Making Ecology Research Results Useful For Resource Management: A Case Study in Visual Analytics

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ABSTRACT

This paper addresses challenges to resource managers' use of scientific research, and reports strategies and informatics tools to ameliorate those challenges. Our work involves repurposing fundamental ecology research data for resource managers, in particular for field foresters who make decisions regarding which trees to leave when harvesting timber stands. We describe needs of managers (e.g., interpreting and implementing value statements from policy, and communicating and justifying decisions to stakeholders) and visual analytics tools and artifacts to repurpose scientific data to those needs. We conclude that visual analytics can produce successful boundary objects to overcome some challenges inherent in differences of approach between researchers and managers, but its use to repurpose data in this way will require further research and development in visual analytics and in the cognitive and social sciences. As adequate informatics tools become available to produce artifacts for repurposing scientific data, interdisciplinary collaboration among research ecologists, resource managers, and biometricians will likely still be needed to produce the artifacts. In particular, future collaboration is necessary to define and test new visual analytics in response to changing policy.

Categories and Subject Descriptors
H.2.8 [**Database Applications**]: Scientific Applications.

General Terms
Human Factors, Design, Management

Keywords
Ecoinformatics, Data Reuse, Visual Analytics, Boundary Objects, Science-informed Policy and Resource Management

1. INTRODUCTION

Natural resource managers implement policy and often are called on to make value-based choices that balance competing interests. Several steps, each of which might be informed by science, occur on the way to final policy implementation: societal values are translated into policy goals, a policy is selected, management strategies are adopted, and actions are taken [17]. In addition, clear communication and transparency among parties are necessary. Some attention has been paid to how scientists inform the beginning stages of this process. While applying ecology research into actions has similar challenges, this has received less attention. Challenges to science-informed management include: transparency, communication across boundaries, and uncertainty. This paper addresses these challenges as they apply to resource managers' use of scientific research when implementing policy. We also report on informatics tools we developed that address these challenges in forest management and that are extensible to other natural resource management problems and other domains.

Repurposing prior research results for natural resource management is critical to making affordable the use of science results in day-to-day resource decisions. Though there is a growing literature on data reuse in the sciences, little work has been done on reuse of scientific data by managers, with some notable exceptions [7].

Forest managers balance conflicting policy objectives: produce timber revenue, preserve forest health, provide habitat, and maintain recreational areas. In addition, managers are accountable to stakeholders for their decisions. The objective of this work was to help managers give more explicit harvest directives and to document decisions. The work serves as a case study in how academic ecology data sets and research results might inform decisions of natural resource managers. In addition, the project strives to bridge the gap between ecology research and field foresters who make day-to-day decisions regarding which stands to harvest and which trees to leave in these harvested stands. We focused on identifying trees with high ecological value since those trees are the best candidates for leave trees. *Leave tree* is defined as those trees left standing in harvested stands. For lands in Washington state, the number of trees that must remain after harvest depends on habitat type and elevation, but typically ranges between 5-50 per acre [23].

We conducted extensive needs assessments on site with managers. Two problems identified during these interviews were 1) a lack of precise operational definitions in policy of ecological terms and 2) the need for tools to help determine which trees to leave after harvest and to communicate these decisions to stakeholders. To address these problems, we designed informatics tools to produce a catalog containing visualizations and precise structural descriptions of about 100 trees from an ecology research database of 1000 trees. This catalog was then used to survey ecologists and managers, and refine definitions and identify trees that best characterize certain ecological values.

From this case study, we infer that visual analytics can be an effective boundary object to promote communication between scientists and managers and to overcome some of the challenges inherent in applying scientific research to resource management. However, using visual analytics to repurpose research data in this way will require further research in visualization methods and in cognitive and social science.

1.1 Current Challenges

Among the greatest challenges we faced in determining how to repurpose research data for resource managers was communicating and handling uncertainty, known to pose problems in developing and implementing policy [6, 11]. New ways of approaching problems generate uncertainty; for instance, scientists find ecosystem-based understanding of old-growth forests valuable, while nonscientists aren't sure how to use the ecosystem-based results to further interests such as protecting endangered species [11]. Time and scale also add to uncertainty. Management strives to work on the landscape scale, while research most often occurs at the plot level. Applying plot level research to the landscapes potentially accumulates errors – uncertainty – that scientists feel must be communicated and addressed. Uncertainty also surrounds the question of how features and functions change through time.

Managers must not only deal with uncertainty in arriving at decisions, but must justify those decisions to the public. Balancing increased public involvement with incorporating the scientific and technical complexities of uncertainty, for example, remains a challenge [13]. Choosing not to deal with uncertainty and public demands can result in conservative decision-making involving little innovation [12]. For instance, adaptive management requires that policies be treated like experiments where mistakes provide opportunity to learn [14]. However, public perception of bureaucracy and mistakes does not accommodate this new paradigm. As public expectations change to encourage a more inclusive role for scientists in bureaucratic and public decision-making [13], acceptance of adaptive management might increase. The involvement of scientists can promote the use of best available science, and as importantly, a likely stronger public support for management decisions. In addition, collaborative efforts that involve stakeholders at all levels tend to have a higher degree of adaptive management [4].

1.2 Our approach: Communicating Through Visual Analytics

Our approach to repurposing research data for resource managers, involved using visual analytics as "boundary objects". Boundary objects are communication mechanisms used to improve understanding across disciplinary or interest group boundaries, and thus among diverse stakeholders about alternative points of view on common areas of interest [19]. The communication of ecological research results to managers and then to foresters is a type of boundary work.

