D. PROJECT DESCRIPTION

I. Overview

A significant challenge of the 21st century is making wise decisions about the use and conservation of the world's natural resources. The scientific research informing these decisions is critical due to the imperatives of human-induced global change and is made particularly difficult by the volume and complexity of environmental data and information. With new sensor and measurement technologies, and forthcoming massive environmental observatories (e.g., CUAHSI[1], NEON[2], CEON[3]), the rate and complexity of new data acquisition is increasing exponentially. The sheer amount of data is daunting, but data deluge is but one factor complicating environmental science research. The grand challenges of environmental science, including biodiversity and ecosystem functioning, hydrologic forecasting, infectious disease, and land-use dynamics (NRC 2001) involve multiple spatial and temporal scales with complex, highly distributed and heterogeneous data. The increasing growth rate and complexity of data are driven by urgent needs to address complex environmental issues that threaten sustainability of ecosystem services. The same issues exacerbate problems of information complexity, overflow, and subsequent communication. Increasingly, scientists and decision makers use massive data sets to make and test hypotheses, predict natural phenomena, and make natural resource decisions and policy. New informatics tools are needed to help them to interpret, communicate, and use this deluge. We have assembled a unique team of environmental, ecology informatics, computing, and social scientists and believe our work will transform how scientists use complex environmental data with *visual analytics*.

Visual analytics, the science of analytical reasoning facilitated by interactive visual interfaces, is used to "synthesize information and derive insight from massive, dynamic, ambiguous, and often conflicting data; detect the expected and discover the unexpected; provide timely, defensible, and understandable assessments; and communicate assessment effectively for action" (Thomas 2005). A multidisciplinary field, *visual analytics* includes the informatics research we propose: 1) analytical reasoning techniques to gain insight into assessment, planning, and decision making, 2) visual representations and interaction techniques to explore and understand large amounts of information, 3) data representations and transformations for conflicting and dynamic data, and 4) techniques to support production, presentation, and dissemination of information to many audiences. Our preliminary work suggests visual analytics can help scientists and decision makers more effectively use large data sets and models to understand and communicate complex natural phenomena (Cushing 2009; Kopytko 2009), and we hypothesize that spatially and temporally explicit visualization of ecosystem phenomena across spatial and temporal scales will enhance the capacity of scientists to deal with massive stores of complex data, and to better understand relationships among ecological processes. That said, it is clear that what drives the visualizations and analytics is the data, and that any effort to provide a visual analytics knowledge system must include not only innovative and appropriate visualization and analytics, but also data integration and data management at many levels of abstraction. Also crucially important are 1) a better understanding of which visual analytics are effective – and why, 2) a better characterization of these visualizations and 3) an understanding of how to best develop visualizations and visual analytics.

Goal: Build capacity to transform environmental science research through the research, development, and validation of *visual analytics* – so scientists can better understand and communicate the environmental science Grand Challenges that span spatial and temporal scales.

Achieving our goal requires close collaboration with environmental, computing, and social scientists. We focus on understanding and explaining complex phenomena and processes over space and time by integrating and visualizing data from many sources, and determining which visualizations are most effective, for what purposes, and with which audiences. Our three objectives, each with specific measurable outcomes, are stated below and shown in Fig. 1:

Obj. 1. *Conduct ecology informatics and computing research to enable the visual analytics of environmental science models and data, iteratively co-developing a proof of concept tool: the* VISualization of Terrestrial-Aquatic Systems (VISTAS) *with environmental scientists. Outcomes: 1) VISTAS, and 2) technology transfer (to help assure eventual sustainability) of EcoInformatics and computing methodology and research that assure usability and system integrity.*

Obj. 2. *Conduct environmental science (ES) research using VISTAS jointly with close collaborators, and study VISTAS' extensibility by developing visual analytics for other ES problems (Case Studies) and* *seeking feedback from a wider variety of stakeholders. Outcomes: 1) new visualizations applied to climate change problems, and 2) published environmental science research that uses VISTAS.*

Obj. 3. *Study and improve VISTAS' co-development process, visual analytics, and usability. Outcomes: 1) an improved VISTAS, 2) understanding of which visual analytics work, and why; 3) best practices for engineering complex scientific systems; 4) determination of prerequisite knowledge and skills for co-developers; 5) process for studying co-development of scientific visualizations and software.*

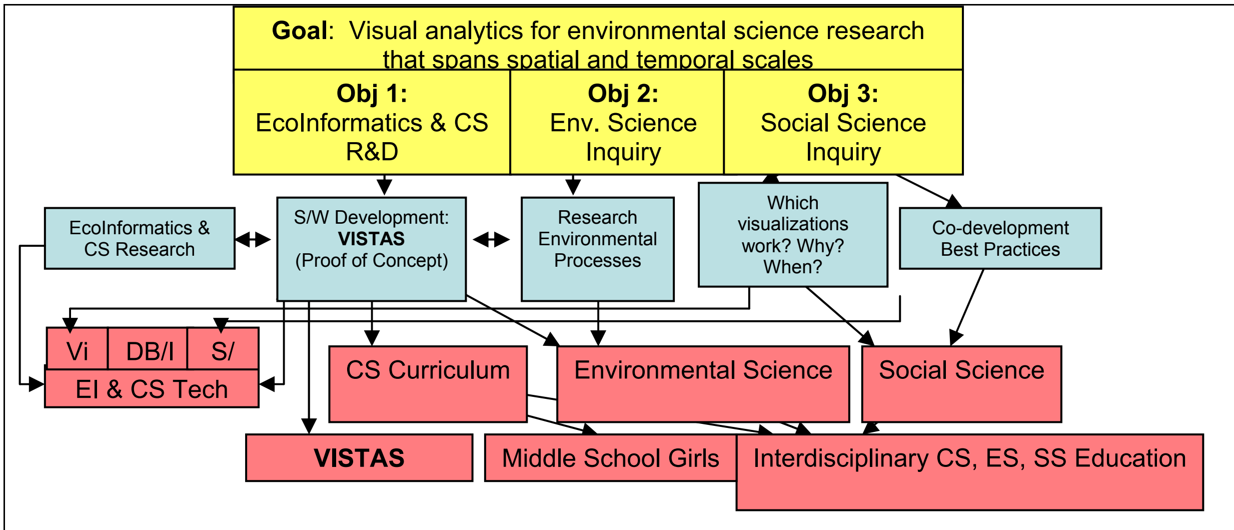


Fig. 1: Fig 1: Project Goals and Objectives linking to discipline specific research objectives. **Yellow** boxes show Project Goals and Objectives; **Blue**: Project Activities; and **Red**: Outcomes, Broader Impacts.

II. Environmental Science (ES) and Ecology Informatics drive VISTAS; Social Science validates it. Here, we articulate the motivation for the proposed work, first with respect to Environmental Science (II-A) and then EcoInformatics (II-B). We argue that the proposed project is motivated by both ES and EcoInformatics. We then state functional requirements and development strategies for the VISTAS software prototype (II-C), and argue that social science methods are critical for determining which visual analytics work with which problems and validating our software co-development process (II-D).

II-A. Environmental Science Research Motivation. Ecologists have long sought understanding of the relationships between organisms, ecological processes, and the environment. We hypothesize that spatially- and temporally-explicit visualization of ecosystem states, processes, and flows across topographically complex landscapes and under varying climatic conditions will enhance scientists' and other stakeholders' (e.g., resource managers and policy makers) capacity to comprehend relationships among ecological processes, ecosystem services and environmental conditions, and to pose testable hypotheses. Fig. 2 shows a scaling process typical of those we have in mind. In particular, we seek: 1) better understanding of emergent properties in complex systems and thus increased ability to limit complexity when "scaling up", 2) increased use of individual natural objects, e.g., trees, forests, water, air, in visualization, and 3) extension of ecology and geoscience findings beyond the plot level.

