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Digital Forestry has been proposed as "the science, technology, and art of systematically acquiring, integrating, analyzing, and applying digital information to support sustainable forests." Although rooted in traditional forestry disciplines, Digital Forestry draws from a host of other fields that, in the past few decades, have become important for implementing the concept of forest ecosystem management and the principle of sustainable forestry. Digital Forestry is a framework that links all facets of forestry information at local, national, and global levels through an organized digital network. It is anticipated that a new set of principles will be established when practicing Digital Forestry concept for the evolution of forestry education, research, and practices as the 21st century unfolds.

Keywords: digital technology; quantitative method; forest sustainability; ecosystem management; global network

ew computationally intensive quantitative methods and digital technologies have been evolving for the past several decades. Enormous amounts of digital data and information are available about the distributions, structures, and dynamics of global vegetation cover, regional forest ecosystems, forested landscapes, stands and trees; much of it in databases on terrain, soil, climate, streams and rivers, wildlife, flora, transportation, and/or human activities, or captured as information in models about these features. Even more exists as a vast archive of raw, remotely sensed data. The synergetic use of geo-spatial, statistical, and modeling technologies together with information technologies are perhaps the most important development influencing the way forestry is practiced, taught, and researched.

The potential for the integrated application of these new technologies is tremendous. Imagine, for example, a forest planner scheduling a complex timber harvest operation. After roadside-parking her truck by a timber tract in which she plans to harvest, she turns on her laptop with wireless network connection, she sees "a digital representation of the forests" on the screen: trees, logging roads, decks, streamside zoning boundaries, and skid trails of the tract surrounding her. After examining details, she visually "flies through" adjacent tracts to have "birds-eye" view of surrounding tracts. A couple more clicks, and information about the tract's topography (slope and exposure), soil conditions, hydrology, and estimated timber volume appears. With a handheld PC equipped with GPS, she steps out of her truck, walks around and starts to collect information on changes in trees, roads, soil conditions, water, and zoning boundaries. She synchronizes the handheld PC with a laptop to upload updates and download new layers to her handheld PC GIS. She then opens a pre-harvest quality assessment component on the laptop and begins to assess the quality of some pruned trees scheduled for cutting. She predicts the defect core size, the log grade mix and measures the amount of juvenile wood, compression wood, and resin cracks. She even suggests cutting alternatives, the logging system, and the most appropriate equipment using a forest simulation model. Back in the office she reviews timber sale contractual terms and related timber laws and regulations. Finally, after days of fieldwork and office research, she drafts a harvesting plan in which she proposes the best cutting alternative that promises the highest operational efficiency, with a minimal impact on the environment and hydrologic cycle.

The scenario described above is not entirely fictitious; many aspects are already here. Data, software and hardware systems, and applications developed utilizing these technologies, have spread widely into various forestry organizations worldwide, allowing foresters to work more efficiently and make more informed decisions in less time. Digital technologies have become a core of modern forestry operations in many countries. Efficiencies have been achieved in such areas as pre-harvest quality assessment, production planning, resource assessment, systems analysis, management, field operation, environmental impact, and day-to-day decision-making.

In short, forestry technologies have become, and are continuing to become, increasingly digital. Unfortunately, the lack of a framework for the integrated application of these technologies impedes the continued advancement of technological developments in forestry. We propose, therefore, the recognition of a new field, which we term "Digital Forestry," and which we define as "the science, technology, and art of systematically acquiring, integrating, analyzing and applying digital information to support sustainable forests." The closely related term, "Digital Forest," is defined as "a digital representation of forestry information." These concepts and definitions were developed at "The 1st International Workshop on Digital Forestry," June 13–19, 2004 in Beijing, China, which was jointly sponsored by Chinese and American forestry institutions and organizations and participating scientists, experts and officials from China, United States, Germany, Canada, and Great Britain.

