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Article

Studying, Teaching and Applying Sustainability Visions Using Systems Modeling

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Abstract: The objective of articulating sustainability visions through modeling is to enhance the outcomes and process of visioning in order to successfully move the system toward a desired state. Models emphasize approaches to develop visions that are viable and resilient and are crafted to adhere to sustainability principles. This approach is largely assembled from visioning processes (resulting in descriptions of desirable future states generated from stakeholder values and preferences) and participatory modeling processes (resulting in systems-based representations of future states co-produced by experts and stakeholders). Vision modeling is distinct from normative scenarios and backcasting processes in that the structure and function of the future desirable state is explicitly articulated as a systems model. Crafting, representing and evaluating the future desirable state as a systems model in participatory settings is intended to support compliance with sustainability visioning quality criteria (visionary, sustainable, systemic, coherent, plausible, tangible, relevant, nuanced, motivational and shared) in order to develop rigorous and operationalizable visions. We provide two empirical examples to demonstrate the incorporation of vision modeling in research practice and education settings. In both settings, vision modeling was used to develop, represent, simulate and evaluate future desirable states. This allowed participants to better identify, explore and scrutinize sustainability solutions.

Keywords: participatory modeling; sustainable futures; transformational sustainability science; sustainability education; visioning; visions

1. Introduction

Visions are crafted to put forward transformational goals, measure progress and build capacity and shared purpose. Rather than concentrating on current and persistent dilemmas, the focus of visioning processes are to clearly articulate future desirable states. Beyond just a comprehensive list of long-range goals, visions should describe the end result of how those goals interact and play out into the future [1].

This suggests that we must ask a lot of visioning processes. However, the lack of theoretical and methodological development within the fields of visioning research and practice limits tangible outcomes and our expectations of the process [2–4]. To begin addressing this gap, a recent review of visioning literature synthesized a criteria-based conceptual framework for developing sustainability visions [1]. Quality criteria for developing robust visioning approaches have identified that visions need to be constructed such that they are: visionary, sustainable, systemic, coherent, plausible, tangible, relevant, nuanced, motivational and shared. Within the reviewed literature, some of these quality criteria were better represented than others; few visioning studies focused on formal procedures for crafting systemic and coherent visions. In this paper, we address how to enhance the systems perspective and methodological capacity for sustainability visioning using systems modeling.

Systemic thinking is a critical challenge for sustainability researchers and practitioners needing to resolve urgent issues, while holistically addressing diverse and complex sustainability challenges. Rather than focusing on a single issue at a time, sustainability perspectives frame the larger social, technological and biophysical context of the issues, including the different roles, needs and values of stakeholders. Even exemplary and highly publicized visions, such as the United Nations Millennium Development Goals, have come under scrutiny for lacking sufficient systemic consideration of the relationships among goals [5].

We describe how systems modeling may be used to support visioning in emerging sustainability plans, programs and education. We demonstrate the role of modeling visions, in participatory and group modeling settings, to engage stakeholders in the process of developing sustainability visions rather than sets of solutions and goals that address individual issues. A tiered approach to modeling visions is presented, but as an enhancement of, not as a reinvention of, the visioning process. We work from solid foundations in visioning to make visioning processes more rigorous and robust. While focused on the systemic criterion, we also examine how other specific quality criteria are fulfilled and may be supported. Finally, examples are provided from two recent projects where we have applied modeling to sustainability visioning. Through these examples, we describe how the process of vision modeling was applied in urban long-range planning and in sustainability education. These examples illustrate the efficacy and power of applying systems modeling to visioning projects in order to better support both sustainability goals and the education of future sustainability researchers and practitioners.

2. The Modeling Approach

2.1. Sustainability Modeling and Current Applications

We broadly define sustainability as a process [6] and sustainability science as a research endeavor to understand this process, while also applying this knowledge to real-world challenges and solutions [7–9]. The process of model development is conducted to better understand systems complexity and how our decisions affect system behavior through abstractions and simplifications of the real world. Modeling can support sustainability science by structuring the process of representing and exploring real-world challenges and solutions (*cf.*, [10]). The value of modeling is evident in:

(1) The process of model framing and construction, where decisions must be made about system boundaries, what to include in the model and how to couple model components;
(2) The formal articulation of assumptions and uncertainties about the system in question;
(3) The visualization of the underlying structure and connectivity of the system;
(4) The exposure, through visualization of model behavior, of system characteristics, such as unexpected outcomes and response thresholds.