The new science of visual analytics, "analytical reasoning facilitated by interactive visual interfaces" used "to synthesize information and derive insight from massive, dynamic, ambiguous and often conflicting data" is already recognized as critical to the defense of this country in preparing for and responding to emergencies [20]. We reason that visual analytics could also be used to re-purpose masses of scientific data for multiple uses, including the use of ecology research data for natural resource management. This work demonstrates that, where research involve real-world phenomena relevant to natural resource management, the visualization of those research data along with summary statistics about the real-world phenomena can be used to communicate research results. Our work involved: 1) creating visualizations of scientific measurements of natural phenomena – thus reusing the research data, 2) providing as an adjunct to the visualizations simple summary statistics, 3) determining which ecological value terms used in policy statements needed clarification for resource managers, 4) using the visualizations as reference for scientists as they sought to more precisely define those terms, and 5) combining the new definitions with visualizations to clarify policy terms to field foresters and stakeholders.

In our work, admittedly a first step to reusing data for management, we sidestepped many uncertainty issues by reporting "raw" research results. In the longer term, however, we think that the flexibility of visual analytics could ameliorate uncertainty issues by allowing for the display and analysis of very large data sets. Adaptive management approaches account for a wide range of possible outcomes by collecting lots of information [14]. In addition, the most popular choice among managers when dealing with risk is to collect more information [18]. Visual analytics can repurpose vast amounts of data by presenting the data in different ways. As no one visual paradigm can address all possible purposes and situations, a suite of visualizations must be developed to accommodate different individuals' analytical reasoning processes [20]. This adds an adaptive feature, while accommodating the needs of diverse users who "see" the world differently.

While visual analytics presents a means to communicate across boundaries and thus is a *boundary object*, additional communication remains necessary to develop successful visualizations. Evaluation and interpretation of visualizations is an iterative process that requires two-way communication [20]. Research has shown that the effectiveness of efforts to mobilize science and technology for sustainability suffered when communication was largely one-way, and when communication was infrequent or occurred only at the outset of an assessment [5]. Visualizations provide focus for gathering what is known by users and what information each user needs. Visualizations are most effective when user needs are incorporated in design; therefore, user-feedback should play an important role in development of visualizations.

When new requirements are present, interpretive differences in what a word, measurement, or outcome means limits the effective management of knowledge across boundaries [3]. Furthermore, jargon, language, experiences, and presumptions about what constitutes persuasive argument often hinders mutual understanding between experts and decision makers [5]. In these instances, the right boundary objects can help establish understanding. To work, boundary objects must be flexible enough to adapt to local needs and the constraints of the parties employing them, yet robust enough to maintain a common identity across sites [19]. Several types of boundary objects exist; however, the visualizations we used are of two types: repository and ideal type. *Repositories* are ordered 'piles' of objects, indexed in a standardized fashion. An i*deal type* is an object such as a diagram, atlas or other description which in fact does not accurately describe any one locality or thing [19]. The catalog of 100 trees is a repository, while identification of the most ecologically valuable trees can be considered an ideal type as it represents an ideal leave tree.

2. Methods

In this section, we describe methods used to 1) determine managers' need for scientist input into their decision making and for information technology and 2) the extent to which visualization might be effective for communicating science input to day to day decisions.

2.1 Interviews and Problem Definition

We conducted two day-long interview sessions on site with experienced resource managers at Washington State forested sites. Managers remarked that new legislative policy was emerging to accommodate ecological, as well as fiscal and aesthetic, values. These new policies were now requiring resource managers to consider ecological values when harvesting state forest lands, and to leave on the land a certain number of ecologically valuable trees. The managers expressed a need for help in making, documenting and validating decisions on which trees to leave, and in communicating their decisions to the public, ecologists, and harvesters. However, we also found that precisely defining desirable leave trees is only the first step. Resource managers also voiced a need for new ecology research because they also need to know whether a candidate tree will likely develop into a desirable tree in the future. In addition, managers expressed interest in extrapolating research results from plots, to site, to landscape. For this preliminary work, we focused on the short-term problem of defining and describing desirable leave trees.

Visualizations of recent forest canopy research data, developed by ecology researchers and computer scientists, were presented to resource managers. It was jointly decided that the visualizations might be useful, but that we needed to explore which features of individual trees were relevant to leave tree decisions, if those features were reflected in the visualizations, and what changes might be needed to reflect information relevant to the managers' decision making.

We also conducted two day-long meetings with ecology researchers where we reported manager needs and brainstormed which research data could be applied to the problem at hand.

The remainder of this article addresses the first step in helping managers reuse scientific research data – defining desirable leave trees. With managers and researchers, we decided to use as a research case study the *Thousand Year Chronosequence*. This prior NSF-funded work by Van Pelt and Nadkarni aimed to study forest and tree structure and established plots in eight forested sites ranging in age from 50 to 950 years (22). The dataset from this study, dubbed the *1kcs*, includes plot-, tree-level data for over 1000 trees on the eight sites, with detailed branch data on over 100 of those trees. The catalog of visualizations depicts all 100 individual 1kcs trees with branch data.

2.2 Catalog Description

Discussions with resource managers and scientists told us that tree and forest structure were indeed relevant to recognizing trees of ecological value. We thus thought to use our existing scientific visualizations that provided 3D interactive viewing of plots and individual trees, and composite views of stand structure. While these were helpful to researchers in considering structural differences and developing hypotheses, they were less useful to the managers for addressing leave-tree decisions. We therefore developed new visualizations and new software that provided: 1) 2D views of individual trees from different compass points and 2) descriptive statistics on individual trees. We then generated a catalog of trees to permit evaluation of ecological values and comparison among different tree types. Each page of the catalog describes one of the 100 1kcs trees and visually portrays the tree crown and lists crown metrics. A 5-page sample of the catalog, as well as the full catalog is publicly available[1].