Although rooted in traditional forestry disciplines, Digital Forestry draws from a host of other fields that, in the past few decades, have become important for implementing the concept of forest ecosystem management and the principle of sustainable forestry. These other fields and their associated technologies include geographic information science and systems, remote sensing, digital image processing, forest biometrics, bioinformatics, statistics, forest modeling and simulation, decision support systems, forest survey and measurement, network communication, computer sciences, knowledge management, digital libraries, and global positioning systems (GPS). Digital Forestry, however, is envisioned as much more than just a suite of different technologies. It is a framework that links all facets of forestry information at local, national, and global levels through an organized digital network, making use of all the aforementioned tools and techniques (Figure 1). This systematic framework approach emphasizes novel linkages among various tools and techniques that have the potential to bind them into a powerful integrated framework, rather than focusing on questions and problems that are already being addressed within the component disciplines (Figure 1). This approach also paves the way for the integration of additional digital technologies as yet unforeseen.

Specifically, Digital Forestry recognizes four basic system behaviors under its framework to facilitate the storage, abstraction, feedback, and integration of forestry information: (1) a network of data and information systems comprising an overall integrated forestry information infrastructure; (2) data and information abstracted at various scales from the local forestry department to the top centralized national or global systems to form multilevel decision-making systems; (3) intervention from higher system prompts a drill down query to the lower subsystems for relevant data exploration and research; and (4) higher subsystems depend on overall linkage and performance of the lower subsystems in which all necessary component technologies play their roles to increase overall efficiency.

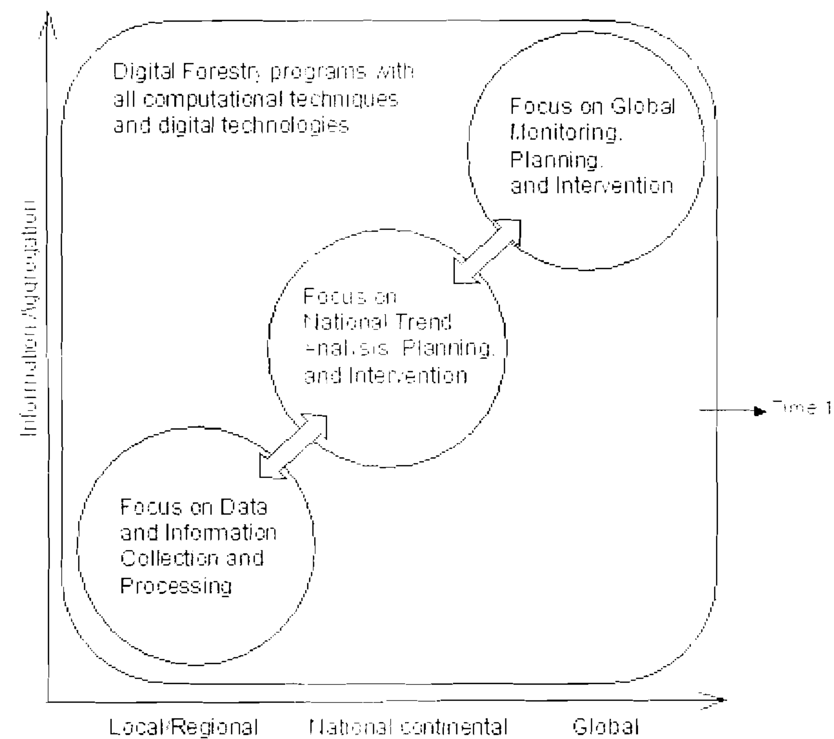

Figure 1. The components and processes of Digital Forestry programs.

Creating new terms to respond to changes in knowledge, use, and practices of forestry is not surprising. "Precision Forestry" is an example of "utilizing high technology sensing and analytical tools to support site-specific, economic, environmental, and sustainable decision-making for the forestry sector" (http://www.cfr.washington.edu/research.pfc/about/index.htm). The "eForest" represents a collaborative effort between researchers and forest resource managers integrating satellite technologies into forest inventory and management (http://eforest.gis.umn.edu/). We regard both of these as different aspects of Digital Forestry.

