the PM process was complete. This is not surprising given the various time and other resource constraints of federal or internationally funded research projects. However, evaluating the quality of decision making and the gathering of data that characterize empirically based outcomes that are generated as a result from PM, and examining their integration into revised planning models, should clearly be prioritized in future PM efforts.

Another similarity between the four studies is that stakeholder or scientist biases and values were elicited only implicitly. Recognizing the role that biases, beliefs, heuristics, and values (BBHV) play in the participatory



a b c

Fig. 4. Final model products. Blue dots represent shallow open wells and red dots represent deep tube wells. The number of working wells increased drastically from (a) 76 open wells until the 1970s to (b) 198 open and tube wells during the 1980s and 1990s, only to collapse back to (c) 59 open and tube wells after 2001. [Color figure can be viewed at wileyonlinelibrary.com]

modeling process, has been an area of focus recent papers (e.g., Glynn 2014, 2015, Hämäläinen 2015, Voinov et al. 2016). The construction of models by itself can sometimes help in bringing out preconceptions resulting from participant BBHV. Structured decision making (Gregory et al. 2012) and the Delphi method (Linstone and Turoff 1975, Hilbert et al. 2009) can also help identify and account for individual or group biases. Other techniques, such as a four-point elicitation process, can also help improve expert predictions (Speirs-Bridge et al. 2010). However, recognizing, and taking steps to mitigate, inherent BBHV that commonly affect the judgement of all participants/experts, at both the individual and the group level, is difficult. Indeed, the PM studies investigated here depended primarily on the collective knowledge brought about by the participant-accepted use of empirical data, numerical models, and maps. These PM tools were thought to help participants transition from individual-level considerations and thinking to broader community-level considerations and planning, but the reporting on these case studies indicated that changes in individual or collective reasoning remain untested hypotheses.

Conclusions

Formalizing the reporting of participatory modeling projects using the 4P framework is a means of facilitating communication between modelers using different tools to engage different communities facing decision-making challenges that are generally unique, but which sometimes have useful similarities. Until recently, insights from PM have tended to be segregated into different tool-based disciplines or outlets, although useful synthesis that provide more insight into the PM toolbox are beginning to emerge (see Mallampalli et al. 2016). For example, advances in system dynamics modeling are not usually published in the same journals as agent-based modeling studies. This is unfortunate and a loss, since many lessons learned from using one approach could be relevant to the other approaches, particularly in terms of understanding how PM fosters different processes and partnerships, which in turn affect outcomes that can be expected. Further comparison of different PM approaches would also produce more detailed understanding of what motivates stakeholder participation, in both the short and long term, with particular emphasis applied to understanding the value (or lack thereof) participants obtain from participation, and how collaborative model building and model-based reasoning can result in social or environmental improvements.

Applying a 4P framework could allow modelers to use insights from other modeling studies to improve their own participatory modeling work. Moreover, these types of comparisons across modeling approaches might reveal when one type of tool is more appropriate than another, for example, the *Process* section should clearly indicate how many participants the modeling approach can accommodate without incurring diminishing returns. Additionally, the use of a formal reporting framework such as 4P may help structure the creation and use of PM databases that could be consulted for comparative use and advancement of the PM and its applications in policy making and community learning.

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