

Which Visualizations Work, for What Purpose, for Whom? Evaluating Visualizations of Terrestrial and Aquatic Systems

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ABSTRACT

A need for better ecology visualization tools is well documented, and development of these is underway, including our own NSF funded Visualization of Terrestrial and Aquatic Systems (VISTAS) project, now beginning its second of four years. VISTAS' goal is not only to devise visualizations that help ecologists in research and in communicating that research, but also to evaluate the visualizations and software. Thus, we ask "which visualizations work, for what purpose, and for which audiences," and our project involves equal participation of ecologists, computer scientists, and social scientists. We have begun to study visualization use by ecologists, assessed some existing software products, and implemented a prototype. This position paper reports how we apply social science methods in establishing context for VISTAS' evaluation and development. We describe our initial surveys of ecologists and ecology journals to determine current visualization use, outline our visualization evaluation strategies, and in conclusion pose questions critical to the evaluation, deployment, and adoption of VISTAS and VISTAS-like visualizations and software.

Categories and Subject Descriptors

J.2 Physical Sciences and Engineering: Earth and atmospheric sciences. H.3.4 Systems and Software: Performance effectiveness. H.5.2 User Interfaces: Evaluation/methodology. I.3.4 Computer Graphics: Graphics Utilities – Application Packages.

General Terms

Measurement, Design, Human Factors.

Keywords

Scientific Visualization, Software Evaluation, Visualization Development Lifecycle, Ecology Informatics

1. INTRODUCTION

A significant challenge of the 21st century is making wise decisions about the use and conservation of the world's natural resources, and increasingly scientists and decision makers use massive data sets to conduct research to that end. The rate and

complexity of data acquisition is increasing exponentially, but data deluge is only one factor complicating environmental science research. Grand Challenges of environmental science [18] involve multiple spatial and temporal scales with complex, highly distributed and heterogeneous data, and research influencing management decisions is particularly difficult due to the volume and complexity of the data, complex nature of interdisciplinary research, and need for dissemination to diverse stakeholders.

Our prior work suggested that visual analytics can help scientists more effectively use large data sets and models to understand and communicate complex natural phenomena [6,12] and we hypothesized that spatially and temporally explicit visualization of ecosystem states, processes, and flows across topographically complex landscapes would enhance scientists' and other stakeholders' capacity to comprehend relationships among ecological processes, ecosystem services and environmental conditions, and to pose testable hypotheses.

Scientific visualization is not a new field, but we have found that ecologists do not take full advantage of existing visualization tools, in spite of a perceived need by some for better visualization. A literature review of visualization tools compared stated desiderata from our collaborators with the state of the art, and we surmised that few tools met the functional requirements articulated by our collaborators. In particular, we found evidence from the literature that few tools focused on environmental processes [1,7,15], or easily integrated complex topography [21] with visualizing diverse data and analytics [24], or allowed users to show data from different studies on the same canvas and scale up or down in both space and time [8,13,19]. We concluded, based on this early review of the literature and on a later survey of ecologists and software (see Section 3) that the perceived need for visualization likely arose because current tools do not provide needed functionality or are too difficult, expensive, or slow to use.

Prior to developing VISTAS, however, we wanted to refine the question of "which visualizations work best for which ecologists in which situations" so that we could answer them as we designed and evaluated the visualizations and software. To that end we felt it necessary to describe how ecologists use visualizations. This paper makes the case for understanding, prior to development, the context in which scientists work – the organizational and professional norms, expectations and practices – as well as the visualization functional requirements for that software. Preliminary work presented in this paper suggests a method that other projects could adopt for establishing the context in which end users work in their specific field. We thus hope to contribute to the field of visualization a way to situate, in the context of the

user’s work, visualization design and evaluation. Even though the work we present focuses on the field of ecology, we believe it is generalizable and applicable across scientific domains.