We reason that seeing the same phenomena displayed at different scales across space and time improves intuition and helps develop new hypotheses – especially in complex, large-scale problems where few analytic tools or research methodologies are available. While our long-term vision recognizes the importance of new media such as VISTAS for a wide range of stakeholders (from specialized scientists, to technicians and natural resource managers, policy makers, educators, to the general public including K-20 students – this project focuses on enhancing scientists' ability to understand natural phenomena and to explain their work to others (scientists of the same or different disciplines, resource managers, and students).

Our recent survey (Stafford, 2009) of information managers (IMs) associated with NSF-funded Long-Term Ecological Research (LTER) sites confirms our own observations that a lack of tools blocks

ES grand challenge research. The IMs, who work closely with scientists at the 26 LTER research sites[4], attest that no one product currently does what we propose, and that VISTAS would be useful to their scientists. IMs further identified data integration as key: researchers struggle integrating data from multiple sources that differ in format, sampling design and collection frequency. The advent of large-scale ecological observing networks has presented the additional challenge of managing very large streams of diverse data. Additionally, scientists have an increasing need to visualize temporal, or 4D, data. With ever-increasing amounts of data at higher resolutions, e.g., LiDAR data, the ability to display large amounts of spatial data without bogging down the computers poses another problem.

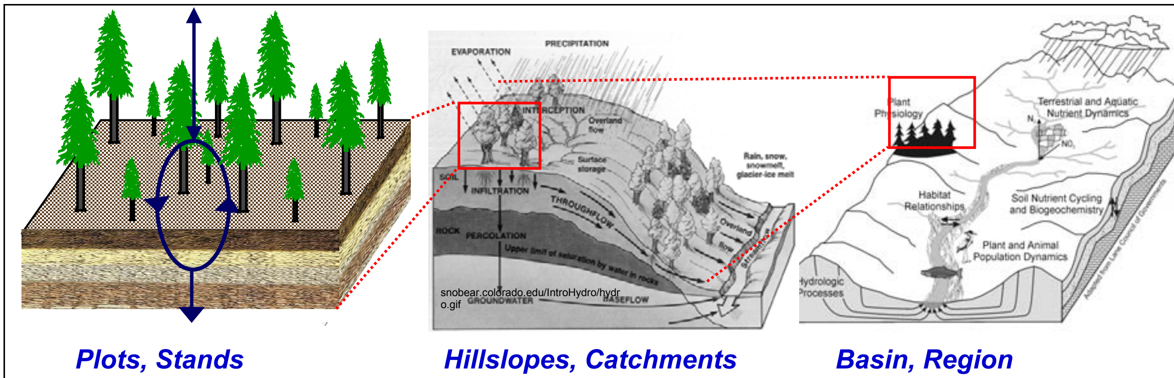


Fig. 2: Eco-hydrologic modeling: Integrate & Scale Up Data from Plots to Region, from Days to Centuries

II-B. EcoInformatics and Computer Science (CS) Research Motivation. Our recent prior work (Cushing 2009; Kopytko 2009) suggests that five issues are key to developing effective visual analytics for ES:

1) **Flexible, intuitive visual analytics** of natural phenomena and environmental processes where visualizations that span spatial scales "safely" take diverse data as input. New visual analytics are critical for gaining intuition about the underlying processes where there are no easy to use tools or generally accepted methodology for developing hypotheses. Scientific visualization is not new and much excellent work exists, but few tools focus on processes (Longley 2009; Beard 2005, 2008; Deveillers 2005), or that easily integrate complex topography (Smelik 2009) with visualizing diverse data and analytics (Thomas 2005). Fewer still allow viewers to scale up or down in both space and time, capacities critical to ES grand challenges (Harmon 1991; Kratz 2003; Peters 2008). Successful efforts to serve these needs will do so with rigorous (e.g., type-safe) end-user programming (Burnett 2009, 2001; Grigoreanu 2008).
2) **Indexing or caching methods to improve visualization performance.** Current research in parallelization and algorithms are important for speeding up rendering, but we found moving data into main memory a bottleneck. We now solve this problem by coding explicit indexes by hand, putting the data into a database. The compute time needed for this is easily amortized, as scientists typically look at a single dataset in many ways once it is connected to the tool, but ad hoc, by hand indexing is error prone and requires technical expertise most scientists don't have and don't care to acquire. A future system must have a more generalized, automated and reliable approach.
3) **Integration, including alignment, of diverse data sets, especially for 2D and 3D spatial data.** Our prior experience with scientists needing to overlay 2D and 3D datasets onto Digital Elevation Maps and data from air- and ground-based Light Detection and Ranging (LiDAR) measurements uncovered the critical problem of aligning datasets. Spatial alignment is necessary for effectively using LiDAR technologies, but as yet there is no reliable way to automate it, and we use error-prone, time-consuming cleaning by hand. We believe computer vision research (Ji 2000; Drewniok 1997; Chen 1990) could help.
4) **Scientific provenance and metadata.** This is now a well-known and well-studied EcoInformatics and CS research area (Buneman 2007, 2006; Bose 2005; Simmhan 2005, Rajasekar 2001), and scientific metadata standards are now also available (FGDC[5], Jones 2005). Less well studied, however, is what metadata scientists actually use, and how to present and use provenance and metadata in data products. Visual analytics must convey more than just engaging images, especially as visualizations are published and passed around on the web among those who did not create them; we therefore seek ways that users

can easily drill down to explore data provenance and metadata of what they view. Delcambre's work with Metadata++ (Weaver 2003, 2004) and Maier's work on product generation (Howe 2002) hold promise.
5) **Characterization and management of uncertain and probabilistic data.** No data are 100% certain, and this is particularly true where data are scaled-up, modeled, or combined. While best practices in Environmental Science include quality assurance (QA/QC) guidelines[6] and statistical distribution error bars as in *Ecotrends*[7], this is inadequate when scientists start combining and transforming data sets to produce other data products. Recently, Suciu presented the database research community with a call to arms for research in uncertain and probabilistic data (Dalvi 2007), and has begun his own work in this area (Dalvi 2009; Suciu 2005). We will seek ways for users not only to characterize the uncertainty of data to be visualized, but for viewers to "see" some indication of the data's uncertain or probabilistic nature.

II-C. Proof of Concept Software System: VISualization of Terrestrial-Aquatic Systems (VISTAS). We aim to address the above issues with a proof of concept system with which scientists can gain insight into the dynamics of complex ecosystems by seeing patterns and relationships emerge from different views of data and model output. VISTAS will meet the needs of environmental scientists whose work requires multiple spatial scales, with diverse data, on questions where there are no readily available methodologies for developing hypotheses spanning spatial scales. VISTAS will enable scientists to compare output of different models and compare models to data, scale visualizations in space to identify emergent properties, and view still or animated model visualizations side by side with data analysis. Work with our science collaborators suggest the following functional requirements:

1) Visualize ecosystem phenomena at multiple spatial scales, from the individual tree or plot levels (1m x 1m), to watershed (1 km^2), to basins (64 km^2) and regional landscapes (2000 m^2);
2) Reliably take as input very large data sets in a variety of formats, where possible without explicitly transforming or converting data, and view multiple data sets on the same canvas.
3) Achieve a visualization – either as a standalone application or as a dynamic library embedded in another application – while the scientist is watching and/or a model is running;
4) View phenomena and landscapes as they change over time, i.e., animation, and export animations;
5) Provide analytics (e.g., simple statistics, charts, graphs) of variables measuring those phenomena side by side with visualization of the phenomena, and export both transformed and aggregate data.

