Sustainable Capacity in Value, Biomass & Carbon
- What Models provide.[1]

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Abstract

Research in inventory, growth models and planning systems peaked between 1980 to 2000. Meanwhile, requirements for precise yield projections have increased for value, biomass and carbon. This paper presents new, integrated models and strategies for assessing sustainable capacity at stand, forest and region levels. New, integrated approaches to inventory design, growth models and planning systems provide insight into native growth capacity, climate impacts and species dynamics not previously observed. These findings identify more robust approaches to field research designs, technology integration and forest-wide planning. A universal modeling system is described which provides more precise yield projections across all silvicultural systems (clearcut, seed-tree, shelterwood, selection). This universal model has been calibrated for tree species in all major forested regions of the country. It provides a means to evaluate carbon capacity and flow at the stand, forest, region and national levels.

Keywords: Yield forecasting, Growth Models, Forest Planning, Sustainability, Mensuration.

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Background

In the period of 1965 to 1970 computer modeling was becoming known in forestry research. Prior to this period all forestry yields were only presented as tables and charts in hard-copy reports and manuals. Significant skills and knowledge were required in statistical methods to produce these reports, but once completed the report became a static reference point. The author was free to move on into other research interests. The report stood on its own.

Also during this period it was becoming increasingly apparent that forest yield capacities were significantly impacted by the kind and intensity of silviculture practiced on a given ownership. The concept of a "working forest" began to have meaning through new findings about substantial increases in yield capacity due to regeneration practices, tree species selection and silvicultural investment. These factors caused the expansion of investment in forestry research in USFS Experiment Stations, Corporate Forestry Research teams and University Cooperative Programs. Many field research trials were initiated across all regions and forest types. The International Biome Program (IBP) sprang up in almost every country, region and research group to better understand the vegetative capacity and character of all forests, wetlands and deserts. Contributions to knowledge about forest growth and yield capacities were frequent and from many sources, both public and private.

As an example of this trend, in early 1972 the Canadian Forestry Service (CFS) held a meeting at the Petawawa Forest Experiment Station in Ontario of forest mensurationists from across Canada to discuss the tree growth simulation program within the CFS (Honer, 1972). A six-member working group (Brian Armitage, Jim Arney, Imre Bella, Jim Cayford, Frank Hegyi and Terry Honer) was appointed to develop recommendations for tree growth simulation research within the CFS (Honer, 1973). Their report includes the following statements:

> *"If the extensive forest management practices in Canada were to continue, yield table methods would probably provide results significant for planning purposes; however, if we assume that forest management will intensify in the future, we will need methods that can used to forecast the outcome of a range of alternative silvicultural strategies. The impact on tree and stand growth of spacing, density, site, defoliation, and fertilization will have to be considered. Finding solutions to these problems through thinning, spacing and fertilization studies, and then fitting this fragmented information together cannot be done effectively with the framework of yield tables."*
> *"… we need a new kind of framework, a model, that is complex enough to combine and integrate the effects of all these factors. What is required is an operational tree growth simulator capable of providing yield estimates for natural and managed forest stands."*

In summer 1972 Dr. Jim Arney sent a personal letter to mensurationists in the West with the following invitation:

> *"Because there is a high level of interest among mensurationists, an informal workshop will be convened on September 6 and 7, 1972 at the U.S. Forest Service, Forest Sciences Laboratory near Olympia, Washington. Interested Mensurationists are invited to participate. No formal papers will be presented so that maximum advantage can be taken of this*

> *opportunity to discuss common problems and evaluate various approaches to tree growth modeling. Enclosed is a list of scientists who have expressed an interest to participate."*

Everyone on the list accepted the invitation. The participant list is of historical interest:

Weyerhaeuser Research Center	Centralia, WA	Dave Bower, Dave Lewis, Jim Woodman, Dale Shaw
Crown Zellerbach Research	Camas, WA	Bob Strand, Jim Lin
MacMillan-Bloedel	Nanaimo, BC	Don Reimer
PNW Forest Experiment. Station	Olympia, WA	Dick Miller, Don Reukema, Dick Williamson, Bob Curtis, Dave Bruce, Don DeMars
Washington Department of Natural Resources	Olympia, WA	Gerry Hoyer
Faculty of Forestry, University of British Columbia	Vancouver, BC	Don Monro
Canadian Forestry Research	Victoria, BC	Jim Arney, Jim Lee
INT Forest Experiment Station	Moscow, ID	Al Stage
Rocky Mt. Forest Experiment Station	Fort Collins, CO	Cliff Myers
NE Forest Experiment Station	Columbus, OH	Sam Gingrich
PSW Forest Experiment Station	Berkeley, CA	Dave Sharpnack
PNW Silviculture Lab	Bend, OR	Walt Dahms, Jim Barrett
British Columbia Forest Research Branch	Victoria, BC	Al Fraser, Nick Kovac