Sustainability models of the current state have some characteristics of models in general, including limitations and constraints posed by the resources on which the represented system depends. There are some characteristics of sustainability models, though, that set them apart from other systems models. We posit that, based on a foundation of sustainability principles [11–13], sustainability models should be: (a) explicitly normative and participatory, with a focus on values and desirability; (b) holistic rather than domain-specific; (c) structured and evaluated based on sustainability principles; (d) actor-oriented (*i.e.*, focused on people, their actions, roles, values and needs) in structure and interpretation; and (e) problem based and solutions oriented. It goes without saying that in the realm of all possible models, many of them will have some, perhaps many, of these five characteristics. We argue, though, that sustainability models should include all of them. This makes them distinct from plausible models or desirable visions that might be used to support sustainability projects, but that do not meet the above characteristics.

Sustainability models are thus more likely to be heuristic, rather than predictive, because of their reliance on normative interpretations of the system. Because sustainability models are not necessarily anchored in our current quantitative understanding of a system, they are likely to be more open to creativity and, thus, to be more nimble, flexible and potentially transformational than more traditional deterministic models. Real-world applications of sustainability models are increasing and are demonstrating growing sophistication. This is particularly true in fields, such as natural resource management for local communities, where there are strong needs to integrate normative perspectives to better assess sustainability outcomes and represent complex social-technological-ecological dynamics [14,15].

Typically, modeling procedures produce either static snapshots of the current system state or dynamic representations of future scenarios that are anchored in present conditions. Normative-based approaches, even those that do include a visioning process, such as backcast modeling [16,17], future mapping [18], horizon mission methodology [19], the impact of future technologies scenarios [20] and sociovision [21], do not explicitly model the future desirable state. Instead, sets of goals, moving targets or indicators representing the vision are generally used to direct and assess scenario pathways. Additionally, most of the formalized backcasting and visioning methodologies listed above (except for the horizon mission and the impact of future technologies approaches) all develop pathways that begin with the present system state and run forward in time with the vision goals serving as a beachhead or to explore potential futures. Even if an understanding of system structure, relationships and dynamics of the current state are simulated, this may not be sufficient to represent systemic features of radically transformed future states. For example, these transformational futures might require the incorporation of novel institutions and the exploration of new relationships and feedbacks, which may be difficult to anticipate without rigorous analysis of interrelated vision goals. We present an approach that explicitly takes into account the interactions among envisioned goals, targets and indicators to better articulate, explore and analyze future desirable states and scenario pathways.

2.2. Vision Modeling

We define vision modeling as the process of constructing sustainability models, such that the structure and function of the future desirable state is explicitly articulated as a systems model. Vision modeling puts emphasis on rigorously describing and clarifying the future state. It allows participants to see that future state (*i.e.*, goals and targets, relationships, exogenous drivers and indicators) from a systems perspective that includes the complexity and the interrelated nature of the components.

We argue that, in many situations, modeling will enhance the process and outcomes of visioning, particularly when model development follows sustainability visioning criteria, such as those put forth in [1]. For example, model development as part of the visioning process includes steps that:

(1) Ensure that the vision is composed of compatible goals, free of conflicts and trade-offs (*i.e.*, coherence);
(2) Reinforce and serve as checks on the plausibility of the visioning goals, because model components must be based on realistic constraints;
(3) Make sure the visioning outcomes are tangible, largely through simulation runs of the model and viewing the targets graphically;
(4) Help to categorize how the specific system components are prioritized and nuanced, through both qualitative and quantitative parameterization of the model that determines which outcomes are sensitive to which assumptions and by how much.

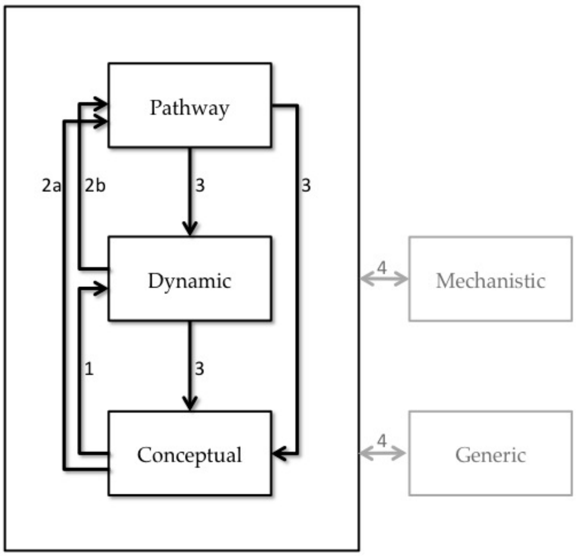
The real power of incorporating modeling into the visioning process is that the models may be used to explore systems-level structural features among the vision components and emergent dynamics among goals, targets and indicators. In this way, modeling enhances systems thinking, while also contributing to the coherence, plausibility, tangibility and specificity of the vision. In summary, models have a long track record of being used to identify and understand problems and explore potential futures. We propose that using models to also help articulate sustainable visions takes them into the realm of scrutinizing solutions and identifying planning opportunities.