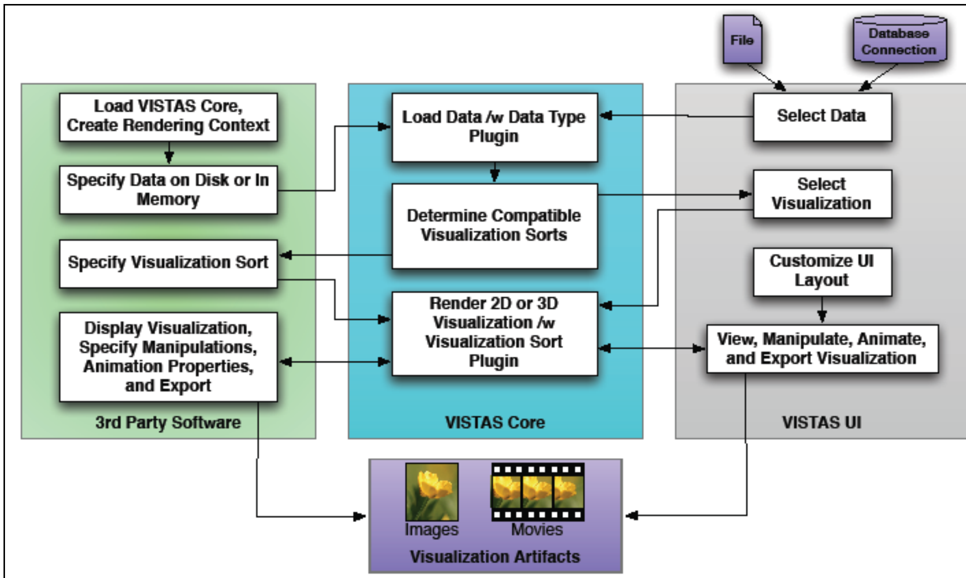


Fig. 3: VISTAS User Workflow. User enters VISTAS through the UI (left column, green), or other software that uses VISTAS as a backend (right column, grey).

Given the above functional requirements, VISTAS will combine onto one canvas visualizations of diverse geo-referenced data representing different phenomena and processes, e.g., 3D trees on a 3D landscape colored to represent land use or topography. VISTAS' landscape textures will commonly represent variables such as land use, climate, water, carbon, nitrogen, toxics, and the growth, death, and decay of plants and soil organic matter on or below the landscape surface. The system will generate animations to show how these variables change over time. We will use plug-ins for common data formats (ArcGRID and ESRI Shapefiles, PostGIS, NetCDF, csv, Excel, image formats, KML, etc.), and provide mechanisms for users to write plug-ins. (*Plug-ins* are software components by which specific capabilities can be added to a larger application. Plug-in inputs and outputs are pre-defined explicitly, and different plug-ins are invoked in different situations. In VISTAS, different file input formats and visualizations are accommodated via plug-ins.) We will provide adequate performance, e.g. render 5-10 sec/frame of a simulation, with data for one frame of about 5 MB, and for a simulation up to 5 gigabytes, plus an accompanying, high-resolution DEM covering resolution of up to 2000 km^2 – providing a range from less than 1 m^2 to 2 billion m^2. VISTAS will run as a stand-alone application or as a dynamic library, embedded as a backend in other software). When embedding VISTAS, provide references to data in memory, interpreted by a specialized data format plug-in. VISTAS will provide simple statistics and other analytics to connect 2D and 3D visualizations, e.g., graph the amount of nitrogen uptake through time for a selected tree in the 3D visualization. A short learning curve should enable users to learn to use it within two to three hours; a user familiar with C++ should be able to write a new plug-in within a week. Fig. 3 shows the VISTAS User Workflow.

Below we outline existing technologies and explain why none currently meets our needs.

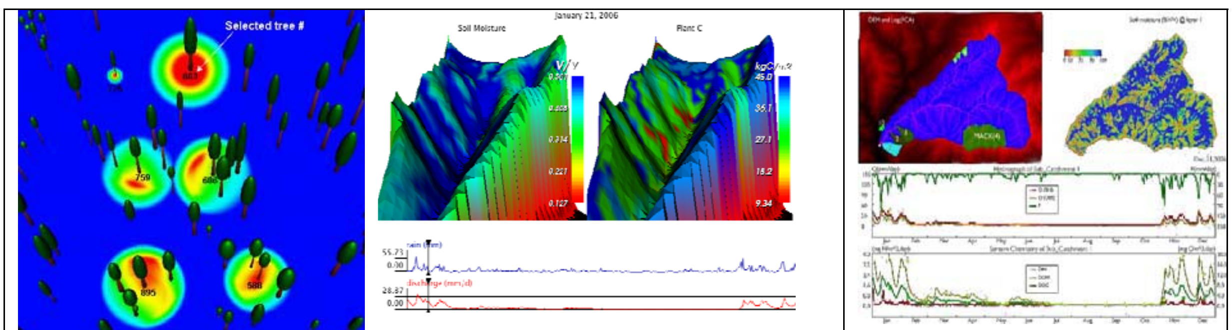
1. **Scientific visualization tools**. *Visualization Toolkit* [8](VTK), OpenDX[9] or our *CanopyView*[10], generate useful images, and provide intuition about the phenomena and some visual data validation, but integrating their images with maps or topography is difficult. Many systems provide some data integration facility, but this remains time-consuming because spatial orientation and scaling must be done.
2. **Existing ecology data warehouses.** Long Term Ecological Research repositories, such as NEON[2], LTER[4,11], LTER climDB[12], EcoTrends[13], and Willamette Explorer[14], provide access to diverse data and good browsing. However, data integration and analysis are typically left to users who must download, combine and analyze datasets. Pre-integrated data stores such as climDB or EcoTrends present analysis results or aggregation, but are of limited utility since they do not provide easy access to source data.
3. **Existing computational or modeling frameworks.** These are insufficient because they are either too specific to an application area, e.g., *UrbanSim* (Borning 2008, 2003) or too generic and do not supply domain-specific support. Further, few computational frameworks provide the ability to view-compare-contrast 3D data and model output with maps or domain-specific visualizations.
4. **MatLab, SAS/SASGRAPH, R, SigmaPlot, Excel.** LTER Information Managers tell us their scientists use these tools for graphs and charts; and ArcGIS, Google Earth, and MatLab for mapping. IMs identified the weakness of these tools as a trade-off between power and usability. Excel's popularity arises from its ease of use and pervasiveness but it lacks creative ways to classify and visualize data. At the other end of the usability spectrum, ArcGIS, MatLab and SASGRAPH are powerful (3D, rotation, multiple coordinate systems, mapping, etc.), but long learning curves mean most scientists rely on staff or students.
5. **Current geographical information systems** (GIS). ArcGIS and Google Earth meet some user needs, but these currently have 3-D limitations. For true 3-D, not only the "x and y" (longitude and latitude), but also the "z" (elevation or depth), are needed. Current GIS often "cheats" by using x-y to hold z in an attribute table, but then height data is not available for analysis (Wright, 2007). In the GIS literature, however, we find major motivation for our work: support for <u>processes</u>. Some geographers contend that underlying data structures force GIS users to think in terms foreign to how they naturally think about the world (Goodchild 2007; Mackaness 2007). Goodchild contends that 1990's GI<u>Science</u> that launched today's GI<u>System</u>s is no longer adequate because it focused on the earth's form – not on the processes that define its dynamics (Goodchild 2004, 2006).

II-D. <u>Social Science Inquiry</u>. While we anticipate that our major ecology domain deliverables will improve understanding of ecosystem complexity, it is critical to measure this through social science methods. The project's EcoInformatics and CS work will enable visual analytics, but the social science inquiry will tell us which visualizations "work" (or not) for which purposes, and with which audiences. Further, the social science inquiry will help us better understand how to co-develop complex software such as VISTAS and how to train domain scientists and computer scientists to that end. Our science collaborators and case study participants will participate in scientific studies and explain research results using VISTAS and VISTAS' visualizations. In addition to domain-specific user-defined data types for input and output data, we will define *visualization sorts*; these are formally described visual templates for viewing data in a 2D or 3D environment. We will test the utility of visualizations and visualization sorts with domain scientists, determine utility of these for scientists to better understand their own work and to explain that work to other scientists, resource managers, policy makers, and students; study extensibility of system to not-foreseen (new) visualization sorts and existing visualization sorts to new visualizations. Results of these inquiries will be fed back into software development and CS research efforts. Outcomes of the social science work will be: 1) improvements to VISTAS, 2) a report of which visualizations work, why, and for what purpose, 3) a documented process for how to study visualization and visualization sorts, and 4) best practices for interdisciplinary co-development of complex scientific software.