Within two years an informal correspondence among a wide geographic array of growth modelers developed. This correspondence was mostly by personal letter or phone conversation among modelers (There was no Internet or email). The correspondence grew to include Al Ek (Wisconsin), Lee Wensel (California) and Harold Burkhart (Virginia). The discussions and comments were highly technical and dedicated to specific model building questions and alternatives. This was a new science and there was ample room to share ideas without treading on anyone else's developmental efforts. As a result, almost none of this is documented in the retrievable literature. Building on this series of correspondence, various forest modelers began documenting their progress. Ken Mitchell (1973) began developing the Tree and Stand Simulator (TASS) at the Research Branch of the British Columbia Ministry of Forests in Victoria. Al Stage (1975) began building the Prognosis growth model at the Intermountain Forest Experiment Station in Moscow, Idaho. Lee Wensel (1977) established a redwood growth and yield cooperative among Northern California forest land owners to build the CRYPTOS and CACTOS growth models. Al Ek and Rolfe Leary (1975) developed the STEMS growth model in the Lake States Experiment Station. Each of these modelers was in contact with the others and aware of the relative success and approaches being attempted elsewhere. There were actual pieces of FORTRAN source code sent among modelers where similar problems were encountered and someone found an efficient solution.

A IUFRO Meeting was held in August, 1973, in Vancouver, British Columbia. At this meeting Don Monro (1973) presented his paper on structure and approaches to growth and yield models. His group labels used to define the types of growth models are still used 37 years later (i.e., Whole-stand; Tree-list, distant-independent; Tree-list, distant-dependent).

Each of these developments in the 1960s and early 1970s cycled back into the inventory methods both in the cruising designs and information retrieval. Since the growth models were requiring tree lists of diameter, height and numbers of trees per acre, then the cruise design began to collect diameter at breast height in addition to tree count on a point sample that previously only required a tree count to determine an estimate of total basal area per acre. This provided stand structure detail for silvicultural regime building.

In the 1970s, point sample cruises began recording all trees (all commercial species) to the nearest 1-inch which were greater than 5-inches diameter at breast height. This provided a more complete estimate of the diameter distribution found in each cruised stand.

Meanwhile, ownerships with interest in moving forward into new silvicultural regimes of young stands quickly noted limitations in their CFI (Continuous Forest Inventory) approach to inventory. It provided good information about past silvicultural treatments; but it provided no basis for evaluating future regimes. In the early 1970s and 1980s, these ownerships switched to more intensive temporary plot designs with fixed-area sub-plots for small trees (less than 5-inches diameter); crown ratio, upper-stem taper, tree age and tree damage measurements. This degree of measurement intensity provided detail about species composition, log size distributions, total basal area and stand height/age indices to site index classification. The permanent plot inventory grid was replaced with a stand-based sample of temporary plots.

Each stand in the forest inventory was now recognized and tracked for its unique species, size, age, vigor and spatial characteristics as well as its unique spatial location in the forest with regard to road access, operability, riparian buffers, wildlife corridors and soil capacities (productivity and sustainability). The geographic information system (GIS) became a critical component of a well designed and managed forest resource landbase.

This progression to a much higher proportion of the forest inventory with direct field measurements resulted in a significant decline in the number of contracted projects for aerial photo-classification and mapping by the mid 1990s. It was common practice in the 1970s to fly a complete set of aerial photography to generate a timber-type photo classification. This was the standard approach to develop a forest-wide inventory. However, once the complete photo-type coverage was available, the inventory forester began cruising stands to convert from a dependence on photo-type labels to a directly measured stand-by-stand forest inventory. The era of aerial and satellite vegetation mapping for forest resources began and ended in a matter of twenty years (1970 – 1990).

A disturbing trend became prominent in the early 1980s. As these new growth models became published, public funding began to decline. This was partly due to a declining national economy, but primarily due to the U.S. Congress identifying that forestry growth and yield research was a "mature" science requiring less funding than previously supported. The number of field research trials being re-measured on a regular basis dropped off to less than 30 percent of previous years. The US Pacific Northwest Forest and Range Experiment Station closed the Bend Silviculture Laboratory in 1996 and dropped all support for ongoing research in Ponderosa Pine and associated types east of the Cascade Mountains. Operating budgets for the PNW, PSW and Intermountain Experiment Stations dropped to nearly zero. By 1998 only salaries for existing scientists remained. By 1990, commitment to internal forestry research organizations in Weyerhaeuser, MacMillan Bloedel and Crown Zellerbach dropped to less than one-tenth of funding levels of the 1970s. However, the need for growth and yield research linked to inventory methods and planning activities within each of the private forestry companies was becoming more visible, anticipated, integrated and demanding.

Transitions in the 1990s

This situation of increased mensurational technology requirements from forest management organizations combined with declining federal support for research opened an avenue of research development not expected – the private research consultant. The personal computer and cooperative sharing of research databases provided a basis to launch applied research and development from a new perspective. Goals and timetables could be agreed upon prior to implementation of the project. Ongoing support was established and total costs were defined. The foundation of success was an agreed level of commitment, integrity and knowledge among all cooperators.

This author took full advantage if this evolution in forestry research and development by establishing and executing a series of independent cooperative research projects. Dr. Arney developed the Stand Projection System (SPS) growth model for west coast forests. It included managed stand projections and inventory updates for Douglas-fir, Western Hemlock, Western Red Cedar, Noble Fir and Red Alder. Tree volumes for any merchandizing limits were determined using Demaerschalk and Kozak's (1977) whole bole taper equations. SPS was distributed including the growth model, a user's guide, documentation and complete FORTRAN source code for $235 (Arney, 1985a). Over 140 copies were distributed in the next four years (Arney, 1985b). In 1986, Arney conducted a one-year cooperative agreement for analysis of the growth and yield of Western Hemlock using the SPS tree-list architecture. A range of other SPS analyses were conducted, including Yields for Hawaii (1988) and Growth Models for Alberta (1991). A new alternative to traditional research and development organizations was established and accepted. It should also be noted that this was the first time a standard modeling structure was applied to multiple regions and species.