3. Applying Modeling

3.1. A Tiered Approach to Modeling Sustainability Visions

We describe three broad approaches—conceptual, dynamic and pathway—for modeling future system states (Figure 1). These tiered approaches may be used iteratively as part of a sustainability visioning process. We distinguish these approaches based on the extent of systems thinking, in representing the systems features of the vision (*i.e.*, structure, dynamics and emergent outcomes), that is found in each. Choosing the appropriate approach will depend on the context of the sustainability endeavor, the project goals and the availability of planning resources.

Figure 1. Modeling sustainability visions: Boxes represent the different systems approaches to modeling sustainability visions. They are connected by potential workflows, shown as numbered arrows: (1) parameterizing functional models; (2a) qualitative; or (2b) quantitative simulations of vision pathways; and (3) iterative model development based on undesirable outcomes or pathway heuristics. The use of (4) generic and mechanistic sustainability vision models, while not discussed in this paper, may have additional utility for visioning research and education.



(A) Conceptual and rapid prototype vision models: Conceptual models (as per Figure 1) are qualitative diagrammatic representations of the connections among the various model components. Conceptual models of future desirable states provide structural representations of vision components and system relationships. They are helpful to structure and organize components of the vision and to check for missing components and inconsistencies (*i.e.*, conflicts and trade-offs) among components. Easiest to construct, conceptual models are the most commonly utilized approach for incorporating systems thinking into participatory settings. Techniques, such as influence matrices and trade-off assessments, explore the interrelations among vision components to identify potential conflicts, trade-offs and synergies [22]. Causal loop conceptual diagrams are used to visualize systemic characteristics, which allows for better identification of potential intervention points associated with highly influential systemic features, such as feedback loops, downstream factors and network structure [23,24]; actor-oriented and sustainability constellation conceptual models incorporate specific actors, rules, norms, needs, wants, resources, technologies and actions in assessing beneficial and adverse effects [9,15,24,25]. Conceptual approaches are typically qualitative representations of a system structure, but relative quantifications may be used to make more nuanced inferences on conflicts, trade-offs and interventions [26].

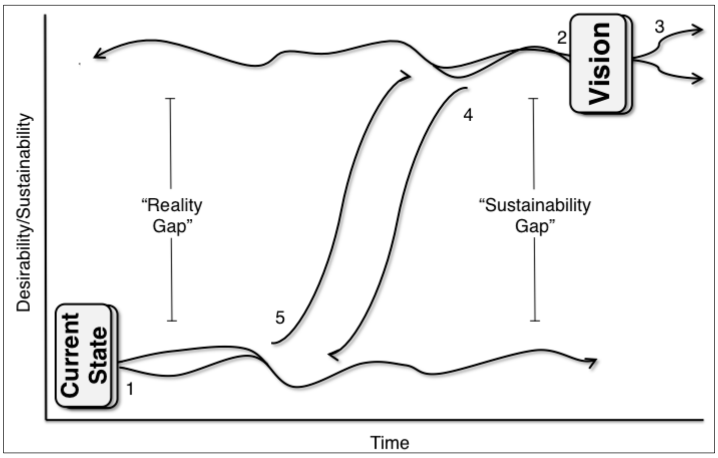
(B) Dynamic vision models (functional, with input-output correspondence): Building on the conceptual modeling approach, dynamic models (as per Figure 1) are built and parameterized, such that the "running" models simulate the dynamics of complex interactions among the system components [23,24]. This increased articulation allows participants to better anticipate non-intuitive outcomes, such as "hidden" conflicts, due to thresholds or non-linearities, which emerge from the inter-relationship of system components.

Parameters for dynamic vision models are selected from evidence-based and empirical work, allowing the vision components and interactions to be more relevant to the real world (*i.e.*, grounded by reality). This enhances the coherence and plausibility of simulated outcomes. Techniques, such as sensitivity analysis and cross-impact analysis [27], inform the selection of indicators, targets and interventions based on how sensitive they are to change and the implications of emergent interactions. An important outcome of dynamic visions models is future projections of systems dynamics and normative trade-offs that emerge from the simulations (Arrow 3 in Figure 2). By simulating potential trajectories of visions, participants can explore the plausibility and viability of diverse envisioned future states. Undesirable or unrealistic trajectories may require a review of certain parameters and underlying assumptions or a return to the conceptualization of the vision (Arrow 3 in Figure 1). Dynamic vision models are constructed to further improve the specificity and coherence of the conceptual vision models, allowing participants to examine the viability and plausibility of the vision.