III. Proposed research. We propose a 3-pronged, iterative, interdisciplinary approach to meet our goal of transforming environmental science research with *visual analytics* that span spatial and temporal scales.

Obj. 1. *Conduct Ecoinformatics and computing research to enable visual analytics of environmental science models and data, iteratively co-developing a proof of concept tool: the* VISualization of Terrestrial-Aquatic Systems (VISTAS) *with environmental scientists. Outcomes: 1) VISTAS, and 2) technology transfer (to help assure eventual sustainability) of EcoInformatics and computing methodology and research that assure usability and system integrity.*

In the past 15 years, Cushing has developed tools for ecologists[15], e.g., *DataBank*, which uses domain specific database components to help scientists design and populate their own databases and *CanopyView,* 2-3D visualization to motivate database (vs. spreadsheet or flat file) use. As her lab became known among local ecologists, they asked her team to do visualizations they could not build on their own, and the first VISTAS was born. Figs. 4a, 4b show some visualizations we can now create; and 4c a current 2D visualization that we can now easily render in 3D. This experience has led us to conclude that the proposed visual analytics is needed, and that it cannot be built with existing technology. Although the current VISTAS handles only a few kinds of visualizations, works only with a few data types, and handles only datasets up to the basin scale (Fig. 4c), it adequately demonstrates feasibility and usefulness.



4a. Effect of tree size & competitors on nitrogen uptake in a 400-yr forest. Visualized patterns not evident in raw data provide new insight into forest habitat structure.	4b. Patterns of soil moisture and plant C for a headwater catchment visualized on 3D topographic data help scientists calibrate simulation models used for scaling up experimental data in space and time.	4c. Visualizations at basin scale help users understand & communicate climate change & forest harvest: stream network, soil moisture, stream water quality & quantity.

Fig. 4: The current VISTAS prototype already helps scientists display & interpret very large data sets. From left to right, visualizations from a) 0.1 km² forest stand, to b) 1 km² catchment, to c) 64 km² basin. (b) & (c) can be animated showing change over time.

VISTAS' requirements were established during a pilot project to understand hydrology and biogeochemistry at the HJA Experimental Forest[21]. One product of the pilot was the capability for 3D viewing of hydrologic processes in multiple soil layers, which added the opportunity to visually interpret changes in vertical vs. lateral water flow within a headwater catchment (Fig. 4b). Participating scientists stated that the 3D visualizations provided a new intuitive grasp of how topography, soils and climate interact to control water and nutrient transport within watersheds and that these visualizations help parameterize and validate the model. The proposed work alleviates barriers faced thus far with VISTAS:

1) **Flexible, intuitive visual analytics spanning spatial scales, "safely" taking diverse data as input.** We intend to accomplish this goal with "Visualization Sorts" and user-defined data types, building on our experience with database components and others' work with data types for end-user programming (Burnett 2009, 2006, 2001), and domain specific languages (Kieburtz 2000). We define *Visualization Sort* as a generalized 2D or 3D visualization, e.g., 1) the *3D DEM-landcover visualization sort* overlays geo-referenced landcover data on a digital elevation map, 2) the *nutrient uptake visualization sort* takes an object with x-y plot coordinates, height, crown radius, soil nutrients as input. These two *visualization sorts*, populated with data, are shown in Figs 4a, 4b. A given visualization sort can be associated with one or more analytics, shown in charts and graphs in Figs 4b, 4c. A given data set can be used as input to more than one *visualization sort*. A visualization sort has a many to many relationship with data type and will be associated with allowable input data types. We expect scientists to use several visualization sorts simultaneously to view several disparate datasets or different aspects of the same dataset, e.g., a *categorical colors visualization sort* might take categorical data such as vector land use data and project corresponding colors onto a 3D landscape, whereas a *categorical symbols visualization sort* might take the same data and represent land use by placing 3D symbols above the landscape. The user could choose to see both visualizations on the same canvas, resulting in a colored landscape with 3D symbols, or one dataset as colors and another as symbols.
2) **New automatic indexing or caching methods to improve visualization performance.** For data management, VISTAS relies on data format plug-ins to load, manage, and interpret data. Depending on the nature and expected size of a data set, a plug-in might load data into memory all at once, keep a fixed-size cache in memory and load new data as needed using a dynamically generated indexing scheme, or keep no data in memory and read data as-needed or "greedily". While our visualization sorts described above should alleviate run-time data type errors, this work will provide for efficient data input for a variety of plug-ins. We accomplished this in the existing system with standard database indexing, but for the future we will need specialized, parameterized indexing and/or caching schemes. We look to Maier's expertise in query optimization to guide this work (Franklin 2005).

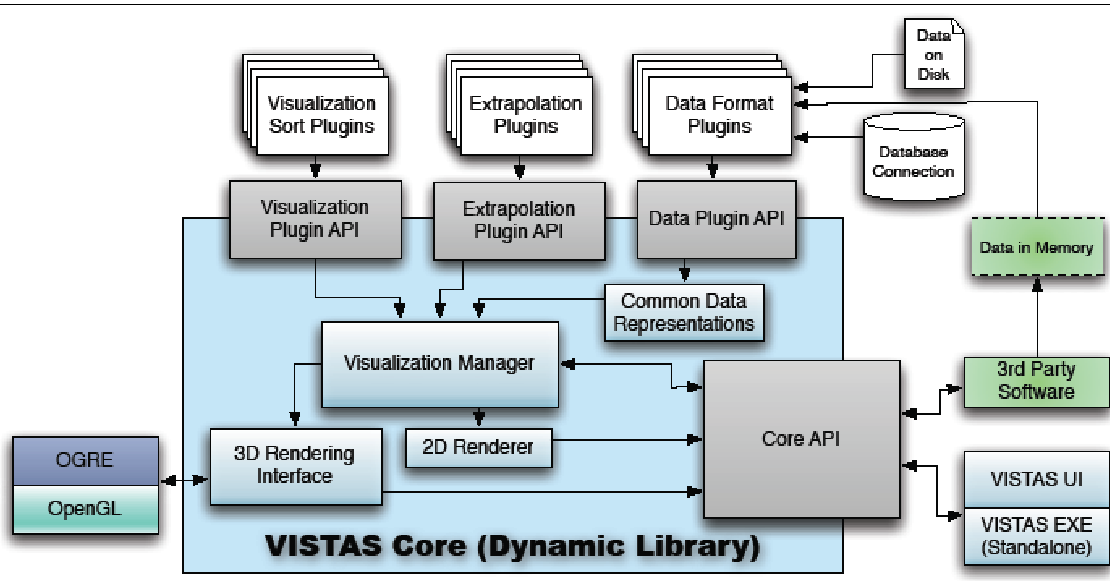


Fig. 5: VISTAS Software Architecture.

The proposed VISTAS software architecture (Fig 5) provides a dynamic loosely-coupled solution for combining disparate data with 2D and 3D visualization to support viewing ecological processes. The architecture has two main components: 1) the VISTAS Core (Dynamic Library) and 2) the Core API and User Interface. The VISTAS Core compiles as a dynamic library, which could be used with the VISTAS UI as a stand-alone, desktop application, or embedded in 3rd party software, such as the GIS-based simulation application Envision. Many sub-components are existing technologies. The **VISTAS Core** will include a 2D renderer and an interface to a 3D graphics rendering engine; it combines data with visualizations via multiple plug-ins. **Data Interpreter Plug-ins** read data from a source (file on disk, database connection, or data in memory) in native format, exposing them to VISTAS in a common representation. Data are then provided to **Visualization Sort Plug-ins**, which generate 2D and 3D visualizations via the 2D Renderer and 3D Rendering Interface. VISTAS' plug-ins are compiled as dynamic libraries, loaded at run-time, and essentially provide user defined types (UDTs) for data and visualizations, and will be generalized and parameterized so that slight modifications, e.g., to a particular visualization, can be done without revising or writing new plug-ins. VISTAS rendering is accomplished via a **3D Rendering Engine**, likely the Object-oriented Graphics Rendering Engine (OGRE[15]), a mature project providing complex scene management and rendering optimization. VISTAS' componentized design means the engine could be replaced without necessitating changes to the rest of the system.