Some companies and some consulting firms have spent months and years in human resources and budgets developed their own unique inventory, growth and planning database software to carry this array of forestry attributes. With the development of micro-computers have come very sophisticated relational database software utilities such as Microsoft's Access. These database utilities surpass anything previously attempted in the forest industry and are being updated and supported on a regular basis. Custom-built forest inventory systems now have all become obsolete in less time than it took to develop them. Examples are easy to identify in both large forest industry organizations and private consulting firms promoting their unique inventory systems only a decade ago. Tied to the software and hardware evolution in micro-computers is the desire to standardize forestry tools among all vendors of software utilities. This drive provides the forest industry, at no direct cost, with the array of tools that have been needed since the desire in the early 1960's to develop long-range sustained yield plans in the forest industry.

Knowledge of efficient, reliable and defensible harvest scheduling methods is integral to commitment to long-term forest ownership and management. This is especially the requirement in a social environment of oversight by special interest groups, regulatory agencies and limited expectations of a robust forest economy. The mensurational integration of these inventory, growth projection and harvest scheduling methods continues to be the foundation necessary for a defensible forest management strategy.

Evolution away from even-aged silviculture

In the latter part of the 1980s, various natural resource interest groups began to promote concerns about clear-cutting practices and their impact on wildlife and the environment. This promoted new interest in alternative methods of final harvest such as seed-tree, shelterwood and selection harvesting methods. The whole stand and tree-list growth models developed from even-aged, single species databases provided limited capacity for projecting all-aged, mixed-species stands, especially when it came to incorporating natural regeneration through the projection horizon. These older models also relied on traditional (example, King 1966) site index, height/age curves for stand projection from age zero. By 1990 many plantations were exhibiting significantly faster growth rates than anticipated in the original 1970s growth models.

The tree-list, distance-dependent growth models by Arney (1972) and Mitchell (1975) had the capacity to handle these more complex stand structures, but they each had their own limitations. The TASS model (Mitchell, 1975) was designed to only start from bare ground for each projection. It could not input an existing inventory stand as a starting condition. The tree-list model by Arney (1972) had very little data behind the initial development of parameters and it was not compatible with the Microsoft Windows environment common to the forest inventory technologies of the 1990s.

Therefore, Arney (1996) conducted a one-year project in Western Oregon to calibrate this tree-list, distance-dependent growth model. It was based on the original 1972 growth modeling architecture but modified to accept a variable number of regions and species. The software was re-written to provide a completely integrated Window-based set of mensurational tools compatible with current forest inventory computer systems. The growth model developed from the Western Oregon analysis was the Forest Projection System (FPS) and the Regional Library was identified as Region 11. Then Arney (1997) conducted a Western Washington growth model analysis using the same FPS architecture in a one-year project. Next Arney (1999) conducted an Inland Northwest growth and yield cooperative project to calibrate FPS for inland species. The growth model Regional Libraries developed from these analyses included Region 13 – Eastern Washington; 14 – North Idaho and Western Montana; and, 15 – Eastern Oregon.

In 1993, Dave Hann (2007) completed a five-year analysis of the tree-list, distance independent growth model, ORGANON, for Douglas and Jefferson Counties in Southwest Oregon. Total cost of the analysis contributed by Boise Cascade and USDI – Bureau of Land Management was approximately five million dollars. The growth model ran in a Microsoft DOS Window requiring text file inputs and outputs. This model never gained a significant level of acceptance by the forest industry due to its text file requirements and limited number of species included. To be functionally incorporated into an operational forestry organization required that organization to employ a computer programmer to build all interfaces between the inventory database, growth model and harvest scheduling utilities. A few companies were large enough to justify this investment, but most were not. Later, a dynamic-link library (DLL) routine of ORGANON was released, but this too required a computer analyst to be maintained within each company that proposed to use this version of the model. As a result, the model has been used in case-study analyses from time to time, but it has never become a work horse inventory update and harvest input functioning growth model.