Visualizations. Visualizations in the catalog included various views of individual trees that were relevant to managers' definitions of leave trees, i.e., a tree profile with foliage and branches, branch schematics (with no foliage), a view of the tree top, an overhead tree view, and a view of the tree with neighboring trees.

The Profile Tree View, shown in Figure 1, depicts the tree's live-branch profile from each of four directions at 45˚ intervals: North, Northeast, East, and Southeast, projected against a flat surface. It highlights gaps and asymmetries in the crown. Each image shows two 90˚ slices of live branches in profile. Branches closer together than one vertical meter are connected. For perspective, branches are projected on the plane perpendicular to the orientation; thus, a branch not on the perpendicular will appear shorter than its actual length.

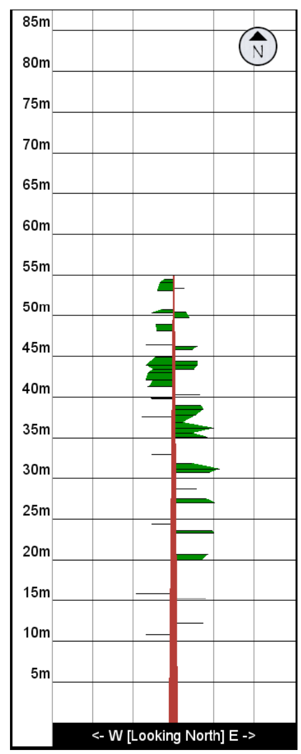


Figure 1. Profile Tree View.

The Branch Schematic View, shown in Figure 2, illustrates overall tree structure, and focuses on reiterations (shown in blue) and epicormic branches (shown in purple). *Reiterations* occur

[1] The catalog is available at http://acdrupal.evergreen.edu/dnr.

when the main trunk or tree top is damaged, and a *reiterated branch* grows parallel to the trunk instead of more or less perpendicular to it. *Epicormic branches* are formed on the outside of the tree bole (trunk) whereas primary branches arise from buds formed as the tree bole elongates; *epicormic branching* occurs in older Douglas-fir often in response to a loss of primary branches and other disturbances that expose the trunk to sunlight [10]. In the Branch Schematic View, primary live branches are green and dead branches brown. Branches were drawn to scale, and very small branches might be too small to see. All branches were drawn ignoring perspective; therefore, branches are full size regardless of where they are located around the stem.

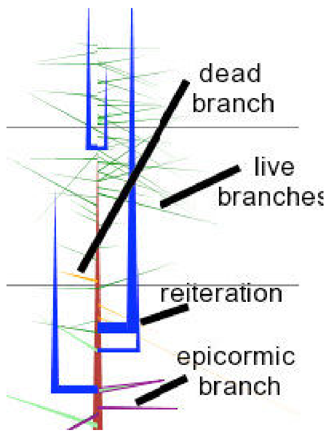


Figure 2. Explanation of the Branch Schematic View.

The Tree Top View, shown in Figure 3, shows whether the top is alive or dead, and highlights small branches that might not be obvious on the Branch Schematic View. Branches less than 4 cm in diameter were not measured.

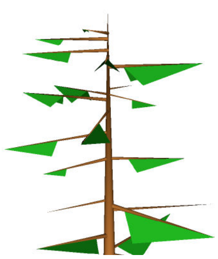


Figure 3. Tree Top View.

The Overhead Tree View (Figure 4) shows the top-down crown projection of the tree, and gives an idea of foliage density and symmetry. The foliage on each branch is drawn as a diamond shape sized proportionate to the measured foliage.

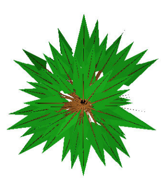


Figure 4. Overhead Tree View.

The Overhead Neighborhood View maps all neighboring trees with diameters greater than 5 cm at breast height. Live tree boles are brown, with a green diamond depicting crown radii measured to the North, East, South, and West. Dead tree boles are shown in red. The tree of interest's crown diamond is highlighted in blue and its bole is rectangular rather than circular. Gray lines between trees are Thiessen Polygons (aka Voronoi Diagrams) defining regions of influence around each of a set of points [9].

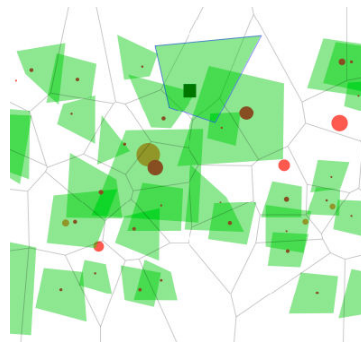


Figure 5. The Overhead Neighborhood View.

<u>Characteristics and Metrics.</u> While visualizations alone were useful for determining overall structure, researchers and managers wanted accompanying data (metrics of tree, crown, and branch characteristics). Tree characteristics included species, diameter at breast height, and tree height. Species included: *Abies amabilis* (Pacific silver fir), *Pseudotsuga menziessii* (Douglas-fir), *Thuja plicata* (Western red cedar), and *Tsuga heterophylla* (Western Hemlock). The site location for each tree was provided as well.

In addition to collected data, we also provided some calculations and summary statistics. Crown characteristics for each tree included: crown volume, crown surface area, and crown gaps. Crown volume and surface area were calculated by dividing the crown into a series of 2-meter conic sections, where h is the height of the section and radii (r and R) are equal to average branch length at the highest and lowest points in the section as shown in Figure 6. Crown volume is the sum of the conic section volumes, and crown surface area is the sum of the outside surface area of all conic sections (S). A gap is defined as a vertical space greater than 1 m with no live branches within 10 degrees. Gap count is the total number of gaps within the crown. Gap sum is the total gap length or the sum of all gaps within the crown in linear meters. Branch metrics were calculated for each tree and are described in Table 1.