The new VISTAS will be usable as a stand-alone desktop application, or as a backend to an existing application: 1) The **VISTAS UI** provides a standalone application. Future users will be able to customize the User Interface, adding or removing views, graphs, statistics, options, and controls, and controlling camera movement and creating animations such as fly-throughs, then exporting such animations as movie files. 2) A future software developer will be able to include VISTAS as a dynamic library in another application, controlling it through the **Core API**. Data-producing applications could provide references to data in memory through a custom data plug-in, negating the need to first write data to disk and considerably reducing the time between data production and visualization and memory use.

Obj. 2. *Conduct environmental science (ES) research using VISTAS jointly with close collaborators, and study extensibility of VISTAS by developing visual analytics for new problems (Case Studies) and then seeking feedback from a wide variety of stakeholders (Symposium on Visualizing Climate Change). Outcomes: 1) new visualizations applied to climate change, 2) published environmental science research.*

The chosen ES problem is to visualize the output of land use and process-based models that simulate cycling and transport of water and nutrients (C, N and P) within plots, hillslopes, and watersheds. This represents the kinds of processes and spatial and temporal scales common to other ES grand challenges, in particular involving the consequences of land use in the face of climate change. We circumscribe the ES goal as follows, to render it feasible: 1) Focus on one region encompassing several ecosystems – the crest of Western Cascades, to the headwaters of the Willamette River, along the Willamette River Valley. 2) Limit our investigation thematically to ecosystem services of water and carbon. 3) Restrict spatial scaling of model results and field or sensed data, at least initially, to one Western Cascades area, and to process-based models: ecohydrology (McKane, Stieglitz, Rastteter – GT- MEL), atmospheric science (Thomas – air exchange between forests and the lower atmosphere) and land use (Bolte – Envision). 4) Limit visualization and animation to four or five spatial scales.

The chosen region is particularly appropriate as a test bed because the heterogeneity and complexity of environmental states and conditions, including topography, precipitation, temperature, soils, and vegetation, are greater in this region than anywhere else in the United States (Hargrove 2003). Projected rapid population growth and climate change are likely to place especially heavy demands on this area's natural resources (Governor's Climate Change Integration Group 2008). Given the ES goal of the project: to gain insight into the complex ecosystem services of water and carbon in terms of their natural and built components and the underlying topography – from the forested lands of the Oregon Western Cascades, to the river valleys of the McKenzie and Willamette (Fig. 7), we set specific staged deliverables to help us achieve project objectives, and eventually our goals. The proposed project area lies in the vicinity of the HJA LTER site which archives[16] very large environmental datasets (Stafford 1984) and thus will provide VISTAS with a wide variety of ES data. Current HJA research focuses heavily on complex interactions between climate and ecological responses, so HJA is an ideal setting for the proposed project because it builds synergistically with ongoing LTER research there, which will provide a 'control' for each investigation, allowing us to examine the interpretation, communication, and use of LTER data in the absence of visual analytics.

We will work with five scientists on the simulation of cycling and transport of nutrients and its effects on land use; each has committed to use VISTAS in their work: 1) Ed Rastetter of the Marine Biological Laboratory, Woods Hole, MA, developer of a biogeochemical model MEL (Rastetter 1992, 1997, 2005), 2) Marc Stieglitz of Georgia Tech, author of a hydrological transport model GT (Stieglitz 2003, 2006, 2007; McKane 2010), 3) John Bolte, creator of an agent-based land use scenario generator *Envision*, a GIS-based decision support tool integrating stressor scenarios, decision rules, ecological models, and evaluation indices within a GIS framework (Bolte 2008, 2007), 4) Bob McKane, current EPA collaborator on Envision Andrews, and 5) Christoph Thomas, Ass't. Prof. OSU, who works with spatially distributed point-measurements of air flow, air temperature and humidity to understand how these vector and scalar fields communicate across the landscape and to investigate motions of scales from tens to hundreds of meters (Thomas 2009, Turner 2009). CoPI Barbara Bond, PI of the H J. Andrews LTER Site (HJA) will organize the spatial and temporal integration research and facilitate the use of HJA data for the development effort.

The ES research plan involves first incorporating visualization and animation into all fluxes (water, carbon, atmosphere, nutrients) for the Andrews watershed in the Oregon Cascades. Once that is complete, we will work at lower spatial scales to visualize "individual tree" models, e.g., McKane's spatially explicit mapping of tree root systems as in Fig. 4a and fluxes through individual trees (Bond 2008), and then the scale of small basins (Bond 2002). Bond, McKane, Stieglitz, Rastetter, and Thomas, funded independently, will develop a simulation of the Blue River basin, which contains Andrews as one of several watersheds. At the far end of the scale, we will be working with coPI Bolte on visualizing landscapes up to 2,000 km^2 (Bolte 2007), aimed to help make decisions affecting tradeoffs among multiple ecosystem services in complex landscapes.

Stieglitz and Rastetter respectively developed GT and the Multiple Element Limitation Model – MBL MEL[17]. McKane and Bond are working with them to combine these into one GT-MEL model providing spatial and temporal information on nutrient acquisition in plants and soils, terrestrial pathways of water flow, and discharge of water and nutrients to surface waters. The same kind of model applies to <u>any</u> terrestrial system – agriculture, forests, grasslands, wetlands, tundra, etc., making GT-MEL an ideal test bed for the proposed visual analytics. Current plans for HJ Andrews LTER research call for coupling the *GT-MEL* process simulation models with the GIS-based model Envision, an agent-based, value-driven model of landscape change in large river floodplains that determines human land use impacts. It incorporated research on fish and wildlife communities, alternative landscape development, quantification of human behavior, and adaptations to resource scarcity (Hulse 2008; Guzy 2008; Bolte 2007, 2008). The tripartite model will be able to simulate human impacts on a wide range of ecosystem services: food and fiber production, carbon sequestration, provisioning of clean water, flood protection and greenhouse gas regulation, thus quantifying the effects of multiple interacting stressors, like changes in land use, land cover, climate, atmospheric CO2 and nitrogen deposition.

Merging GT-MEL with *Envision Andrews* provides a regional scale visualization and animation problem for VISTAS. We thus see VISTAS improving understanding of ecosystem services over five spatial scales: fluxes within individual trees (roots, stems, leaves), hillslopes, small watershed (Andrews Watershed 1), large basin (McKenzie Basin), and region (Willamette Valley). During this grant, we commit to completing visualizations at the first four scales (up to large basin), and to making some headway at the 5th (regional) scale. Success using VISTAS to visualize and animate outputs of complex models with relevant field and sensor data, at different spatial scales, to an adequate and meaningful level of representation, would provide evidence that VISTAS is applicable to many other ES problems.

<u>Case Studies: VISTAS extensibility</u>. We will spend the first two years of the project working intensively with our close collaborators on developing visualizations for their problems. Then, we will test our assumption that our collaborators' visual analytics are representative of other complex ES problems, convening a group of five scientists whose work constitutes case studies differing from our collaborators' work. Prior to each case study, the scientist will provide a written description of his/her scientific problem along with the data or model used to solve it; they will convey barriers to solving their problem and preliminary ideas for visualizations to gain insight into the problem, or increase explanatory power of their results. In consultation with each scientist, we will engage one educator or resource manager to identify and characterize difficulties in conveying the problem or research results to non-researchers.