2. VISUALIZATION OF TERRESTRIAL-AQUATIC SYSTEMS (VISTAS) PROJECT

VISTAS aims to devise, develop and test visualizations so scientists can better understand and communicate the environmental science Grand Challenges. We reason that seeing the same phenomena at different scales across space and time improves intuition, thus helping develop new hypotheses and explain results to collaborators and others. The VISTAS’ project focuses on visualizing 3D representations of natural phenomena over time at various spatial scales by using the output of environmental sensors, and of land use and process-based models that simulate cycling and transport of water and nutrients (C, N and P) within plots, hill slopes, and watersheds, in a single geographical area – the H.J. Andrews Long Term Ecological Research (LTER) site (andrewsforest.oregonstate.edu). The environmental science goal of the project is to gain insight into and to communicate the complex ecosystem services of water and carbon in terms of their natural and built components and the underlying topography.

3. ECOLOGISTS’ VISUALIZATION USE

Since the project’s inception we have surveyed visualization use by ecologists within the LTER, in research publication, at some visualization centers, and by our own collaborators. Our goal in these surveys has been to understand the domain-specific (i.e., ecology) context in which our partners are working in order to better evaluate the visualizations and software tool we are developing. In particular, we aim not only to better understand the functional requirements of the desired visualizations but also the use to which those visualizations would be put and the barriers to use that visualization innovations might face when we look beyond development to integration into existing software tools and adoption by the community. We believe that understanding the context of use is important for effectively evaluating visualizations during the design phase and afterwards. Because the computer scientists on the project were unsure of how to proceed, we called upon our social science collaborators who advised, as a first step towards achieving this goal, determining ecologists’ current visualization use.

The 26 U.S. Long Term Ecological Research sites involve 1800+ scientists investigating ecological processes over long temporal and broad spatial scales (lternet.edu). In 2010, we asked the LTER Information Managers what software their scientists use for visualization. They reported that no single product enabled LTER scientists to easily view on one canvas 3- or 4-D ecological phenomena across spatial scales, and that researchers struggled to integrate into visualizations data from multiple sources where data differed in format, sampling design or collection frequency. This survey confirmed our preconception that there were few if any existing tools that accomplished what our collaborators want.

Next, we surveyed ~25,000 visualizations in 1,142 articles from 8 ecology journals published July–December, 2011. This survey met two needs: 1) determining what types of visualizations ecologists use when publishing research results and 2) defining more explicitly the kinds of visualizations our collaborators want and seeing where (if at all) similar visualizations appear in the published literature. Figures in the surveyed journal articles were categorized as: graph, map, chart, photograph, illustration, or computer generation of natural phenomena. We recorded scale

and phenomena, whether visualizations were natural or conceptual, and whether natural phenomena were representational or symbolic. We used those visualizations to develop a profile of Visualization of Interest (VOI) as “like” those our collaborators want: is 3-D; shows multiple time or spatial scales; represents natural phenomena; uses color to convey information; has extruded volume; compares models with other models or with physical reality, or compares physical realities; and/or simulates what one would see if looking directly at the phenomenon. Table 1 shows how VOIs distribute across the journals surveyed [9]. In particular, we see that not all ecological journals are equal – that ecologists who publish in certain journals (e.g., hydrologists and ecosystem scientists) make greater use of visualizations than those who publish in other journals.

Table 1. Journals surveyed for visualization use, from highest to lowest percent of articles with one more “Visualizations of Interest”. Future work will analyze whether and why some fields use visualizations like VISTAS’.

Journal	Proportion (%) of articles per journal containing 1 or more VOI
Water Resources Research	20%
Ecosystems	19%
Journal of Hydrology	11%
Canadian Journal of Forest Research	9%
Boundary Layer Meteorology	7%
Agriculture and Forest Meteorology	6%
Atmospheric Environment	4%
Ecology	2%

In order to refine our growing understanding of the domain-specific context, we surveyed visualization use at 172 presentations at the Ecological Society of America (ESA) 2012 conference (Portland OR, August 5–12), using our VOI definition. We wanted to know whether a change in media presentation – oral versus print – makes a difference in visualizations use. ESA conference presentations used more visualizations, and photographs, but not statistically significant greater VOI; we again saw that some sub-disciplines (e.g., hydrology) and some ecologists (e.g., those using sensing devices as LiDAR, or those creating education software) used more VOI than other ecologists.