Theoretical Challenges. Most sciences, disciplines, and technologies that fall within the Digital Forestry framework are either available today, or are rapidly being developed. Nevertheless, the Digital Forestry concept is, by its nature, dynamic. Advancing the principles underlying the concept of Digital Forestry on a worldwide basis faces many challenges.

The preeminent challenge is the articulation of an initial theory for the integrated application of the various disciplines and technologies that will allow foresters to work more efficiently and to get things done faster and better. Any such a theory cannot be wholly dependent on purely technological solutions, but will need to remain faithful to the initial motivating concepts of ecosystem management and principles of sustainable forests. Taking into account both the technological and non-technical components of the Digital Forestry concept, a theory of Digital Forestry will need to account for the values, standards, systems, applications, practices, education, and technologies that support all facets of sustainable forests at local, national and global levels. We also envision that such a theory would facilitate a shift from compartmentalized to holistic approaches to problem solving.

Technological Challenges. Even if we succeed in delivering an effective theoretical framework for today, technological challenges remain because every science and technology that is included under a Digital Forestry umbrella will continue to evolve. Below are just a few examples:

• Data Acquisition. Remote sensing will likely continue to serve as the primary data-acquisition tool for assessment of forest health, hydrology, environmental and climatic conditions, and spread of forest fire and insect damage at various scales. Advances in high-resolution remote-sensing technologies, along with effective image-processing methods, are required to provide better capabilities for estimating forest inventory parameters in a timely, accurate, and cost-effective manner. Further development and validation of statistical models, using high-resolution, remotely sensed data, are necessary and their applications to different forest types worldwide are also required. Combinations of high resolution, multi-spectral- and hyperspectral-imagery data will be needed to provide detail digital information on the coverage of sustainable forests. LIDAR offers the potential to measure forest structure attributes directly (Maltamo et al. 2004), instead of the indirect approach required with traditional imaging technologies. Mass storage, new database-access tools, and a metadata standard must also evolve.

• Forest Visualization. The rapid increase of graphics hardware capabilities in recent years, largely driven by the gaming industry, has enabled the development of ever more realistic graphical renderings of forested landscapes. Information derived from stand inventory databases or remote sensing technologies can be used to generate accurate and nearly photo-realistic visual representations of the forest (Ager and McGaughey 1997). Such virtual perspectives (Fisher and Unwin 2002) will be useful for harvest planning, resource management, fire fighting, and operational decision-making. To be valid, the forestry information must be available for update in a timely manner, and not be cost prohibitive. The visualization must be linked with environmental and operational parameters and allow interactive query to support comprehensive analysis, assessment, and planning (Stoltman et al. 2004)

• Wireless Communication Systems. Wireless communication already plays a key role in many types of forestry operations. Web-enabled wireless systems already in place, such as lumber, inventory, sale, and management, are primary tools for foresters in the field in many countries. Potential applications of Digital Forestry would be significantly enhanced worldwide, if wireless capability and GPS satellite communication were extended and enhanced in forest areas where mobile laptop PCs and Pocket PCs can be connected with strong signal strength to provide high-speed data services.

• Forest Modeling. Simulation models predicting forest growth are useful tools for planning forest management. Different forest management strategies can be simulated with these models and analyzed using different indicators describing yield, stand structure, and species composition. Well-tested forest models are often available at the local scale for different forests worldwide (Shugart 1998, Vanclay 1994). A new challenge would be to develop regional level forest models that are simple to use and can simulate a wide range of different management options to link with the global models.

• Global Interoperability. Interoperability is an essential attribute of forestry databases and information systems. Standards and common terminology are therefore the building blocks of the foundation on which innovative and scalable products in the Digital Forestry field can be built. With data and metadata standards and common middleware, digital information will flow efficiently throughout the forestry systems managed by an organization, a nation, or a global agency.

Potential Implications. Digital Forestry remains largely a concept and still leaves much to be developed. Forest scientists and practitioners are now starting to face this new challenge and may ask how the concept can be better studied and applied to their own fields. Below, a few conjectures are presented.