Each case study will also engage one student who will work with the VISTAS programmer to use VISTAS to develop visualizations. At the end of the case study period, we will convene case study participants, with the VISTAS project team and our five collaborating scientists, to review and vet the new visualizations. We will classify the new visualizations into three categories: 1) ones we could accomplish with no changes to VISTAS, 2) ones we could accomplish within one month by writing new plug-ins or visualization sorts, and 3) ones not provided for in the original functional requirements that would require major extensions. The VISTAS team will prioritize category 3 visualizations, and decide on an implementation plan for the remaining year of the project.

Mid-way through year 3 of the project, we will further test VISTAS extensibility with a Symposium: *Visualizing the Future in the Pacific Northwest*, to which we will invite a range of stakeholders: scientists, resource managers and other decision makers, educators, and students. This one-day workshop on the scientific issues involved in determining future ecological change in the Pacific Northwest will involve our science collaborators and case study participants, who will use VISTAS visualizations to present ES research. They will discuss the extent to which the visualization helped them. During breakout sessions we will seek feedback from participants on the extent to which VISTAS conveys research results.

Obj. 3. *Study VISTAS' co-development process, visual analytics, and usability. Outcomes: 1) an improved VISTAS, 2) understanding of which visual analytics work, and why; 3) best practices for engineering complex scientific systems; 4) determination of prerequisite knowledge and skills for co-developers; 5) process for studying co-development of scientific visualizations and software.*

Prior to, during, and after the development of the visualization products, we will collect information including: expectations for usability of scientific results and visual analytics; problem framing; knowledge of and expectation for visualization products; and attitudes about and experiences working with members of the interdisciplinary team. Information will be collected primarily through semi-structured interviews with participants, although existing scales measuring environmental attitudes (Dunlap 2008), and preferences for science in decision-making and general attitudes toward science (Steel 2001) will also be used so comparisons with larger national and international samples can be made. In addition, "scoping" and development meetings will be observed to determine how shared understanding of user needs is developed and then framed as a visual analytics problem, as well as how the visualization tools serve as boundary objects to facilitate collaboration. Approximately three months after completion of a visualization product, semi-structured interviews will again be conducted with study participants. In addition to the questions and scales used earlier, we will also assess satisfaction and usability. Qualitative information will be analyzed through thematic coding that will set baselines and changes in understanding, preferences, and expectations of case participants. In addition, contextual information about the specific cases will be collected for cross-case comparisons as required. Information from work with ES collaborators will be analyzed to identify issues specific to the co-development process as well as general processes for developing and using visualization products for communication.

Case study research is a traditional approach in both social and ecological research where, in some cases, dynamic phenomena are examined in situ. While statistical control is impossible in most case studies (they are unreplicated), this approach is appropriate for developing an initial understanding of complex causal paths and mechanisms, and identifying causal inputs and interaction effects that might not be operationalizable as variables in a statistical study (Yin 2008). Case studies are particularly helpful for generating theory in a developing field. We will analyze the cases using a pre-post test design (Jensen 2001) to explore how the visualizations as well as the process of developing the visualizations affect the ability of scientists to 1) understand their data in innovative ways and 2) communicate that new understanding to others including nonscientists (e.g., Burleson 2005).

We recognize limitations to case studies and address these with the pre-post test design and use of multiple methods to track key constructs and processes. While case studies do not substitute for randomized control treatment experiments, many phenomena of interest are not amenable to traditional, positivistic scientific approaches. Due to the dynamic and complex nature of both social and ecological systems, generalizability is a problematic concept when exploring phenomena in situ. The goal of case studies is typically testing of and/or generalizing to theory, including the development of models, which can then be tested in subsequent case studies or through more traditional scientific methods.

Research Design and Methods. This comparative, *pre-post test* design has three phases in which we explore changes in the way participants view and communicate their scientific results before and after involvement in the visualization development. For each of the cases, in the ***baseline*** phase we will work with participants to document their current understanding of their data, their expectations for the visualization products, and their ability and tools used to communicate their science to others including non-scientists. During the ***visualization*** phase we will observe case participants work together to create the visualization products. The ***post-assessment*** phase seeks to determine changes in understanding of data and ability to communicate their science as a result of participation in the visualization development. We will also explore the usability of different types of visualizations, identifying the characteristics that contribute to or distract from usefulness.

Using a semi-structured interview approach with both groups and individuals allows for an initial set of questions developed from existing knowledge and the current literature as well as follow-up project relevant questions that arise during the interview. Group interviews will be video-recorded and individual interviews will be audio-recorded and all subsequently transcribed for analysis. In addition, development meetings with scientists will be video-recorded and transcribed for analysis. Using the techniques of the clinical interview allows us to create complex and rich descriptions of participants' basic understandings of their science and the visualization products. Content analysis of interviews and observations allows us to compare pre- and post-visualization development data. We will also analyze across development processes to identify any context-specific lessons learned and best practices. During this phase we will also complete a comprehensive evaluation of the program, focusing on changes in the capacity of participants for understanding and communicating the results of research.

Lach has research experience in understanding how scientific information, especially complex information, can be utilized by decision-makers. In research funded by NOAA, she and colleagues explored how water resource managers around the country might integrate probabilistic climate forecasts in short- and long-term decisions (Lach 2005). In research funded by NSF, she and colleagues are exploring expectations by managers for the role of ecological science (and scientists) in national resource decisions(Lach 2003; Steel 2001). She has extensive experience in the qualitative methods described here, including program evaluation.

IV. Collaboration Plan and Time Table.

We have engaged a new team of PIs, collaborators and participants: Project PIs are drawn from several disciplines and have in common the expertise, experience, and drive to create intelligent information systems to address grand challenge ecology questions.

PI Cushing will provide overall project coordination. She has 25 years experience with NSF, government, and private sector projects, and significant experience in databases, ecology informatics, and software engineering. She will be responsible for the EcoInformatics research, and coordinate the *Northwest Computer Science Consortium to Enhance the Study of Climate Change.* Jointly with coPI Bailey, she will conduct monthly development staff meetings, and organize quarterly all-hands project meetings and annual all-hands project reviews. She will work with Evergreen colleagues to include materials from this project in the undergraduate CS and ES curricula, and into the professional master's ES program. She will engage one graduate student and two or more undergraduates in this research.

CoPI Bailey (Computer Science) has significant expertise in scientific visualization, 3D interactive computer graphics, GPU programming, and stereographics, as well as in scientific software development. Bailey will guide graphics and visualization research, lead the VISTAS development effort with the graduate student, and work on curricular development for graduate and upper division CS and middle school girls. He recently surpassed the 3,200 students-taught mark, and has won 8 university teaching awards and 2 education-outreach awards.

CoPI Lach (Social Science) has significant experience with environmental researchers and managers on communicating and integrating scientific results into operational and policy decisions. Working with a graduate student, she will be responsible for tracking, documenting, and publishing regarding the co-development process and will work closely with the scientists to determine which visualizations work and why.

CoPI Bond, currently PI of the NSF-funded H.J. Andrews (HJA) Long Term Ecological Research Site, has provided environmental science vision for this project, and was instrumental in building this project team and setting the domain science goals and objectives. She will continue to serve in that capacity, helping to assure ready access to HJA LTER data, and will participate in the Case Studies Workshops (Years 2, 3) and in the Symposium *Visualizing Climate Change* (Year 3), as well as annual project reviews assessing and suggesting realignment of goals and objectives.

Environmental Science Collaborators are chosen for scientific expertise, fit with the project, and record of collaboration. They will work closely on VISTAS' co-development, visualizations, and visualization sorts, defining VISTAS requirements, and contributing data, algorithms and models. Although each collaborator's ES research is funded independently of this proposal, each collaborator (except McKane, a full time EPA employee) will be compensated $10,000/year for two years for the additional work involved in VISTAS co-development, e.g., preparing data, reviewing visualizations, attending project reviews.