We also informally surveyed some visualization software: The Visualization and Analysis Platform for Ocean, Atmosphere, and Solar Researchers (vapor.ucar.edu), Man Computer Interactive Data Access System (McIDAS), and The Integrated Data Viewer (IDV) (unidata.ucar.edu/software for both McIDAS and IDV), observing that the complexity of our collaborators’ data and complex input data descriptors for visualization software and the resulting perceived or actual difficulty of transforming data might deter our scientists from using those tools. As David Maier points out in his keynote talk to the 2012 Scientific and Statistical Database Conference: “Few individuals know the complete range of data holdings, much less their structures and how they may be accessed” [16]. VISTAS’ informal tool survey added evidence to the contention that perceived or real input and output data format incompatibilities act as a barrier to sophisticated visualization use.

Finally, VISTAS’ computer and social scientists interviewed domain collaborators on their current use of and need for visualization software. Expectations for VISTAS are quite high, and include merging or layering data of various scales (e.g., per second data with per day data) so that research results of several projects can be viewed on the same canvas. Current collaborators

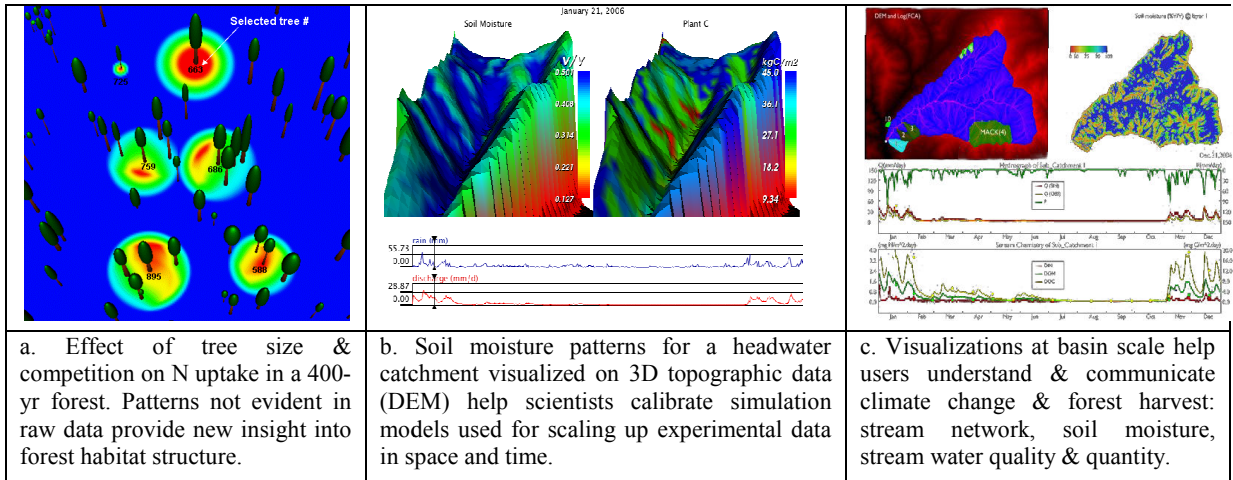


Figure 1: VISTAS aims to help EPA scientists McKane and Brooks display & interpret data. From left to right, visualizations of a) 0.1 km² forest stand, b) 1 km² catchment, c) 64 km² basin. Animations of (b) & (c) will show change over time. Visualizations 1a and 1b were created by a VISTAS prototype.

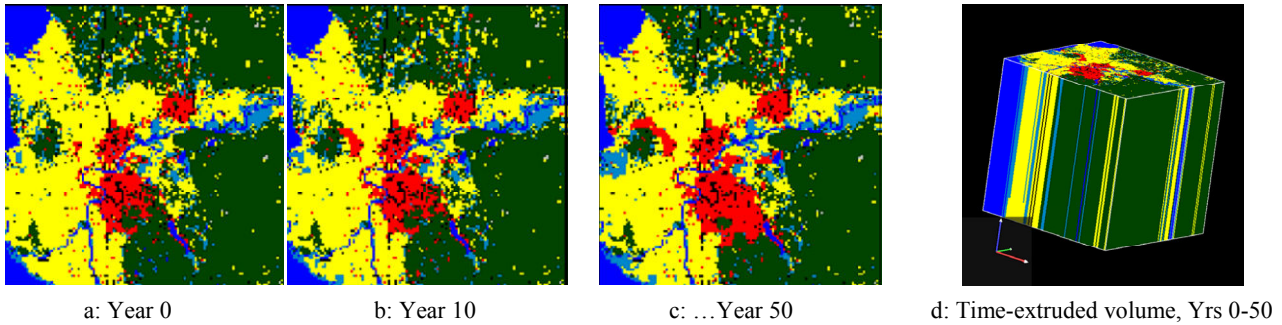


Figure 2: ENVISION maps 10-year intervals. VISTAS combines years into a 3D image, to explore changes over time.

reported how they have used or expect to use VISTAS to enable discovery, generate and test hypotheses, and report results.