(C) Pathways of vision models: More cogent assessments of plausibility require the characterization of the sustainability gap between envisioned goals and initial conditions (see [28]; Figure 2). Pathways of vision models may be either qualitatively crafted from conceptual models or quantitatively simulated using dynamic vision models (Figure 1). These pathways are distinct from the potential future trajectories simulated by dynamic vision models (Arrows 2 and 4 *versus* Arrow 3 in Figure 2). Vision model pathways are simulated backwards (*i.e.*, from the vision to the present conditions) through a heuristic process of identifying the components and conditions that need to be in place in order to achieve the vision (e.g., actions, policies, technologies, institutions). Using this procedure, it is likely that some of the pathways that are directed backward from the vision will not intersect with current state conditions, and the difference between the two is what we call the "reality gap" (Figure 2). The models thus become a critical tool in also identifying how disparate (and in what way) future ambitions may be from what is actually plausible (*i.e.*, the "sustainability gap" in Figure 2).

This approach is also distinct from, but potentially complementary to, backcast modeling, where pathways starting from the current state intersect with pre-determined envisioned future goals (Arrow 5 in Figure 2). Conducting both scenario pathway approaches (backcast modeling and vision modeling) may increase the number of potential interventions and options that are available. A comparative approach that contrasts vision pathways with those from other scenario approaches may also enhance the understanding of how the balance of deterministic and normative perspectives can shape scenario outcomes. One example of this is enhanced understanding of how starting from current state conditions affects the resulting visions. The emphasis of the pathways approach, however, is not merely to better understand methodological distinctions among scenario approaches, but also to enhance the process of visioning by rigorously describing and scrutinizing the visions using systems modeling. The purpose of the pathways approach is to increase the relevance of the vision by exploring and articulating what is needed to achieve a desirable, plausible and sustainable future.

Figure 2. A nuanced description of the pathway approach from Figure 1. Numbered arrows represent: (1) models of the current state that simulate projected pathways into the future; (2) models of the vision that simulate pathways backwards from the envisioned future state; (3) models that project the vision itself into the future; and (4 and 5) pathways simulated to interconnect the vision and the current state. The "reality gap" and "sustainability gap" both represent the potential lack of correspondence between pathways originating in the different time horizons; these gaps are needed to better understand how to craft the interconnecting pathways (Arrows 4 and 5).



3.2. Engaging Participants in Sustainability Vision Modeling

Regardless of the approaches selected, we argue that vision modeling activities should be conducted in participatory settings [1,22]. Many different interpretations of participatory modeling are found in the literature, with greatly varying levels of participatory involvement and a variety of approaches to modeling [29]. We stress the importance of participatory settings where stakeholders are highly engaged in the co-production of the models and not just involved as model users or data sources. Stakeholders should actively participate in all stages of the construction, calibration and validation of the models. This will enhance their understanding of model limitations and their confidence in the model itself and should encourage end-user implementation.

A primary challenge of participatory modeling is ensuring that analytical procedures are understood and that different knowledge systems, norms and values are properly negotiated [30,31]. Effective incorporation of stakeholders into analytical processes requires a strong investment in capacity development in order to maximize model construction success and facilitation, to negotiate consensus and achieve buy-in. Early research on enhancing creativity in participatory modeling suggests that gameplay and art-based activities may help prepare participants to engage in more challenging formalized tasks [32,33]. Analytical and creative procedures can be complementary without being modular, sequential or linear. Since vision modeling approaches are meant to be applicable in a variety of fields, prescriptive approaches on how to integrate creative and formal activities are not feasible. Our focus is on developing and engaging procedures for visions modeling, and in the next section, we demonstrate the efficacy of our approach with vision modeling case studies from urban planning and sustainability education.

4. Real-World Examples of Modeling Sustainability Visions

The two examples in this section demonstrate the application of vision modeling in urban planning and sustainability education. Both of these case studies have an urban focus, because we conduct most of our research on urban systems. As we note above, the visions modeling approach we are demonstrating here has wide applicability. For both case studies, we describe the setting, goals, approach and methods and highlight key differences in the ways visioning modeling was used (Table 1). Finally, we discuss the outcomes of both case studies to demonstrate how vision modeling can be applied to develop perspectives and methodological capacity in systems thinking in a wide diversity of real-world sustainability projects.

Table 1. Two examples of vision modeling projects. ASU, Arizona State University; LAITS, Learning by Authoring Intelligent Tutoring System.

Project Name	Phoenix General Plan Visioning Study	ASU Sustainable Ecosystems undergraduate course
Project setting:	Urban planning research	Sustainability education
Project goal:	Develop rigorous visioning process and product	Teach sustainability education competencies
Goal criteria:	Sustainability visioning quality criteria [1]	Sustainability education competencies [34]
Explicit role of vision modeling:	Addressing systemic criterion	Teaching systems thinking competency
Engagement setting:	Participatory modeling (fifteen two-day village workshops and one one-day city-level workshop)	Group modeling (in-class) 28–35 students per class Groups of 3–5 students
Vision modeling approach (scope: scale):	a. Conceptual (whole system: city and villages); b. Dynamic (subsystems: city)	a. Conceptual (subsystems: city); b. Dynamic (subsystems and integrated subsystems: city); c. Pathway: (integrated subsystems: city)
Modeling methods:	a. Causal loop diagram, influence matrix, network analysis b. Stella models and game-based systems map	a. Dragoon models and LAITS tutor system b. Dragoon models and LAITS tutor system c. Dragoon models and LAITS tutor system; sensitivity analyses
Outcomes:	Systems conflict and trade-off revisions to the vision; participants (self-assessment survey) and practitioners (debriefing) reported enhanced systems perspective	Pre- and post-assessments demonstrated enhanced capacity for systems thinking and anticipatory competency building