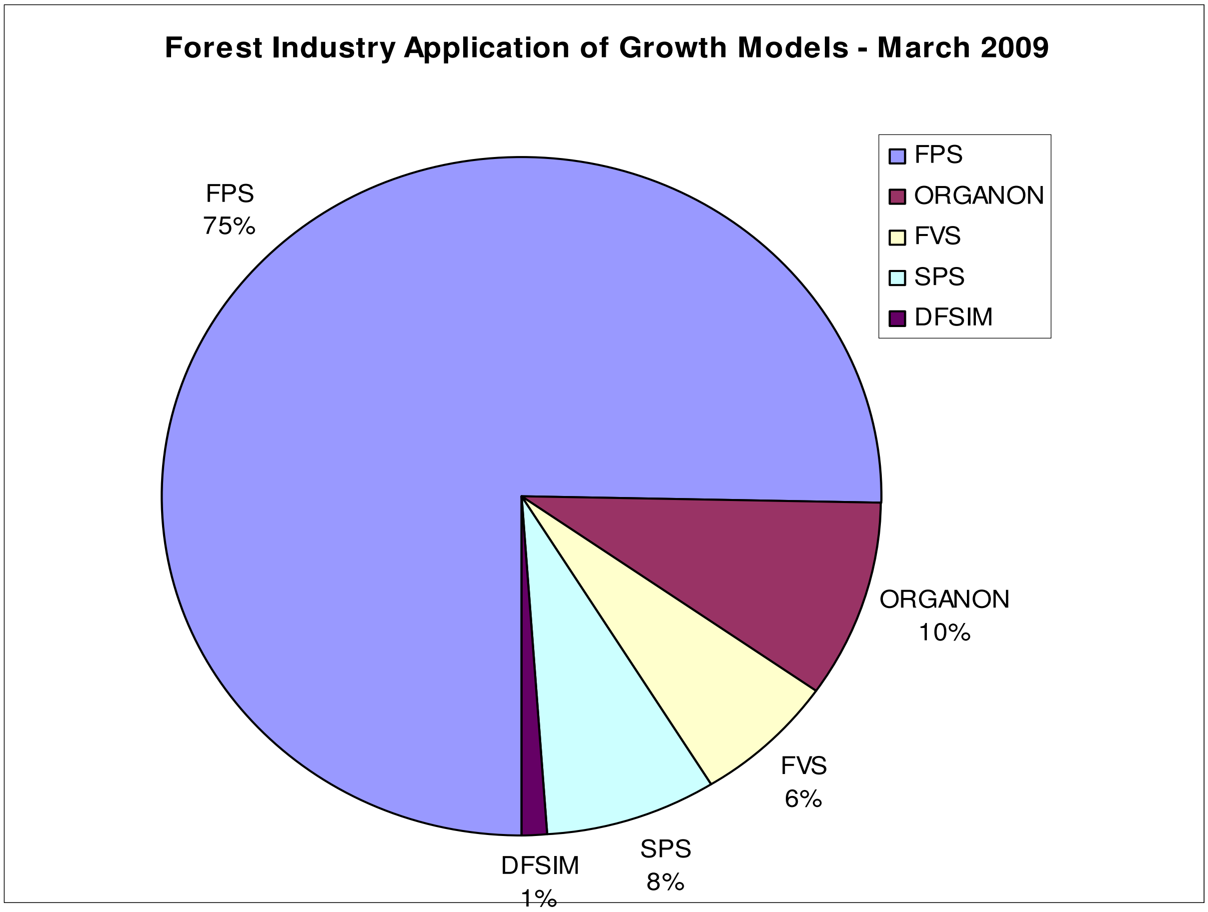
These results from the release of new mensurational technologies that do not get embraced and accepted by the forest industry are not so much the fault of the forest analyst imbedded in the project. These results are mostly due to a lack of understanding by the host organization (University or Experiment Station) about the evolving industry needs and how these new technologies integrate into the other current technologies being applied within the forest industry. The analytical investments in DFSIM and in ORGANON were significant and historically important. However, they were both delivered slightly behind the evolution of technology in the forest industry. The result was predictable had anyone evaluated the impacts of ongoing developments in other mensurational endeavors (inventory and planning in these cases). A survey in 2009 tallied the models used in the West by over eighty private, corporate, tribal, county, State and Federal forest management organizations (Figure 1).

Declining funding of forestry research through 1985 – 2010 has resulted in the following summary of ongoing growth model support in the West:

Growth Model	**Developer**	**Status**
Prognosis	Al Stage / Bill Wycoff	Retired
FVS (Prognosis)	Ralph Johnson / Gary Dixon	Retired
DFSIM	Bob Curtis / Gary Clendenen	Retired
TASS	Ken Mitchell	Retired
Cactos	Lee Wensel	Retired
Cryptos	Lee Wensel	Retired
ORGANON	Dave Hann	(Retired)?
SPS	Jim Arney	Not supported
FPS	Jim Arney	Active
PPSIM	Don DeMars / Jim Barrett	Retired

These funding shortfalls were affecting the forestry schools as well. Undergraduate and graduate student interests shifted to environmental sciences and away from quantitative sciences such as mensuration and statistics. Faculty retirements in mensuration and timber management have been (and are being) replaced with emphasis in wildlife, environment and social sciences.

Figure 1. Survey of Growth Models used throughout the West in 2009 by all organizations.



University-hosted Cooperative Research Programs

This situation is not unique within forestry research on growth models. The desire by many companies to get involved in forestry research and development was discussed earlier as the catalyst which caused a wide array of research cooperative programs to emerge. A mentioned earlier, these cooperative research programs were primarily hosted by universities with faculty members as the project directors. Significant amounts of funding have gone through these cooperative research programs over the past three decades. These programs have installed extensive numbers of field trials in genetics, fertilization, thinning, vegetation control, nursery practices and planting stock. However, the benefits to the faculty member for investing in these programs were never adjusted to recognize these commitments. As a result, the university cooperatives have installed, measured and collected vast amounts of research information. However, once the faculty member develops preliminary results there is an immediate push to publish these results in a “refereed” journal. This is essential to the faculty member for merit salary advancement. However, the forest industry participants are left with minimal conclusions, tools and procedures to implement these results into their internal forest planning analyses. Further, the faculty member receives no merit for providing ongoing support of previous published results. Consequently, most cooperatives have gathered great amounts of research information and have provided little technology transfer to the industry cooperators or ongoing technology support. With more difficult economic times, these research cooperatives will cease to exist due to a lack of insight at the outset about what constituted the full depth of a robust research and development program. Thirty years of experience has shown us that the research must be current, relevant and supported for the project to endure.