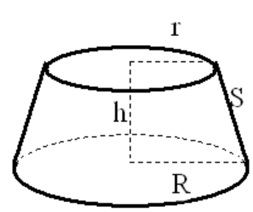


Figure 6. Diagram of conic section used to calculate volume and surface area.

Table 1. Description of branch metrics.	
Characteristic	**Description**
Mean length	The average length of all branches, live and dead.
Mean height	The average branch height above the ground. Calculated with both live and dead branches.
Mean diameter	The average diameter of all branches on the tree, live and dead.
Largest diameter	The diameter of the largest branch.
Largest 10 diameter	The average diameter of the 10 largest diameter branches, live and dead.
Total branch count	Count of all branches on the tree
Epicormic count	Count of epicormic branches on the tree.
Dead count	Count of dead branches on the tree.

2.3 Survey and Analysis

Resource managers reported that terms describing ecological values of trees were often too vague to use in the field for identifying leave trees prior to harvesting. Working with biometricians and ecologists who themselves work closely with resource managers; we devised a survey that would use our catalog (visual analytics) of actual trees to refine descriptions of ecologically valuable trees. The survey asked the same set of structural and value questions for each tree in the catalog, and was conducted via Survey Monkey or via hard copy. Structural questions included rating each tree according to: 1) multiple or reiterated tops, 2) symmetry of the crown in terms of opposite quadrants, 3) symmetry of the crown in terms of adjacent quadrants, 4) continuity of the crown, 5) fullness of crown, 6) quantity of large branches, 7) quantity of epicormic branches, 8) quantity of dead branches, and 9) likelihood that the tree will remain standing in twenty years. Respondents were asked to rate these particular features because the presence of these structural features was identified as contributing to different ecological values. Crown symmetry, continuity, and fullness are indicators of crown vigor or crown decadence [2, 21].

Value questions included ranking the tree according to: 1) value for late succession wildlife, 2) value for late succession wildlife 20 years in the future, 3) value for legacy structure, 4) value for legacy structure twenty years in the future, 5) current marketable timber value, and 6) the change in timber value twenty years in the future. Legacy structures are features that are typically associated with older trees and provide structural diversity. Living and dead structures that persist after large disturbances, such as fire or storms, are termed biological legacies [8].

Responses were averaged for each tree and examined to understand how values relate to each other, and how structural features relate to overall legacy structure. The statistical package R was used to calculate a spearman rank correlation test to determine how closely correlated structural features were with legacy structure value [16]. Finally, trees were sorted according to average rank to find the best candidates for leave-tree status.

A qualitative section at the end of the survey provided respondents with an opportunity to provide feedback on visualizations and metrics. Respondents were asked to choose the visualizations and metrics that were helpful in answering each question in the survey. These responses were reviewed to evaluate the practicality of the visualizations for this type of work.

3. Results and Discussion

Eight forest ecologists completed the survey. Although our sample size is small, clear patterns emerged as we sought to refine definitions of ecological value for leave trees. Figure 7 shows the correlation between wildlife value and legacy structure, indicating that value for legacy structure is a good surrogate for value for late succession wildlife. In addition, legacy structure now and twenty years in the future are closely correlated (Figure 8). This suggests that within a 20-year time frame legacy value is not likely to change. In some instances, even a considerable change in crown structure would have little effect on legacy value. For example, if a large living tree with high legacy value experienced top damage, it might still meet other criteria, e.g. large branches or reiterations. Alternatively, ecologists might not have sufficient insight to judge future changes in legacy value, a research need that has been expressed by resource managers.

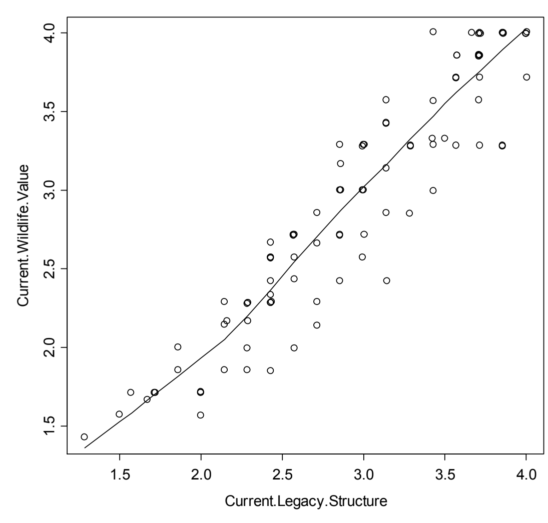


Figure 7. Average response for wildlife value plotted against legacy structure.

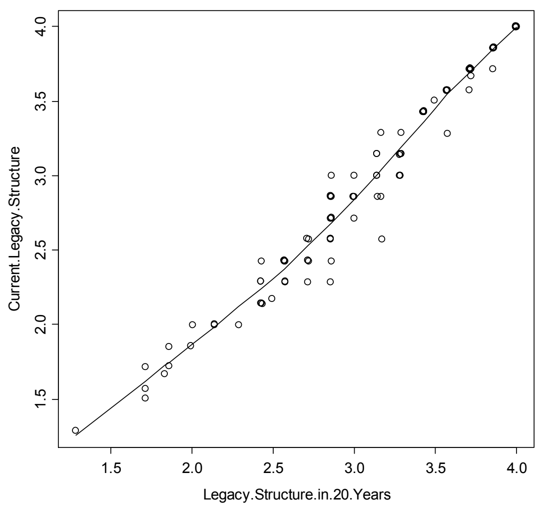


Figure 8. Average response – legacy now vs. legacy in 20 yrs.