4.1. Urban Planning Example: Phoenix General Plan

The Phoenix General Plan project is a state-mandated, long-range planning process focused on developing a comprehensive vision for the City of Phoenix (AZ, USA) in order to guide future decision-making in all city departments [35,36]. In this study, a key research hypothesis was that an emphasis on systems-based approaches would be an effective way to enhance the quality of this sustainability visioning process. Our research objectives were to design, conduct and test a rigorous visioning process informed by the sustainability visioning quality criteria of Wiek and Iwaniec [1]. The process, results and appraisal of this project are detailed in Iwaniec and Wiek [37], and we summarize them in the context of vision modeling below.

In preparation for the city's decadal update of its General Plan, the City of Phoenix Planning Director approached faculty from Arizona State University (ASU) with expertise in urban sustainability research to collaborate on innovating the city's planning practice for the General Plan 2050. Through this partnership, we incorporated modeling into the visioning process, and the City of Phoenix conducted its first planning-directed stakeholder engagement of the General Plan since the 1970s. In this sustainability visioning process, we co-developed several participatory models of the future desirable state(s) based on stakeholder elicitation, analysis and evaluation of future-oriented values and preferences.

Conceptual models of the visions were created with each of the fifteen villages that make up the City of Phoenix, as well as an aggregate model for the entire city created by researchers and city planners. Over 750 (total, non-unique) individuals participated in the fifteen two-day village workshops (30 workshop days, 13–40 participants/day). Participants provided detailed vision narratives, which were then deconstructed by researchers and planners into key vision elements (e.g., "abundant vegetation", "enhanced walkability", "reduced heat", "abundant shade" and "responsible water use") with associated stakeholder values and preference. Conceptual systems models were constructed from these vision elements by identifying systems relationships that connected the elements (*i.e.*, causal loop diagrams and influence matrices). In these participatory settings, several analytical activities explored and evaluated the vision models, including:

(1) Causal loop diagrams and network analysis were used to analyze the overall system structure and relationships among the vision elements;
(2) Consistency analysis was performed using influence matrices to identify trade-offs and synergies among vision elements;
(3) Diversity appraisal was used to identify similarities and differences among the vision models from different stakeholder groups (e.g., heterogeneity among the fifteen village visions).

Several dynamic models were then created by parameterizing subsystems models selected from the overall conceptual model of the city's vision (e.g., Figure 3). Subsystem models were constructed to further engage participants with portions of the vision that had potential, systemic and normative trade-offs and conflicts. In a follow-up, one-day city-level workshop, over 100 participants worked in small groups (6–8 participants/group); each group interacted primarily with one of eight subsystem models (16 groups total). Modeled subsystems included vision elements based on: (a) potential conflicts and trade-offs; (b) prioritization scores; and (c) the betweenness centrality of the network.

To parameterize vision elements in the subsystem models, the stakeholders negotiated the prioritization (priority score) of each vision element. For example, high, medium and low priorities represented stated preferences for the vision element "abundant vegetation" corresponding to goals of 33%, 23% and 13% tree canopy cover. In this urban desert ecosystem, the vision element "abundant vegetation" had direct (parameterized) impacts on the vision element "responsible water use". Additionally, in this case, where both the "abundant vegetation" and "responsible water use" vision elements were prioritized as high, there were clear systems trade-offs among the goals that needed to be explored (Figure 3). From the causal loop diagrams, researchers used isee systems STELLA to input parameterized values and crafted game-based systems maps (e.g., game boards, as per Figure 4a). Game boards were direct representations of the model structure, and game board activities were facilitated by researchers who had direct access to the models. Researchers provided real-time feedback on model dynamics and outcomes to update the game boards. Overall, these game board activities allowed participants to:

(1) Familiarize themselves with their group's subsystem by providing visualization and narratives of the vision elements, relationships and overall subsystem;
(2) Explore potential implications of various changes to the vision and negotiate trade-offs and conflicts (as per the example in Figure 3 and Figure 4a);
(3) Appraise the sustainability of the final negotiated vision by responding to open-ended questions based on sustainability principles (informal appraisal).

Figure 3. Simplified representation of urban vegetation submodel from Phoenix General Plan Update: vision elements included in this subsystem represent stakeholder preferences for "abundant vegetation", "enhanced walkability", "reduced heat" (urban heat island, or UHI), "abundant shade" and "responsible water use". This conceptualization is simplified by excluding non-essential parameters and connections to the other vision subsystems.