Sadly, the research activities prominent in most of the US Forest Experiment Stations, universities and cooperatives in recent years have only focused on individual components of forest management. Typical of this view are research activities regarding sampling designs, nursery practice, nutrient gains, genetic selection, herbicides, growth models and more recently environmental concerns. None of these components has been integrated into an overall framework for a forest land management organization to integrate into their forest planning structure. However, pieces of these research programs do get integrated into various public regulatory structures which act to constrain the options available to the forest landowner. This situation only increases the risk of more aggressive silvicultural scenarios when benefit and risk are difficult to quantify. The outcome has been a trend away from intensive forest management to more custodial approaches or outright disposal of the ownership. *The message – informed decision-making requires fully integrated, robust models.*

Where are we now?

In the 1960s and 1970s it was typically required in the university senior year of forest management to work in teams in a classroom and field setting to develop a forest inventory, yield projections and alternative harvest schedules. They integrated these components into a final report which produced a recommended forest management plan for a school forest or large tract of land. The graduating seniors were expected to understand and implement these types of planning activities upon successful employment in a forestry organization. That expectation by the employer is not different in 2009, but the methods are no longer taught nor exercised in the university setting prior to graduation. As a result, the graduating foresters are not equipped to handle the range of tasks essential to developing an active forest management plan for the organizations who have hired them. This conclusion has been confirmed repeatedly in the past twenty years where this author has hosted in excess of 28 post-graduate workshops where the land management organization is paying the workshop fees for their forester to learn basic inventory and harvest planning methods. The forestry education is now happening after graduation with a B.S. degree in forest management, not before.

In 2002 the National Research Council established a committee to look into the status of forestry research in the United States. The report, “National Capacity in Forestry Research”, has some very specific observations and conclusions (Cubbage et al, 2002). These include:

> *“Our national capacity in forestry research appears to have waned even as the demands placed on our forests and the need for enhanced technical knowledge have increased.”*
>
> *“The reduction in capacity in the USDA Forest Service is cause for concern.”*
>
> *“In the committee’s opinion forestry research capacity is at a crossroads, if not a precipice.”*

> *"In brief, this report suggests that our current forestry research capacity is neither adequate now, nor poised for success in the coming years. This report identifies significant declines in real research capacity, fragmented cooperation, and poor communication among principal providers and users of forestry research, inadequate support of both foundation and emerging disciplines, and little strategic planning to address future forestry research needs."*
>
> *"Declines in fundamental disciplines have been observed in faculty and support staff of universities and natural resource agencies." "University programs should assume a renewed commitment to the fundamental areas of scholarship and research in forest sciences that have diminished in recent years."*
>
> *"Our review and our recommendations can be used to shape future forestry-research efforts, enhance research capacity, and encourage public and private interests to help to achieve a strong research foundation for sustainable forest management."*

Significant portions of the report referred to establishing "Centers of excellence in forestry". The concept was to bring research, development, education and implementation into an integrated program which would provide a permanent foundation while maintaining a forward-looking structure of effective and financial performance.

One significant recommendation that continues to be overlooked:

> *"Recommendation 5-2 Clear federal research facility mandates – such as long-term ecological research sites, experimental forests and natural resource areas, and watershed monitoring facilities – should receive priority for retention and enhancement, and a system of periodic review of all facilities should be implemented and maintained."*

This report by the National Research Council is 144 page in length and should be required reading for every forestry manager in the country. Fundamental knowledge about forest management is being lost and most current research programs are losing focus. In this author's opinion, it is not just forestry research at a crossroads, but all of forest management in this country is at a precipice!

Moving forward in 2010

What is missing – integration of technologies and how to use them. It is time to look past the individual components and to look at forest management as a whole. It does not matter what the intended forest management goal may be; the components are the same and the integration of forest dynamics, silvicultural options and administrative constraints must all be considered as an integrated composite. There is a core educational foundation that must be provided regardless of the mission or goal of the organization which employs these graduates. That core no longer exists in any forestry school known to this author or the authors of the National Research Council report.

In 1983, Arney wrote a two-page personal letter[3] to every forestry dean in the West with a concern “about the strength of our biometrics research programs here in the Northwest”. The emphasis was on a fully integrated program in inventory, growth and planning technologies from research to education. Various responses resulted including the action by Dean Ben Stout at the University of Montana in hosting the newly formed Inland Northwest Growth & Yield Cooperative (INGY). It also facilitated the thrust into the Stand Management Cooperative (SMC) at the University of Washington. However, not one dean of a forestry school responded with an interest in taking on this leadership opportunity in forest mensuration. By 2002 this situation was apparent to the National Research Council committee resulting in Recommendation 4-2. It has now been eight years and no forestry school has taken on this challenge.