Collaborators Bob McKane and Allen Brooks, EPA [22], report that the VISTAS prototype allows them to show and compare ecosystem variables on enhanced 3D topography side by side in an animation, and thus to tune their model (VELMA). They have also used VISTAS visualizations to present results and anticipate connecting VISTAS directly to their model to watch the simulation “unfold” and select result variables to save or analyze (See Figure 1).

Collaborator John Bolte’s agent-based land use scenario generator *Envision* (<http://bioe.orst.edu>) is a decision support tool integrating stressor scenarios, decision rules, ecological models, and evaluation indices within a GIS framework [4]. He has used VISTAS coPI Bailey’s extruded volume visualization to “see” when and where *Envision* predicts landscape changes [20]. Bolte wants to use VISTAS to show different scenarios side by side, in 3D, animated, as an *Envision* simulation runs (See Figure 2).

Collaborator Christoph Thomas, a micrometeorologist, works with spatially distributed point-measurements of air flow, air temperature and humidity to understand how these communicate across landscapes [23]. To scale up to the watershed level he needs to develop new models and wants to draw on intuition gained from viewing his data with McKane’s and Brookes’ ecohydrology model results. He also would like air flow visualizations that provide more intuitive understanding than the visualizations he currently uses (See Figure 3).

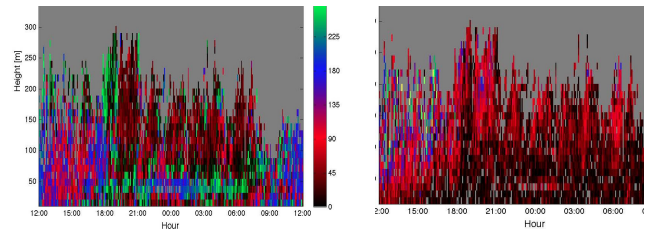


Figure 3: Wind direction (left, 0-360) and speed (right 0-10 m s⁻¹ by time, x-axis: time (noon to noon), y-axis: height 0-400m). Graph created in MATLAB from data generated by a Metek PCS 2000-24 Sound Detection and Ranging (SoDAR) device, located at the HJA LTER, Oregon (44.211777N, -122-255954W).

These activities – the journal and conference survey, the ongoing interviews with our ecologists, and the survey of current software – yield an understanding of the *context* in which we are developing the VISTAS software tool prototype. Context, we believe, will play an important role in our evaluation process. For example, with further scientist interviews or surveys we aim to learn whether lower use of visualization results from a lack of need or of access to appropriate tools, perceived time to learn/use or cost of tools, or practical aspects as difficulty getting data into visualization tools. We are also analyzing our survey database of 32,000+ visualizations, looking for patterns to discover characteristics of effective ecology visualization and to define

effective visualization by using Bonoma's Framework for definition building from case studies [2]. We believe that conducting these research activities concurrently with software development will increase the usefulness of the software tool.

4. VISTAS' EVALUATION PROCESS

VISTAS' user-driven, case study approach to design, development, and evaluation focuses on scientists' use of visualization throughout the research process [3]. Evaluation of visualizations and software uses mixed social science methods and includes semi-structured interviews with all team members (users and developers) during software design, implementation, and deployment. In-design evaluation will use paper prototyping and evaluation of proposed visualizations [11]. We are particularly interested in whether VISTAS' visualizations suggest new hypotheses and enable discovery and whether our collaborators can make effective use of VISTAS visualizations when presenting results to wide audiences (including other scientists, decision makers, the public, and students). For the analysis framework we use theories from cognitive science (Joint Activity Theory [5], Distributed Cognition [10], and Marr's Tri-Level Hypothesis [17]).