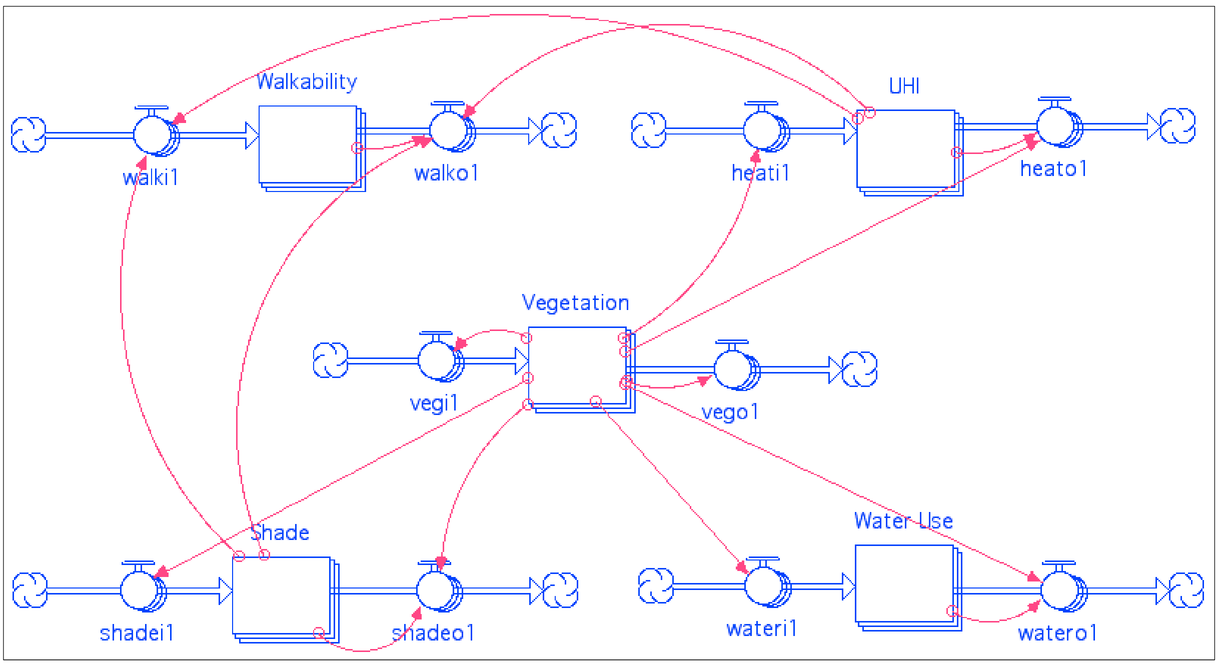


Figure 4. Vision modeling activities: (**a**) the Phoenix General Plan Update workshop game board (note that the same vision elements and relationships, represented as boxes and red arrows in Figure 3, are represented as circles and green arrows in the image); and (**b**) ASU Sustainability Ecosystems Course.

(**a**) (**b**)

Outcomes of these participatory activities, specifically based on changes in stakeholder priorities for vision elements (which represented changes to the model parameters) and by adding/removing vision elements and relationships (which changed the structure of the model), represented the final negotiated vision. Finally, the participants provided detailed actor-oriented narratives to add specificity and further describe the vision models. These "day in the life of…" narratives were used to communicate key elements, relationships, qualitative descriptors and simulated outcomes to describe how the visions "play out" for use in the broader outreach and dissemination of the General Plan. At the end of the workshop, participants were administered self-assessment surveys followed by facilitator debriefing [37].

4.2. Education Example: Sustainable Ecosystems Course

Sustainable Ecosystems (SOS 326) is an upper-division, three-credit course taught in the School of Sustainability at ASU (Tempe, AZ, USA). In both the fall, 2013, and spring, 2014, semesters, roughly half of this course involved having the undergraduate students collaborate in small group settings to construct, explore and peer-tutor models of the Phoenix urban ecosystem (Figure 4b). The classes had 35 and 28 students, respectively, and the groups were typically 3–5 students. The overarching goal was to use object-oriented modeling and tutorial software to teach sustainability science competencies, with a particular (and obvious) emphasis on the systems thinking competency [34]. A key hypothesis was that the construction, documentation and use of ill-defined models would be a more effective way to experience, and thus to learn, systems thinking when compared with simply exploring an existing model or not using models at all. Ill-defined model construction is when students must locate, digest and filter considerable information to determine how to approach model development, how to conceptualize their system and how to quantify relationships in their model [38]. Some student groups constructed status quo plausibility-based scenario models (SQ) from student-identified sustainability challenges and information on the likelihood of current trends. Other student groups constructed future desirable state vision models (FDS) based on their own sustainability visions that fit within defined "real-world" constraints (e.g., a hotter and drier climate that steadily reduced water availability) and on aspirational and evidence-based interventions. The students began modeling exercises only after lectures had introduced critical background information, particularly on systems dynamics.