Researcher	Institution, Environmental Science Expertise, and Project Role
Bolte, John	Prof. and Dept. Head, Biological & Ecological Engineering, OSU. Develops multi scale bio-complexity models for resource management, and authored *Envision*. Bolte will work closely with VISTAS developers on visualizations, visualization sorts, and implementation of the VISTAS API as a backend to *Envision*.
McKane, Robert B.	Ecologist, Western Ecology Division, U.S. Environmental Protection Agency. He has collaborated with Bond, Bolte, Stieglitz, and Rastetter on hydrology and climate change for the HJ Andrews and Willamette Region. In that role, he has been co-developing VISTAS with Cushing's lab.
Stieglitz, Marc	Assoc. Prof. Georgia Tech. School of Environmental Eng'g and Earth-Atmospheric Sciences. Hydrologic and atmospheric modeling at large spatial scales; GT author. Stieglitz will work on VISTAS visual analytics for GT model data.
Rastetter, Edward	Sr. Scientist, Marine Biological Laboratory, Woods Hole. He models how ecosystems are regulated through interactions among carbon, nutrient, energy, water cycles, and authored MEL. Rastetter will work on VISTAS visual analytics for MEL model data.
Stafford, Susan	Prof. and Dean Emeritus, Dept. of Forest Resources, Univ. Minnesota. Prior chair of the NSF BIO Advisory Committee and now of NSFs Advisory Committee on Environmental Research and Education; see *Transitions and Tipping Points in Complex Environmental Systems* (NSF 2009). Stafford also led the NSF-funded *New Media Workshop on Citizen Science in a Wired World*. She will organize our Year 3 *Symposium on Visualizing Climate Change* and contribute to outreach to resource managers and the LTER IM Community.
Thomas, Christophe	Ass't. Prof. College of Oceanic and Atmospheric Sciences, Oregon State Univ. He is a recent NSF CAREER Awardee whose interests include atmosphere-vegetation interaction, atmospheric turbulence, scale transitions from milliseconds to hours and days, and spatially distributed sensor networks. He will work on VISTAS visualization of air exchange between forests and the lower atmosphere.

Northwest Computer Science Consortium to Enhance the Study of Climate Change. The CS Advisory Board, under Cushing and including Bailey, will meet annually to review the project's progress, and suggest ways recent CS research can be applied, thus improving the project's CS research and disseminating project artifacts to the CS community. Each member's research is targeted for inclusion in VISTAS. Orr will be paid two weeks per year and others for 2-3 days per year (all as consultants).

Researcher	Institution, CS Expertise, and Project Role
Burnett, Margaret	Professor, OSU. Programming languages, HCI, and software to support end-user programming. She will help the team add CS rigor (type checking) in matching data and visualization types, and with usability testing.
Delcambre. Lois	Professor, Portland State Univ (PSU). Database semantic models and metadata. Delcambre will work with the team to exploit domain expertise as superimposed information to enhance information retrieval and analysis.
Maier, David	Professor, PSU. Data interchange, data-product generation, data stream & database query processing. Computer science issues in environmental observation & forecasting. He will help assure state-of-the-art data interchange, & visualization indexing & query.
Orr, Genevieve	Professor and CS Dept. Chair, Willamette Univ. Computer graphics and undergraduate curricular innovation (NSF CPATH grant coPI). She will develop curricular materials and work with the team on visual analytics research, and is active in ACM SIGGRAPH education activities.
Shapiro, Linda	Professor, Univ. Washington. Computer vision, multimedia retrieval, and biomedical informatics. She will work with the team on computer vision inspired pattern matching to align diverse data sets.
Suciu, Dan	Professor, Univ. Washington. Formal theory applied to data management, semi-structured data, query, type inference, compression, unreliable inconsistent data. He will work on the uncertainty and probabilistic aspects of VISTAS data, type inference.

Case Study Participants: The case studies will determine VISTAS' extensibility beyond the research of the ES collaborators. We defer final selection of participants until mid way through Year 1 when we have a better idea of how to assure environmental science coverage, but have begun preliminary discussions with: 1) Keith Olsen, Research Associate, OSU, who is responsible for the HJA LTER Air-based LiDAR data; 2) Dominique Bachelet, Assoc. Prof., OSU, who has worked with us to visualize her climate change models; 3) Monika Moskal, Assoc. Prof, Univ. Washington, a spatial environmental scientist who works with ground-based LiDAR, 4) Carri Leroy, Faculty, Evergreen, who has expertise in ES statistics and analysis, 5) Dylan Fischer, Faculty, Evergreen, who directs The Evergreen Ecological Observation Network (EEON)[18]. For each case study scientist, we will engage a partnering Natural Resource Manager or Policy Maker from the region.

Project Timetable			
Objective	**Year 1**	**Year 2**	**Year 3**
Overall Project Goals (All Hands)	Setup project organization & communication. Plan Case Studies Workshop. Present preliminary results. Release VISTAS Prototype.	Determine VISTAS extensibility with Case Studies. Publish results. Release new VISTAS.	Final VISTAS Prototype. Symposium: *Visualizing Climate Change in PNW*. Publish results & co-dev't. best practices.
Obj 1 EcoInformatics & CS R&D	Re-implement VISTAS with new architecture and recent CS research results. 1st of 3 annual CS Consortium Meetings.	Prioritize, conduct new CS research; abstract visualizations into "sorts". Develop new visualizations.	Implement new CS into VISTAS, refine all current visualizations. Test & release.
Obj 2 ES Inquiry	Articulate & prioritize VISTAS requirements; Contribute model data. Test, critique new VISTAS.	Reprioritize VISTAS requirements. Co-design & test new vis. Evaluate research results w/ vis.	Publish & present VISTAS visualizations w/ research & teaching.
Obj 3 Soc. Sci Validation	Observe co-development process; develop scientist baseline mental models	Continue observations of scientists; study case study co-development.	Identify changes in scientist mental models
Broader Impacts (Technology Transfer, Curriculum, Dissemination)	Update & Publish ES/CS0 modules. Visualizations for Algorithmic Art & G7-8 girls. Student research. Initiate industry and LTER contacts.	Refine prior curricula. Ingest ES Vis into undergrad CS graphics. Continue G7-8 girls pgm. Student research. Present VISTAS to industry & LTER.	Vis. For Enduring Legacies. Refine & publish curricula. Continue G7-8 girls pgm. Student research. Plan tech transfer. VISTAS LTER Workshop.

Communication Strategies. During proposal development, interactive internet meeting software was used frequently and effectively to enable regular communication among the PI and her VISTAS team with the co-PIs. Internet conferencing will continue to be used at regularly scheduled monthly meetings (weekly when deemed necessary). Travel funds have been budgeted for the yearly all-hands meeting.

V. Dissemination, Technology Transfer, and Broader Impacts of the Project's Intellectual Merit. This project takes seriously obligations to assure dissemination and technology transfer (sustainability) of research results and tool development beyond this NSF funded project, and the integration of broader impacts with its research. PIs Cushing, Bailey, and Bond have long standing contacts with the scientific software producers (e.g., ESRI, Google, IBM, Microsoft, National Laboratories, Super Computing Centers, LTER Information Managers). In addition, PIs Cushing and Bailey and Collaborators Bolte, Rastetter, Stieglitz, Burnett, Delcambre, Maier, Shapiro, and Suciu have all published software and have experience with both scientific and informatics software users beyond the relatively small circle directly involved in R&D activities in this proposed ABI Innovation Project.

Broader Impact efforts start in Year 1 and continue throughout the project. We include explicit plans for disseminating R&D to the larger Environmental Studies, EcoInformatics and Computing communities, and for integrating interdisciplinary research results into undergraduate and graduate curricula, and into student research. We also plan to include the project's visual analytics into a girls' middle school program. Women PIs and collaborators (3 of 4 PIs, 5 of 12 collaborators, 3 of 5 case study participants) serve as role models and mentors for women in the computing, social, and environmental sciences; all have records of outreach to and mentorship of young women. We will publish and present curriculum development both regionally and nationally. In addition to the usual dissemination of research results (journals, conferences, project web site) and our Year 3 Symposium *Visualizing Climate Change*, we outline below specific plans for technology transfer and outreach.