Another aspect of the VISTAS' evaluation process, outside the scope of this paper, is that we also observe the context in which the scientists and computer scientists are working together to produce the desired visualizations.

5. CONCLUSIONS: OPEN QUESTIONS

BELIV 2012 workshop participants called for including disciplines outside computer science when developing evaluation processes for information or scientific visualizations. To that end, a primary contribution of VISTAS is the integral involvement of social scientists in the evaluation of VISTAS' visualizations, software, and development process. Two years into this 4-year project, we are using social science methods, in conjunction with the PIs expertise in computer graphics, software engineering, database systems, and environmental science, to refine and answer the four questions articulated.

We hope our approach using mixed methods for defining and analyzing context through (a) surveys of published visualizations, presentation media, and current tools, and (b) ongoing surveys and interviews with end-user ecologists will yield evaluation techniques that could be adopted by other visualization development projects. We have refined the general questions posed below and are specializing and continuing to refine them for the domain in which we work (ecology). We will thereafter again generalize those refined and specialized questions. We believe that the questions can then be specialized and applied by others to domain-specific scientific visualization projects outside ecology and that the questions will help others establish and analyze the context in which end users function, providing insight not only into design features as they are being developed, but also into potential end-user education and training activities.

1. *How and why do particular end-users use visualization tools?* In our study, we observe through our surveys and context-building activities that most ecologists use charts and graphs to report results, unless they use analytical methods or data collection processes during the research process that also produce visualizations.

2. *Which of our targeted end-users do not or would not use our visualization tool, and why not? Why do some end-users make*

greater use of visualization than others, and does visualization use vary with stage of research?

The first two questions are closely related. We are beginning to understand why certain ecologists use "visualizations of interest" and others do not. Our study is confirming our prior suspicions that scientists are not likely to adopt new methods that they perceive are too expensive or onerous to use, or until a critical mass of colleagues adopt them. Scientists also might use new visualizations when the tools they use to acquire data can later be used to analyze data and produce visualizations. Finally scientists working within an established disciplinary paradigm [14] might, as we found, be satisfied using traditional charts, tables, or statistical graphs, while those working across existing paradigms or in new paradigms might perceive a need for novel visualizations and be willing or able to go to extra effort or expense to generate them.

Greater visualization use seems to occur when many colleagues in the discipline use visualization, when data collection and visualization are closely integrated in time, or when ecologists are working on new problems, across disciplines, or in new paradigms. We suspect, from our surveys and interviews, that scientists will use VISTAS visualizations to refine models, form testable hypotheses, explain problems to new colleagues, or to explain results to new audiences. However, more work needs to be done to understand at which stage visualizations such as VISTAS will be most useful and this work will direct both evaluation and development.

3. *What are the characteristics and criteria for "good" visualization or "good" visualization tools?* To answer this question, we focus on the task of *definition building* of a "good" visualization, an inductive research activity, through the ranking and analysis of the current use of visualization within certain contexts. We found that the concept of *good visualization* is dependent on many factors, and that it may change as new tools make it possible for more sophisticated visualizations.

4. *What are the strengths and limitations of a "special purpose" (vs. generalized) approaches to visualization and visualization user interfaces?* While VISTAS visualizations are not particularly novel (see Figures 1 and 2), integrating different types of visualizations from different data formats and different spatial or temporal scales *is* novel and is one of our collaborators' highest priorities.

That said, our surveys have shown that many of the "visualizations of interest" that we discovered are "special purpose;" and we assume there are likely good reasons for this. Do particular kinds of visualizations require particular user interfaces? VISTAS aims to place different visualizations on the same canvas. To what extent can its visualizations and user interface be generalized to accomplish this? What strengths and limitations might "general purpose" user interface approaches bring to visualization? Adding new functionality to overlay different visualization types onto the same canvas will likely require altering the user interface to drive them, and these extensions might make the existing interface less effective or less easy to use. Needing distinct user interfaces for different visualizations would not only impede development, but also might make VISTAS more complicated to use. By understanding the context in which our collaborators use our visualizations we will be better placed to evaluate tradeoffs between a more complex user interface and less functionality.

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