Our in-class modeling activities (conceptual, dynamic and pathway models) focused on urban ecosystems in general and the City of Phoenix in particular. Students were initially divided into small groups of 3–5, and each group was charged with developing a model of one of three closely-coupled subsystems of the urban ecosystem: (1) water; (2) green infrastructure; and (3) transportation. The three subsystems corresponded to city department role-playing activities associated with the model development: (1) Phoenix Water Services; (2) Parks and Recreation; and (3) Street Transportation and Public Transit. For each of the subsystems, SQ and FDS models were constructed and tutor systems developed. Groups used the Dragoon modeling software [39,40], developed at ASU, to create these subsystem models, document the models, list assumptions, justify the decisions and create (using a single Dragoon command) a tutoring system for teaching other students about their model. The tutoring system had tutees re-create the group's model from the documentation, provide constructive feedback on the model and potentially revise the model. This activity, which is called LAITS (Learning by Authoring Intelligent Tutoring System; see [39,40]), was intended to create more engagement with the models and their details than having the model's creators simply show the model to the other students. The progression from learning the software to using a fully integrated systems model of the Phoenix urban ecosystem included:

Step 1: Instruction was provided on how to navigate and use Dragoon, largely through simple, but steadily more complex modeling exercises, and a pre-assessment of systems thinking skills was administered.

Step 2: Small groups of students were assigned to collaboratively model one of the three subsystems (*i.e.*, water, urban vegetation, transportation) from either an SQ or FDS perspective. In the subsystem modeling narrative, we provided students with suggestions about where to begin their search for critical information and how to decide the state variables, model structure and parameterization of variables (e.g., city and departmental visioning documents).

Step 3: The student groups who were modeling the same subsystem then used the LAITS activity to critique and learn from each other's models. With their new deeper understanding of each other's models, these groups hybridized their subsystem models into a single subsystem "consensus model" that included key components of their individual group models. This resulted in one SQ consensus model and one FDS consensus model for each of the three subsystems. At the end of this group exercise, students submitted peer- and self-evaluations of their group's dynamics and effectiveness. We used these evaluations to strategically reform the next set of modeling groups.

Step 4: We then reorganized the students into new groups, ensuring that each new group had "expertise" from each of the three subsystems. These new groups were tasked with collaboratively coupling and integrating the three consensus subsystem models into a "whole-city" model. For example, in many cases, the students coupled the water and urban vegetation subsystems through water use for irrigation and coupled these to the transportation subsystem via urban heat island dynamics and air pollution, noting that irrigated vegetation mitigates both, while transportation exacerbates both.

Step 5: Once the whole system models were parameterized and running, the students used the pathway approach to run 50-year scenarios beginning from either today (the SQ groups) or from 2050 (the FDS groups). They used sensitivity analysis to find the potential "best" intervention points for sustainability transitions and where the models, and thus, the Phoenix system, might be too inflexible to allow for sustainable transitions.

Final Step: These new groups used the LAITS activity to explore each other's models. Each group presented their final systems models, scenarios, narratives and (for the FDS groups) visions to the rest of the class and led discussion on their findings (e.g., reality and sustainability gaps, creativity and feasibility of the models and recommended transition strategies). Students again filled out self- and peer-evaluations based on their group experiences, and on the last day of class, we re-administered the systems thinking pre-assessment, but as a post-assessment for direct quantitative comparison of the progress made after the semester's modeling activities.

5. Discussion and Synthesis

The usefulness of modeling for heuristics, representation, learning and discovery has been well documented [41]. We recognize that the systems dynamic modeling approaches described here (Figure 1) do not represent the only form of system modeling (e.g., decontextualized-generic or specific-mechanistic modeling) or other broad categories of complexity modeling (e.g., spatially-explicit, process and agent-based) that may be useful in sustainability visioning settings [42]. The use (and hybridity) of different modeling approaches may emphasize different visioning quality criteria (e.g., systems modeling for developing systemic and coherent visions; spatially-explicit models for spatial tangibility; process models for operational nuance and specificity; and agent-based modeling for actor-oriented relevance). While not commonplace, there are examples of spatially-explicit models being used to support visioning processes [43–45]. These models are incorporated as either expert-based data or late in the participatory process for visualization and stakeholder review rather than being integrated throughout the visioning process. Recent work in linking agent-based and systems modeling approaches has been used in natural resource planning [46] and may have interesting applications to specifying actor-oriented visions to better articulate who is implementing changes, how rules and norms drive action and who is affected by these actions.