Timber-value and legacy value are correlated at low values, but timber value plateaus and decreases, while legacy structure continues to increase as shown in Figure 9. This result suggests that, at the tree-level, timber value and legacy structures are not competing. Furthermore, the points numbered in Figure 9 correspond to trees that received a similar ranking in legacy structure, but differ in the ranking for timber value. For instance, tree 7 and tree 62 both received a ranking of 2 for legacy value, but tree 62 has a much higher timber value than tree 7. If both of these trees were in the same stand, then according to these results the obvious choice would be to harvest tree 62 and leave tree 7.

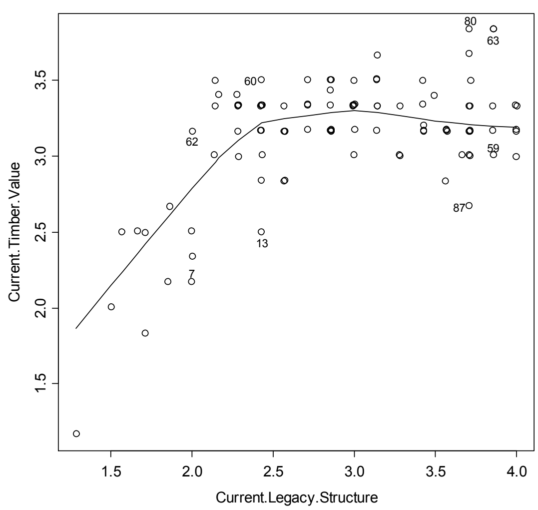


Figure 9. Average responses–timber value vs. legacy structure.

Table 2 displays correlation results between structural features and legacy value. According to our results, crown fullness and crown continuity have a negative relationship with legacy value. This suggests that the number of gaps in the crown can be used to determine legacy value, although only 30-40% of variation in legacy structure is explained by crown gaps. Crown asymmetry was not significantly correlated with legacy value. One explanation is that symmetry is a difficult feature for respondents to judge. Alternately, other features might be more indicative of legacy value than asymmetry. In addition, the production of epicormic branches in Douglas-fir could cause the tree to become more symmetrical over time. The data set contains mostly Douglas-fir, and epicormic branches have a strong correlation with legacy value. This effect might supersede the importance of asymmetry and crown gaps in determining legacy value. Asymmetry appears to be a poor indicator of legacy value.

Table 2. Results of Spearman-Rank Correlation test of the relationship between structural features and legacy value.

Structure	p-value	rho
Crown Continuity	<0.001	-0.43
Crown Fullness	0.003	-0.30
Opposite Symmetry	0.278	-0.11
Adjacent Symmetry	0.092	-0.17
Large Branches	<0.001	0.86
Epicormic	<0.001	0.78
Reiterations	<0.001	0.61
Dead Branches	0.010	0.26

Of structural features that were correlated with legacy structures, large branches had the strongest relationship followed by epicormic branches in Douglas-fir, as shown in Figures 10 and 11, respectively. In addition, reiterations or multiple-tops showed considerable correlation with legacy structure (Figure 12). However, this graph shows that the absence of reiterations did not always translate to a low legacy value. Trees that received the lowest reiterations rating (1, an absence of reiterations in the tree) received a wide range of ratings for legacy value.

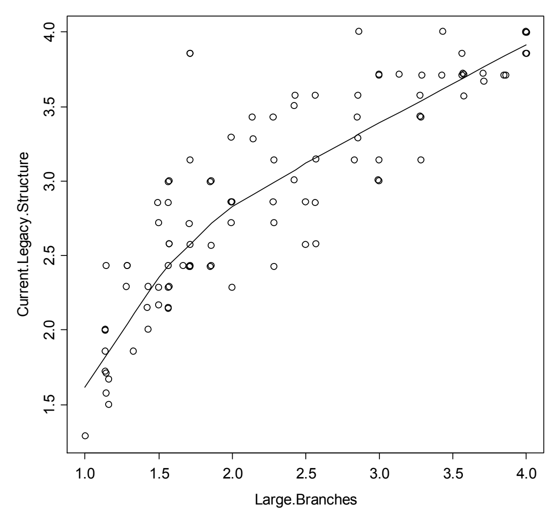


Figure 10. Relationship between legacy structure and large branches.

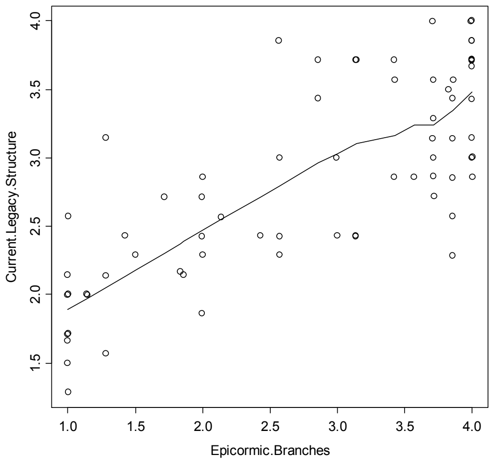


Figure 11. Relationship between legacy structure and epicormic branches in Douglas-fir.

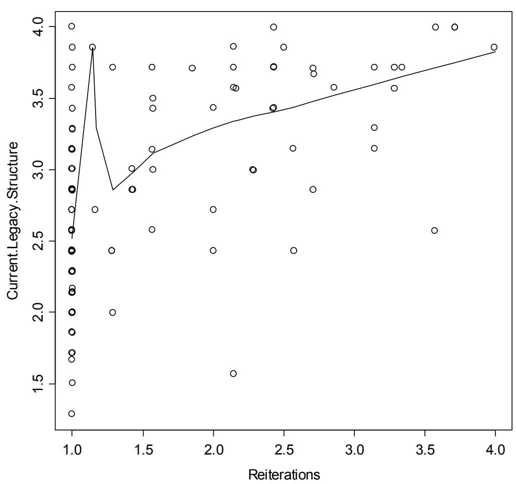


Figure 12. Relationship between average ranking of legacy structure and reiterations. A rating of "1" indicates that the tree has no reiterations.