• To Add Values. Application of Digital Forestry concept could add values to the existing programs in natural resources education by providing students with a better understanding of the integrated use of technology to support sustainable forestry. We must recognize the importance of maintaining a highly trained community of "Digital Foresters" who can carry out duties using the most appropriate data and technologies to support ground operations. To train a new generation of Digital Foresters, ultimately it will be necessary to develop new curricula focused in this area. For example, graduate students in forestry or natural resource management might take separate classes such as forest management, remote sensing, and geographic information systems. After completing these courses, the student will likely be able to plan and conduct a timber inventory, build growth and yield models using appropriate regression techniques, manage and analyze stand databases in a GIS, and use high resolution remotely sensed data to delineate stand boundaries and classify land cover, respectively. However, the coursework in each of the separate courses will not address methods for linking GIS data sets with forest growth models to project the spatial distribution of forest resources in future landscapes, or for linking these simulated landscapes with graphics programs to produce photorealistic 3-D visualizations. As such cross-disciplinary applications become more common in forestry, it will become imperative for students to have the skills to implement them and the ability to develop novel linkages as new questions and problems arise. It is recommended that forestry schools examine their available resources and expertise and establish interdisciplinary research and education programs in Digital Forestry. Cooperation with other disciplines, such as geography, informatics, and computer sciences could greatly enhance the programs.

• To Increase Efficiency. Digital Forestry could improve the effectiveness of already existing government programs. The China Forestry Administration, for example, has been working for several years to build the country's digital forestry information system. This ongoing program is expected to greatly improve China's technical capability in forestry in the years to come. However, without a deep and clear understanding of the integrated values the Digital Forestry concept may be a system of disconnected technologies: a national system that may not have the organization and hierarchical linkages necessary to provide true opportunities for cross-linking and multidisciplinary cooperation. For example, national guidelines for forest inventory and mapping will need to be compatible across a broad range of forest ecosystems, ranging from the tundra to the tropics. The data collected in forest inventories will need to be compatible with models used to project stand growth, fire risk, and wildlife habitat suitability. The information derived from these data sets must be useful for strategic planning at the national level, and for implementation of specific management practices at the local level. It is recommended that the national or federal government agencies explore the Digital Forestry programs within suitable agencies in partnerships with universities and develop and implement the concept.

• To Implement Integrations. The International Union of Forest Research Organizations (International Union of Forestry Research Organizations (IUFRO)) global forestry information system (GFIS) program is one of the primary cases from which the concept of Digital Forestry is originated, and this concept in turn adds a new perspective to the future development of GFIS. The realization of GFIS provides multiple benefits to information users and providers worldwide, including facilitating user-friendly access to a greater amount of forest-related information (http://www.gfis.net/). However, forestry organizations must be aware that many systems may not produce the right information in the right format when critical information is needed to fight against threats, and therefore backup and rescue systems may need to be integrated into the overall system. Digital Forestry approaches are the means of addressing these challenges and allow the integration of component technologies together with non-technical elements to support a successful suite of responses to threats and disturbances of forest ecosystems at a global scale.

On The Next Level. Human societies and individuals depend on forests for timber, fuel, paper, food, medicine, rubber, and hundreds of chemical products. There are also the issues of maintaining species diversity and overall ecosystem health. It is therefore alarming that globally, forests are being cut down more rapidly than they can be regenerated. The biodiversity that is being lost with the lost forests means that potential new medicinal and chemical resources, yet to be discovered or exploited, will also be lost. Sustainable forestry, both in terms of forest renewal, and in biodiversity conservation, still remains as a global priority, and there are many barriers to managing for sustainable forests including population growth, land-use conversion, legal constrains, and technological limitations (Floyd 2002).

With the initiation of Digital Forestry, foresters of the world will be able to consider an entirely new approach necessary to address the challenges of deforestation, biodiversity loss, and sustainable forestry. It is anticipated that the Digital Forestry concept will provide a conceptual basis for the evolution of forestry education, research, and practices as the 21st century unfolds. Looking ahead one thing is clear: with a focused vision of the techniques and technology of Digital Forestry, we will have a view of the path ahead, and will be able to rapidly move forward on that path to new levels of integrated forestry.

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