Various techniques suitable for future-oriented studies exist in the literature. These include syntheses organized by research objectives [47,48], by methodologies [27,49] or by applications that they can support [50,51]. What is still needed are performance-based comparisons among diverse approaches to visioning [52,53], scenario development [51], participatory modeling [54,55], enhancing creativity and the supportive use of state-of-the-art technology [32], which may be used to further develop and advance sustainability visioning research and practice. It is important to emphasize that vision modeling is an intervention to traditional visioning (and sustainability education), and as such, studies will be needed to evaluate how modeling can be used to enhance sustainability visioning processes (how participants are engaged and how modeling affects deliberative, explorative, analytical and reflexive processes) and products (quality of the visions, capacity building and implementation).

We present vision modeling as an approach to address the need to advance the research, practice and education of sustainability visioning if we expect visioning to be a serious tool to guide transformational change. Our two examples illustrate the application and potential role of vision modeling in urban planning participatory settings and sustainability education. While the main goals of the two examples were different (*i.e.*, developing a robust urban planning vision and teaching sustainability competencies to students), both approaches demonstrate how vision modeling can be applied to develop perspectives and methodological capacity in systems thinking (Table 1).

In our urban planning study, modeling activities contributed to several of the sustainability vision quality criteria we presented above [22,37]. While the primary goal is to describe how systemic methodological approaches enhanced the visioning process, we also found that modeling contributed to the coherence and plausibility of envisioned goals. Potential trade-offs and conflicts were resolved by analyzing not only obvious direct relationships, but also indirectly connected goals. Modeling also served as a plausibility "filter" on interventions and targets (e.g., by exposing biophysical constraints, such as the maximum amount of transpirative cooling possible by desert *versus* mesic vegetation). The co-production of the vision model reinforced stakeholder buy-in and developed a shared proficiency in resolving normative conflicts, as well as direct and indirect systems trade-offs. Further re-enforcing these findings, we found that capacities for systems thinking among the stakeholders (based on self-assessment surveys) and practitioners (based on facilitator debriefing) were enhanced.

In the education settings, existing sustainability competencies and learning objective [34] were used to design the sustainable ecosystems in-class modeling activities. Specifically, we focused on the systems thinking, anticipatory, interpersonal and normative and strategic competencies [34]. In this ongoing study, we found that vision modeling did enhance sustainability education competencies in our students, specifically their systems thinking and anticipatory competencies. Our preliminary analysis of formal pre- and post-assessments demonstrated enhanced capacity in systems thinking capacities and anticipatory competency building. Normative and strategic competency building was not explicitly assessed, but was included in peer-tutoring assessment guidelines and in rubrics used to grade the modeling process and final models. Peer evaluations assessed at regular intervals through the modeling process also showed that the group modeling activities contributed to interpersonal competency building and enhanced student collaboration skills. We posit that many of the "real-world" issues that our student will face after graduation will lie at the intersection of these competencies (*i.e.*, the process of modeling alone can be used to develop systems competencies and visioning to develop normative competencies) and that through the integration of these approaches, their ability to identify and scrutinize solutions will be enhanced.

6. Conclusions

Pursuing sustainability visions engenders a deep understanding of the interactions, feasibility and outcomes of our normative choices and goals. The literature is replete with calls for rigorous systems thinking in sustainability practice and research. Yet, we still readily encounter critiques of hastily conducted endeavors that lack a thorough analysis of trade-offs, interconnected indicators and goals and emergent complex dynamics. "Wicked" sustainability challenges foster tensions between the urgency of needs and the timely implementation and need for a comprehensive and long-term perspective. Any modeling methodology used to craft sustainability visions should appropriately reflect this tension: the need for desirable results under realistic conditions and the need for robust long-term sustainable solutions. We argue that the visions modeling approach we present and demonstrate here does just that.

Using systems modeling in participatory settings to craft, represent and evaluate future desirable states supports sustainability visioning quality criteria by developing and simulating desirable, plausible and sustainable visions. Incorporating this visions modeling approach into visioning processes will allow practitioners and researchers to better identify, scrutinize and think critically about solutions. The participatory co-production approach we describe here will build sustainability capacity in today's decision-maker community. Additionally, the use of this visions modeling framework in sustainability education will better prepare the next generation of sustainability scientists and practitioners to meet ever-growing challenges.

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Author Contributions

All authors had an important role in crafting this manuscript. David M. Iwaniec, Daniel L. Childers, Kurt VanLehn and Arnim Wiek designed and preformed the research: David M. Iwaniec, Daniel L. Childers and Kurt VanLehn conducted the Dragoon/LAITS classroom study. David M. Iwaniec and Arnim Wiek conducted the City of Phoenix study. David M. Iwaniec and Daniel L. Childers wrote the initial manuscript draft, and David M. Iwaniec, Daniel L. Childers, Kurt VanLehn and Arnim Wiek contributed to all subsequent drafts and the final version. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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