Candidates for leave tree status were evident; given that consensus of high legacy value was reached among all survey respondents for a few trees. The branch schematic view for two of those trees, a Western red cedar and a Douglas-fir, are shown in Figure 13. In contrast, Figure 14 shows Douglas-fir that received an average ranking of moderate and limited value for legacy structure respectively.

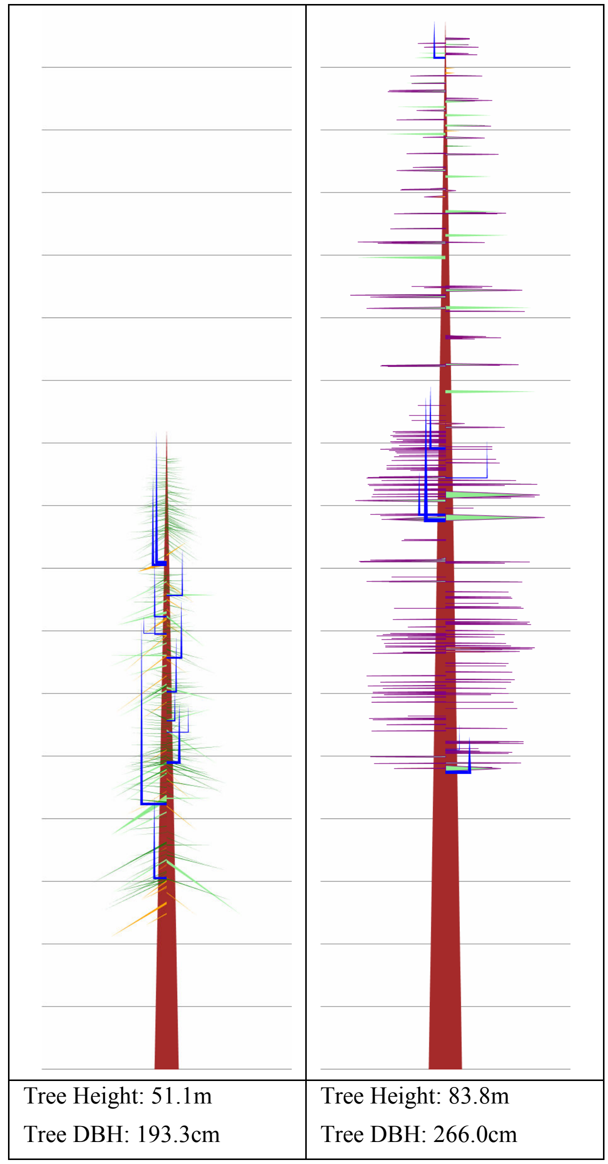
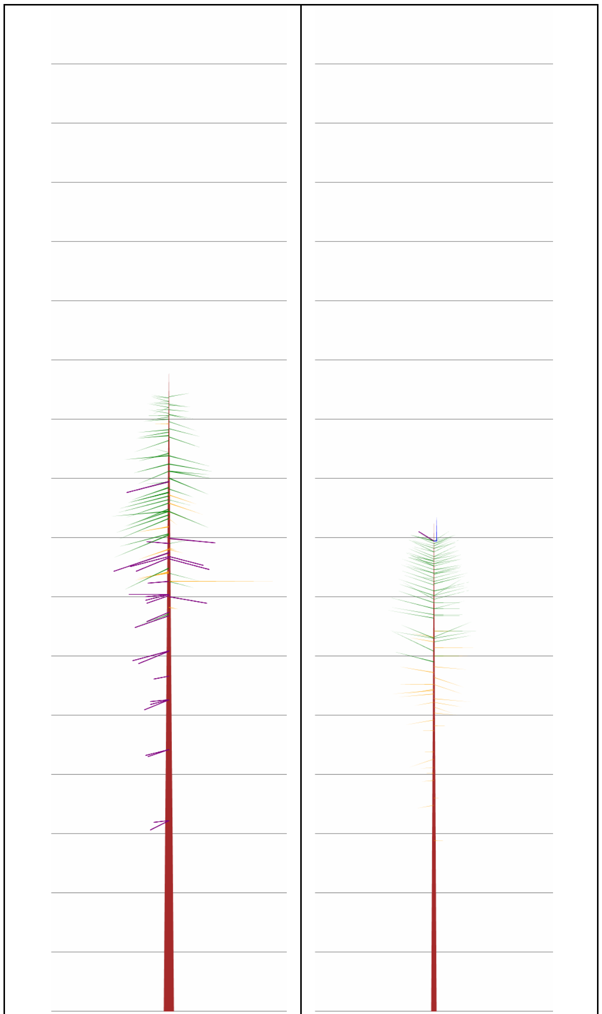


Figure 13. The Branch Schematic View of trees that respondents agreed were of high legacy value. Image on left is of a Western red cedar, while the image on the right is of a Douglas-fir. Reiterations are in blue and epicormic branches are in purple. DBH stands for diameter of the tree at breast height.



Tree Height: 54.2m Tree DBH: 86.2cm	Tree Height: 41.9m Tree DBH: 45.2cm

Figure 14. The Branch Schematic View of trees that received an average rating of moderate and limited value for legacy structure. (Note: Not to scale with Figure 13). DBH stands for diameter at breast height.

Finally, responses to questions pertaining to which visualizations and metrics were useful in addressing each of the questions confirm that each "user" is indeed different, and a variety of visualizations is necessary to accommodate these differences. While certain visualizations such as the branch schematic view and profile tree view were clear favorites among users, respondents differed widely in how they approached each problem, and what information they used to answer the questions. Furthermore, some respondents commented that specific features, such as the Thiessen Polygons, did not provide any needed detail, while other respondents found those same features to be highly valuable. Despite these differences in approach, respondents often had considerable agreement in their answers.