> *“Recommendation 4-2 Universities should develop joint programming in geographic regions to ensure a ‘critical mass’ of faculty and mentoring expertise in fields where expertise might be dispersed among the universities.”*

A) Establish a demonstration “Working Forest” with a Sustainable Management Plan.

What is a “Working Forest”? It is a forest under an active forest management plan which maintains a vigorous, healthy, dynamic growth capacity across the full ownership. All acres are detailed and tracked in a stand-based inventory including such factors as tree species, size, density, structure, soil capacity, treatment history, health, access and operability. A management schedule has been developed where every acre has a silvicultural regime assignment. The silvicultural plan is updated and reviewed annually including all harvests, regeneration, growth and mortality. Note that the management goal has not been specified as yet.

A “Working Forest” may be managed under a set of clearcut regimes, seed-tree regimes, shelterwood regimes or selection-only harvest regimes. There may also be any combination of these different silvicultural systems incorporated into one sustainable management plan for this forest.

An integrated forest management system of procedures and analytic tools is essential to each forest land manager. There is no assumption here that any specific integrated system will meet all needs. However, it can provide a standard or threshold as a reference point for more customized or sophisticated approaches. This reference point is essential for public acceptance of forest management as a profession grounded in fact and integrity. Too often the forest industry is presented as “extracting” the remnants of a “fixed natural resource” rather than managing a “renewable natural resource”. Contrary to popular public sentiment, clearcutting a stand does not produce a permanent scar on the surface of the earth. Since we provide no integrated view of forest management anywhere for public access, we are subject to all criticism, founded or un-founded, without defense. However, we could and should provide a standard. That standard should be a demonstration working forest with a “sustainable” forest management plan that is available for public viewing, dialogue and understanding.

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[3] Personal correspondence. Dean John H. Ehrenreich, September 26, 1983. College of Forestry, Wildlife & Range Sciences, University of Idaho, Moscow, Idaho.

Sustainability is undefined in much of the context which it is used in the current public dialogue about forest management. To determine if a crop is sustainable, it requires more than one harvest or rotation of that crop. The series of harvests make up the evidence of sustainability or the degree of sustainability. The degree of sustainability could imply a gradual decline, incline or variability over the time horizon of interest. For forest management the time horizon must be at least a full rotation of the crop or effective life span of the specific forest under consideration. Two rotations (even-aged silviculture) would provide good evidence of the degree of sustainability of the selected forest management plan. However, since a single rotation encompasses decades of time, reasonable confidence in sustainability may be obtained in one and one-half rotations by close observation of the developing inventory relative to the scheduled (or anticipated) development.

In a mensurational sense, this definition of sustainability provides wide latitudes of alternative management scenarios. For example, a four thousand acre tract is sustainable if eighty acres are harvested each year and replanted to be harvested again in fifty years. Every year has the same harvest and regeneration plan, forever. However, the same tract could be harvested completely (all acres) in one year and replanted. The plan would wait fifty years to then harvest the complete tract again and replant. Every fifty year cycle is the same, forever. This management plan is also sustainable, but the variability within the planning period is extreme. This second plan is likely not to be socially, politically or environmentally acceptable. Where then is the compromise for "sustainable" forest management? What degree of annual perturbations in inventory and harvest are acceptable? No existing forest ownership is completely balanced in all age classes and stages of development at this time. Therefore, how much variability is acceptable from year to year and decade to decade to achieve sustainability? Only an integrated forest management plan considering all soil, site, silviculture, wildlife and environmental factors can provide that answer. Where is that integrated planning system that everyone accepts as providing a defensible answer? It is not available from our federal experiment stations or universities. For forest management to be publically accepted, it must be demonstrated to be sustainable. The tools and techniques currently exist. There just has not been sufficient focus or commitment to integrate them into a reference point – a demonstration "working forest".

The term "*Sustainable*" implies and begs for a statement of the "*time frame*" under consideration. However, a time frame is almost never provided in public usage of sustainability for forest practices, regulations or goals.

The time frame must be defined in order to determine "*repeatability*" of growth, harvest, investment, cash flow and/or revenue in subsequent time frames into the future. If these practices are repeatable in future time frames, then these practices are sustainable. Sustainability may be fully defined, if both the time frame and repeatability in future time frames are considered.

Interestingly, it should be noted that this definition is complete and sufficient for forestry usage. However, it does *not* imply or require a constant level of growth, harvest, investment or revenue within the time frame being considered.

In this discussion, it is appropriate to introduce the concept of a "planning horizon" for determining sustainability of harvest on a given block of forest land. The Planning Horizon is the "time frame" within which the harvest level is being determined. The Planning Horizon should be sufficiently long enough for the forest land base to cycle through all growth phases (regeneration to harvest) on each and every acre. Inclusion of these growth phases is necessary to define the sustainable capacity of this ownership. In the West, this Planning Horizon should be specified as being at least sixty to one hundred years in length. Habitat Conservation Plans based on a fifty-year planning horizon are obviously not addressing sustainable capacity!

Primary factors which determine the Sustainable Capacity of a Forest

1) *Sustainable Capacity* – The highest annual sustainable harvest levels will not be achieved until the entire inventory becomes well-stocked and equally-distributed geographically in all age classes. This may require as much as a full rotation length into the future to achieve. The magnitude is determined from the soil-site capacity and silvicultural strategy employed.