1) Research Dissemination and Technology Transfer: Involving computer scientists in EcoInformatics. *The Northwest Computer Science Consortium to Enhance the Study of Climate Change* will aim not only to improve this project's intellectual merit, but also to encourage the CS research community to integrate environmental science informatics needs into their own research. In addition to the impact of our research within CS, we expect our software, data, and models to provide systems and test data for future CS research. We therefore pledge to: **1) Articulate CS research problems inherent in tools for ES grand challenges.** We will seek expert advice for our own research and for dissemination from our newly formed *Northwest Computer Science Consortium to Enhance the Study of Climate Change*. This consortium of seven senior computer scientists will convene annually to review our research and software deliverables, identify new CS research directions, and help disseminate those to the CS community. **2) Publish software and datasets that can be used by computer scientists in conducting research to help environmental scientists address grand challenges.** While ES data are available (e.g., NASA's EOS[19], EcoTrends[13] (Servilla 2008), P2ERLS[20], NEON[2], and CUAHSI[1]) and are likely to increase in the next decade (e.g., DataONE[21]), published software and datasets, accompanied by CS research publications(Cushing 2007a; Bowers 2004; Gomes 2005, The Cornell NSF Expeditions Project[22]), increase the ability of CS researchers to conduct both basic and contextualized research.

2) Technology Transfer: Outreach to information managers, environmental scientists, and industry. Conducting basic ecoinformatics and computing research and creating a software prototype that meets needs of the environmental science research community is a first step towards providing needed informatics to this community and transforming research practices. The information technology must also be disseminated and adopted. We seek to move from data to knowledge, and from knowledge to action, and will disseminate our work to those who provide software support to environmental science researchers (e.g., Super Computing Centers, National Labs, and the LTER Information Managers). The science collaborators have also agreed to present VISTA visualizations with their findings. We will also present results to industry leaders who now provide technologies for environmental science researchers (ESRI, Google, IBM, Microsoft).

3) Broader Impacts: Outreach to decision makers. *Transitions and Tipping Points in Complex Environmental Systems* (NSF 2009) recognized a need to better integrate knowledge across disciplines and called for the advancement of decision support tools using visual analytics. If this project is funded, PIs Cushing and Lach, and collaborators Stafford and Bolte will initiate follow-on work involving the direct use of VISTAS and other visual analytics by resource managers and policy makers in Washington and Oregon. Stafford also led the NSF-funded *New Media Workshop on Citizen Science in a Wired World* (Exploratorium, 2008) which looked at ways new media can enhance environmental literacy.

4) Broader Impacts: Integration of our research results into education for upper division and graduate environmental science and computer science, and with interdisciplinary research experiences for undergraduate and graduate students. All PIs will also engage undergraduate and graduate students in interdisciplinary informatics and environmental science research. We believe that most future development of scientific software will be accomplished by scientists themselves, rather than by computer scientists, and that therefore it is critical to educate tomorrow's scientists and resource managers with an understanding of computer science that goes beyond that needed only to effectively use software. Therefore, PIs and Collaborators will develop course content for environmental science students, and PIs will contribute VISTAS information to the newly NSF-funded digital clearinghouse to advance education about climate change for undergraduate students and faculty (Climate Adaptation and Mitigation E-Learning – CAMEL), which will be part of The Encyclopedia of Earth[23].

PIs Cushing, Bailey and Collaborator Orr commit to developing CS curriculum that uses the project's research. As environmental scientists seek collaborations with computer scientists, we will interest CS students in EcoInformatics by using scientific data and applications in CS courses. We have preliminary evidence that visualization and socially relevant applications draw new students to CS, broaden participation, and increase retention (Cushing 2007b). Bailey has developed a 3D-teaching program and

Orr is coPI of the NSF-funded CPATH Project *Building the Northwest Distributed Computer Science Department (NWDCSD)*[24]. This project will use NWDCSD mechanisms for validation and dissemination, and builds on Orr's prior work with arts students[25] (Orr 2009a,b,c) and Cushing's with CS and environmental science students (Cushing 2007&2009). This work complements the SIGGRAPH 2010 Workshop *Inspiring Computer Graphics Education with Scientific Data* proposed by Orr and Bailey.

Finally, because there is evidence that new media, incl. visual analytics, can enhance and improve environmental literacy and spark interest in science (Economist 2007; Exploratorium 2008; Kuester 2006, Zyda 2007), two smaller projects reach out to populations where increasing participation in science has proven difficult: middle school girls and Native Americans. Women remain underrepresented in computer science and in technical environmental science fields, and girls are often lost to science in the early teens. Bailey will extend his existing summer program for middle school girls (shape, sketchup, and gamemaker[26]) with visualizations from this project. Also, Evergreen supports educational programs for and about Native Americans, including Native American Studies, NW Indian Applied Research Institute, a graduate program in Tribal Administration, and the Reservation Based Community Determined Program (serving six reservations)[27]. NSF, and Lumina and Gates Foundations, recently funded the *Enduring Legacies Native Cases Project* [28] which will develop teaching resources on key Indian country issues. We have begun discussions with *Enduring Legacies* PI Barbara Smith on how our project might co-develop one visualization of science data with the Northwest Indian Fisheries Commission, to illustrate one Native story related to climate change.

VI. Results from Prior NSF Support

CUSHING: *RUI: Forest Canopy Databases and Database Tools*, 2004-9, $877,099, DBI-0417311, enables end-user design, implementation, and visualization of databases (Cushing 2007a; Nadkarni 2008; Cushing 2009; Zeman 2006); the work has resulted in software[29], a model database for teaching (Cushing 2007b), reuse of data for resource managers (Kopytko 2009), and subsequent grants from NSF CISE/IIS (0639588 *From Measurement to Management*, $99,985) and 0917708: *2- and 3-D Visualization of Ecological Phenomena* $74,997). She has organized eco-informatics workshops and community building[29] projects, incl. an NSF ICER initiative[30], and CSEMS scholarships (DUE-0220876).

BOND has been funded by numerous NSF grants, incl. as PI of the H.J. Andrews LTER. The most recent relates to this project: *Airsheds, isotopes and ecosystem processes in complex terrain*. Eight undergraduates (3 NSF-funded REUs, 5 with other support) conducted related research; 1 PhD and 1 MS student completed degrees associated with it; 3 more PhD students are expected to complete degrees soon. To date, the project has produced 3 refereed papers (a 4th in review, 3 to be submitted), 2 Ph.D. dissertations, a book chapter, 8 invited presentations, and 13 volunteered presentations.

LACH: *Changing Expectations for Science and Scientists in Natural Resource Decision Making. Societal Dimensions of Engineering, Science, and Technology (0427494).* This project included a national survey and 5 in-depth case studies with scientists, resource managers, NGOs, and the public on expectations for how science might be used to make resource decisions. We found that for all but resource managers, there is increasing expectation and preference that scientists get more directly involved in interpreting and integrating scientific results into decision processes; resource managers preferred that scientists help interpret, but weren't as interested in integration. NGOs and the attentive public were much more likely than scientists and managers to prefer scientists to advocate for policies implicated by their own science. Multiple papers and presentations were published and a book-length manuscript is in preparation.

BAILEY: EIA-9809224: *A Network-Based Solid Freeform Fabrication Facility for Scientific Visualization*. The Center for Visualization Prototypes was created and has been used by hundreds of scientists. We acquired a Z406 color prototyping machine, interfaced it to the Web, and created automatic submission and checking routines (Bailey 1995, 1997, 1998, 1999a, 1999b, 2002; Clark 1997, 1998). This project was featured in *Discover* (Svitil 1998). Bailey has also researched interactive methods for volume visualization. The *Volume Explorer* will be a cornerstone in this new project(Bailey 2000, 2004). Much of this process was summarized in a CACM feature article (Bailey 2005).