4. Conclusions and Future Work

While we will likely develop additional software to make the visualization tools more interactive than they are now, and testing of the definitions and visualizations by resource managers in the field is still necessary, we are encouraged by our results. We see very specific ways in which one set of research data can be repurposed using informatics tools to create visual analytics as boundary objects. From our survey, specific candidate trees with high legacy value clearly emerged from existing branch-level research data. We thus believe the visual analytics help answer questions about how to define terms specifically enough for field use.

We have argued from one example study that it is possible and practical to repurpose ecology research data using visual analytics as boundary objects between scientists and resource managers. The ecology research to collect these data cost considerably more than $350,000, but the informatics and ecology research and development to repurpose the research data for resource managers cost less than $50,000, much of which involved software development that will be useful elsewhere and has already proven useful to our collaborating scientists as well as managers. While results of our survey are directly applicable only to ecosystems similar to those in the Pacific Northwest, the methods and software used here are directly applicable to other ecosystems and resource management problems with similar research data sets. Since the software is now written, generating catalogs for new data sets can be done very inexpensively, and new surveys can be undertaken at reasonable expense as policy evolves to help define value-laden terms for managers.

Subsequently to our work, discussions with James Hotvedt, Lead for the Olympic Experimental State Forest Land Planning Project and for the State Trust Lands Habitat Conservation Monitoring Plan, confirmed our initial conclusions that state forestry policy is changing relatively quickly due to new public interest and findings in ecological values. This in turn confirms our observation that, if research results are to be used to help with resource management decisions, they must be able to be repurposed, perhaps several times, as new policy is introduced. For example, variable density thinning practices are now being proposed in lieu of the current single leave tree policy and reusing our research results to accommodate this possible policy change would involve including in the visual analytics more detail on surrounding trees; this could be done with new visual analytics and would not necessarily require additional ecology research. Further, early papers that established the scientific basis for variable density thinning randomly selected plots to take or leave [1, 2] ecologists now suggest that physical features of the land be used to select collections of trees to leave. Data for most physical land features (topography, soil type, etc.) are readily available and visual analytics could be used to complement data in such legacy data sets as the 1kcs.

We reason that further efforts such as ours that build on foundational ecology research would produce, at relatively little cost, not only useful results for resource management, but also increasingly more general informatics tools and a body of expertise that could be applied more broadly. Of more general use than this particular study are the software used to generate visualizations and the catalog generator. To explain the value of such software, we describe the catalog generator in some detail.

Canopy Catalog aims to simplify and expedite the process of creating, maintaining, and distributing a data- and image-rich catalog. The catalog generator combines separate files with data, statistics, and visualizations into a report template generated by the user. Without the generator, combining these data and images was a very time consuming task, as data and images for each of a hundred pages had to be placed and formatted by hand. We developed the software because field-testing the catalog with users suggested changes to the layout or structure of the pages that often necessitated modifying the entire catalog, page by page; this was clearly prohibitive.

Canopy Catalog allows users to perform batch page creations, as well as batch value and image imports. Users can easily view previews of any page, which can be re-generated when necessary using new data. By the time of the first release, it will also enable users to determine page order by hand or by sorting criteria, export individual page, or export the entire catalog as a single PDF file. Future goals for the software include collaborative authoring capabilities such as change tracking, and advanced design and editing controls. The software was implemented with the Python programming language and designed to run identically on Mac and Windows platforms. To maximize portability, Catalog database files are self-sufficient and contain all data and images necessary to render any page in the catalog. For convenience, files also include a cache to store rendered page previews and image thumbnails, reducing the number of instances in which a user must wait for rendering.

An unexpected side effect of this work has been closing the loop from the resource managers back to the scientists: artifacts produced to answer resource manager questions have caused our science collaborators to reexamine "old" data and catalyzed a new research project (that involved transforming and then analyzing the "old" data set to answer new questions). Further, the ways in which our visualization tools were extended for resource management are proving useful to our scientist collaborators, and previously unknown data errors have come to light with new visualizations and metrics.

Remaining work for this project involves putting into practice, i.e., field-testing with resource managers and foresters, the use of the definitions and visualizations, and seeking feedback and refinement on the visualizations. As the value of our work seems to lay in making explicit what are necessarily somewhat abstract policy statements by displaying specific real-world trees that meet (or don't meet) certain policy objectives, one obvious outcome would be to create training tools for foresters. Researchers at Washington Department of Natural Resources have suggested that the survey results be used to build "idealized" leave tree images – in producing a pamphlet much like the Old Growth Guides[2] now used to train loggers and foresters to reconstruct stand history and determine tree and stand age. The natural question that arises is whether computer-generated images or artistically rendered hand-drawn or even photographic images better convey the information. If one decides to use computer-generated images, one still needs to determine whether iconic or photo-realistic images are more appropriate to the population. To answer this question, a usability study of the images with persons who would use the pamphlet in the field is in order. The question we anticipate is whether foresters and loggers are willing to apply visual schematics of example trees to what they see when on site in the forest. Some managers suggest that photorealism would be more acceptable; scientists, on the other hand, generally have found that photorealism, though technically feasible, hides salient features of the sample trees.

We also anticipate the need for developing additional software beyond the catalog generator – interactive visual analytics software usable in the field or when training field workers.

The second (major) area for future research involves combining research results at multiple spatial scales. This is critical to repurposing research data to management or policy needs because researchers rarely conduct research at spatial or temporal scales needed for management. First, we see specific ways that the research results at the plot- and individual-tree level could be combined with research at the site level to produce useful results to resource managers. For example, new technology, e.g., light detection and ranging (LIDAR), is enabling the collection of detailed structural data at scales directly relevant to managers' needs, though it is not yet possible to deduce detailed individual tree structure from LIDAR images. Consultations with LIDAR experts working on extracting forest and tree structure from LIDAR lead us to believe that data at that spatial scale could be combined with data such as ours (at a finer scale) to induce individual tree structure in ways that the managers would find helpful [15]. Identifying potential leave trees via LIDAR maps would also likely alleviate issues arising from managers and loggers not being able to determine certain characteristics in the field; many structural details in the 1kcs were reported by researchers who climbed trees to collect those key measurements. It will also be important, when using visual analytics from LIDAR to combine research results from multiple scales, to determine how people cognitively connect visualization of data at one spatial scale to those of data collected at "neighboring" spatial scales, and to create and test management conclusions drawn from sample visualizations of data at different spatial scales.

A third important area for research involves acquiring better understanding of how uncertainty can be measured when scaling up (or down), and how it can be conveyed to a variety of audiences.

Finally, social science research is also needed to determine the extent to which the visual analytics, such as those developed here, work as boundary objects to increase communication among researchers and managers. This work is outside the scope of this project but critical for future applications of visual analytics to the repurposing of scientific data.

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[2] http://www.dnr.wa.gov/ResearchScience/Topics/ForestResearch/Pages/lm_oldgrowth_guides.aspx

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6. References.

[1] Carey, A. B. and R. O. Curtis, 1996, Conservation of Biodiversity: A Useful Paradigm for Forest Ecosystem Management. Wildlife Society Bulletin 24: 610-620.

[2] Carey, A. B., J. Kershner, B. Biswell and L. Dominguez de Toledo, 1999, Ecological Scale and Forest Development: Squirrels, Dietary Fungi, and Vascular Plants in Managed and Unmanaged Forests. Wildlife Monographs: 3-71.

[3] Carlile, P. R., 2004, Transferring, Translating, and Transforming: An Integrative Framework for Managing Knowledge Across Boundaries. Organization Science 15: 555-568.

[4] Cash, D. W., 2001, "In Order to Aid in Diffusing Useful and Practical Information": Agricultural Extension and Boundary Organizations. Science, Technology, & Human Values 26: 431-453.

[5] Cash, D. W., W. C. Clark, F. Alcock, N. M. Dickson, N. Eckley, D. H. Guston, J. Jager and R. B. Mitchell, 2003, Knowledge systems for sustainable development. Proceedings of the National Academy of Sciences 100: 8086-8091.

[6] Cushing, J. and T. Wilson, 2004, Eco-Informatics for Decision Makers: Advancing a Research Agenda Report of an NSF- and USGS/NBII-sponsored Workshop on Eco-Informatics for Resource Management Decision Makers. The Evergreen State College, Olympia.

[7] Edwards, P. N., S. J. Jackson, G. C. Bowker and C. P. Knobel, 2007, Understanding Infrastructure: Dynamics, Tensions, and Design Report of a Workshop on "History & Theory of Infrastructure: Lessons for New Scientific Cyberinfrastructures".

[8] Franklin, J. F. and J. A. MacMahon, 2000, Messages from a mountain. Science 288: 1183-1185.

[9] Heywood, I., S. Cornelius and S. Carver, 1998, An Introduction to Geographical Information Systems. Prentice Hall.

[10] Ishii, H. and E. D. Ford, 2001, The role of epicormic shoot production in maintaining foliage in old *Pseudotsuga menziesii* (Douglas-fir) trees. Canadian Journal of Botany 79: 251-264.

[11] Lach, D., 2009, Moving Science and Immovable Values: Clumsy Solutions for Old-Growth Forests, T. A. Spies and S. L. Duncan, eds. Old Growth in a New World: A Pacific Northwest Icon Reexamined. Island Press, Washington D.C.

[12] Lach, D., H. Ingram and S. Rayner, 2005, Maintaining the Status Quo: How Institutional Norms and Practices Create Conservative Water Organizations. Texas Law Review 83: 2027-2053.

[13] Lach, D., P. List, B. Steel and B. Shindler, 2003, Advocacy and Credibility of Ecological Scientists in Resource Decision-making: A Regional Study. BioScience 53: 170-178.

[14] Lee, K. N., 1993, Compass and Gyroscope Integrating Science and Politics for the Environment. Island Press, Washington, D.C. Covelo, California.

[15] McGaughey, B., 2008, Personal Communication. USDA Forest Service, Pacific Northwest Research Station, Seattle, WA.

[16] R Development Core Team, 2007, R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

[17] Scott, J. M., J. L. Rachlow and R. T. Lackey, 2008, The science-policy interface: what is an appropriate role for professional societies? Bioscience 58: 865-869.

[18] Shapira, Z., 1995, Risk Taking: A Managerial Perspective. Russell Sage, New York.

[19] Star, S. L. and J. R. Griesemer, 1989, Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. Social Studies of Science 19: 387-420.

[20] Thomas, J. J., K.A. Cook and National Visualization and Analytics Center, 2005, Illuminating the Path: The Research and Development Agenda for Visual Analytics, J. J. Thomas and K. A. Cook, eds.

[21] Van Pelt, R., 2007, Identifying Mature and Old Forests in Western Washington. p. 104. Washington State Department of Natural Resources, Olympia, WA.

[22] Van Pelt, R. and N. M. Nadkarni, 2004, Horizontal and vertical distribution of canopy structural elements of *Pseudotsuga menziesii* forests in the Pacific Northwest. Forest Science 50.

[23] WA State DNR, 2007, Forest Practices Illustrated: A Simplified Guide to Forest Practices Rules in Washington State. p. 151. Washington State Department of Natural Resources, Olympia, WA.