2) *Regulations and Restrictions* – Habitat Conservation Plans and State regulations, which invoke mandatory maintenance of riparian buffers, nest site buffers, maximum clearcut sizes, green-up harvest scheduling delays, minimum forest cover constraints by watershed and exclusion of clearcut regimes, create a complex and intense reduction in annual harvest capacities for at least one full rotation of harvesting activities or until the forest has evolved into the conditions in Item (1).

3) *Growth Capacity* – Rates of forest growth within the restricted acres identified in Item (2) have no bearing on the justification of harvest levels in the operational acres (i.e., the argument that harvest does not exceed growth). A parallel example is checking account withdrawals which cannot be offset with transfers from a locked savings account. Growth in the locked savings account has no bearing on the capacity of the checking account to sustain repeated withdrawals. Only growth capacity of the *operational acres* has significance to the sustainable harvest capacity of a tree farm.

4) *Silviculture* – The highest sustainable harvest capacity and value on any given forest acre is from a series of repeated clearcut harvests and plantations. Conversion to a series of partial cuts or selection thinning will only remove an equal volume of timber to the clearcut regime, at best. Any partial cut regime series causes more logging costs, road maintenance and damage to the regenerated forest than a clearcut regime. A given acre managed on a partial cut regime will be entered from two to four times to achieve the same harvest volume as one entry of a clearcut regime. A partial cut regime has little control on tree species selection or stocking density and it typically transitions into more shade-tolerant, less valued timber species. A clearcut plantation regime sets tree species, stocking and uniform distribution.

5) *Residual Inventory* – A working forest inventory will evolve to an average age of one-half the harvest age and an average standing inventory equal to the total net acres times the volume per acre of a stand at one-half harvest age of the average site capacity of the tree farm.

6) *Forest Health* – The maintenance of forest health and minimization of risk to wildfire is best achieved through active silvicultural regimes based on even-aged clearcut final harvests. This is contrary to public perception, but well documented and demonstrated in science.

B) Establish a Center for Research, Development and Support for Working Forests

Given the declining status of our federal research programs and university staffing, the 2002 National Science Council recommendation to develop regional "centers of excellence" in foundation forestry sciences is compelling.

In 2002 Drs. Jim Arney and Kelsey Milner established the Forest Biometrics Research Institute (FBRI) just as the National Science Council report was being published. They obtained IRS 501 (c) 3 non-profit research corporation status for the Institute effective August 14, 2003. Through cooperative database sharing agreements and past research by Arney, the Institute has gathered the single largest and most complete permanent plot research database in the West. Growth projections for natural stands, plantations, vegetation control, fertilization and thinning in over two dozen species throughout the West have been developed and verified from these databases.

The FBRI maintains, enhances and supports a fully integrated inventory, growth projection and harvest scheduling software system for use by all forest management organizations. It provides a textbook, "Biometrics of Forest Inventory, Forest Growth and Forest Planning" (Arney, Milner and Kleinhenz, 2007) and an annual series of continuing educational workshops in forest management methods, practices and tools.

Over seventy forest land management organizations currently support the research, development, education and service functions of FBRI. This organizational structure is unique in forestry but common in many other disciplines. A non-profit corporation exists to serve a mission. That mission for FBRI is enhancement and application of forest biometric methods and principles. It cannot deviate from that mission by structure of its Bylaws. Over the past forty years foresters have observed this mission to change within other structures including USDA Forest Service Experiment Stations, Universities, research cooperatives and consulting organizations. The rates of these changes have depended on the personalities in management positions in various years. Perhaps the FBRI non-profit mission is the structure which the National Science Council committee was attempting to discover?

C) The Ten Principal Components of Forest Models

Through forty years of past research and development in the West, this author has identified ten principal components common to most past biometrics research from all agencies which make up core elements of a robust forest management system. These principal components have been integrated into a software package identified as the Forest Projection and Planning System (FPS Version 6.95). FPS is supported and distributed by the FBRI research, development and services organization identified earlier. These components are contained in the following list:

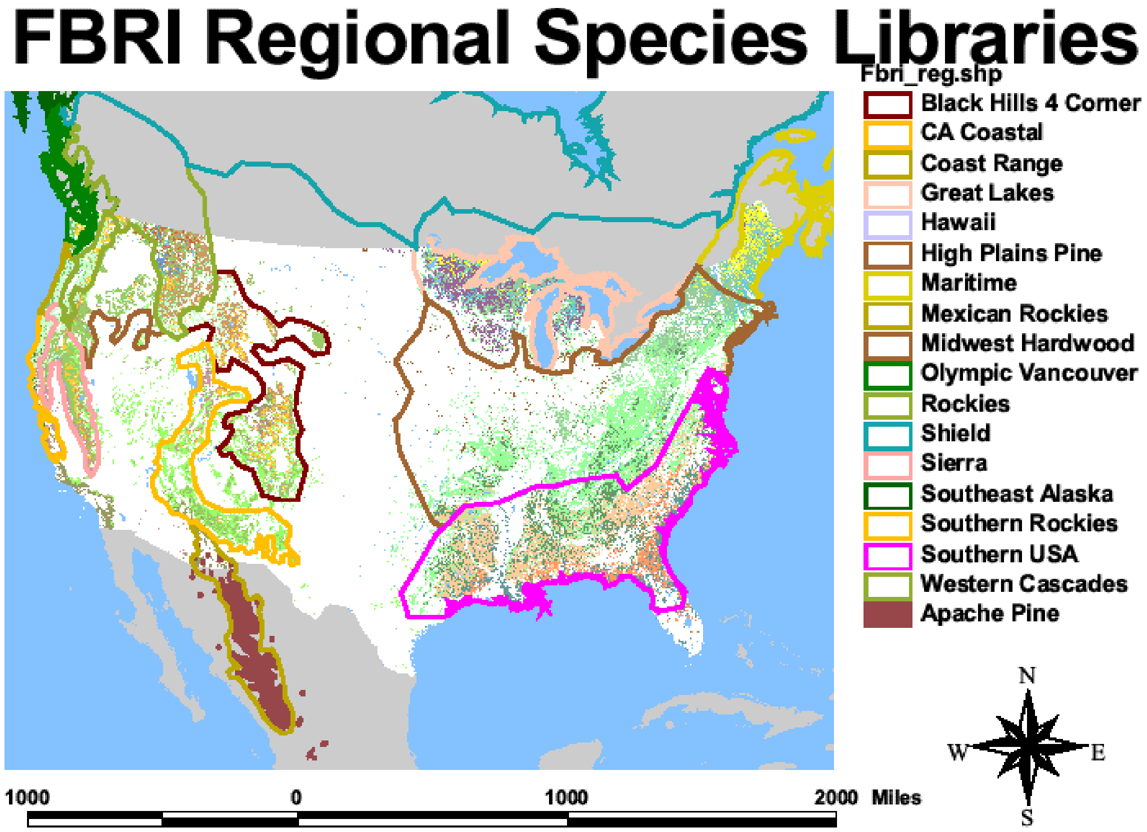
1) The native macro-site capacity of the forest for maximum tree growth and survival;
2) The native macro-site growth constraints given the geographic range of a species.

3) Tree regeneration rates and survival given alternative levels of silvicultural investment;
4) Accurate quantification of individual tree diameter growth given site and silviculture;
5) Accurate quantification of individual tree height growth given site and silviculture;
6) Accurate quantification of individual tree mortality given vigor, species tolerance and silviculture;
7) Individual tree taper profiles which quantify merchantability, biomass and carbon capacities;
8) Individual species tolerance for shade and capacity to maintain crown vigor for growth;
9) Genetic variability within and among tree species for growth, vigor and survival; and,
10) Species ranking of specific gravity among bole, bark, branches and foliage for biomass and carbon capacities.

The FBRI forest model (FPS) applies all of these principal components in a single, unique software and database structure identified and referenced as the Regional Species Library. It is the only forest inventory, growth projection and forest planning package available in the United States where all species-specific parameters reside in an external database. No equations exist within the FPS software other than standard calculations of acres, basal area, stand density measures, log values, harvest costs and discounted cash flows. All site, taper, growth and mortality of each and every species are defined in the external Regional Species Library database. To add or modify parameters for a tree species or region requires no changes to software. All regions (NW, SW, NE, SE) of the North American continent use the exact same set of software tools. This is unique to this FPS architecture among all forestry software currently available from any source – public or private (Figure 2).

The FBRI Regional Species Library currently contains parameters for all ten principal components identified earlier for each of 140 tree species in thirteen States and three Canadian Provinces. These parameters are derived from a database library containing over 20,000 permanent research plots and 13,000 felled-trees including growth and mortality observations for more than fifty years. There is no forestry research organization with a more silviculturally and geographically diverse array of direct field observations of the growth and mortality dynamics of forest tree species than is encompassed within this FPS Regional Species Library.

Figure 2. Distribution of FPS Regional Species Libraries in 2010.



The strength of this approach to forest models is due to two primary factors:

1) The Regional Species Library is completely non-parametric in structure (there are no equations);
   As non-parametric methods make fewer assumptions, their applicability is much wider than the corresponding parametric methods. In particular, they may be applied in situations where less is known about the application in question. Also, due to the reliance on fewer assumptions, non-parametric methods are more robust.

   Another advantage for the use of non-parametric methods is simplicity. In certain cases, even when the use of parametric methods is justified, non-parametric methods may be easier to use. Due both to this simplicity and to their greater robustness, non-parametric methods are seen by some statisticians as leaving less room for improper use and misunderstanding.

2) All calibrations of the ten principal components rely on (or are fully based on) balanced orthogonal distributions of field observations.

> *Orthogonality is a property of factorial sample designs that is very desirable. It guarantees that the sample design provides observations of the effect of one factor or interaction clear of the influence due to any other factor or interaction. The factorial design is orthogonal if it is balanced in assignment of observations in a completely crossed design where every level of each factor is observed at every level of every other factor. A balanced factorial design is one which each level of each factor has the same number of observations. These properties provide assurance that all cross factor variance is minimized or eliminated in the experimental design. This property has resulted in many successful experimental designs where sampling was time consuming, expensive and the number of primary factors is significant (Kurosaki et al, 2008; Wang and Wu, 1989; Gupta and Nigam, 1987).*

The significance and power of these two factors should not be under-estimated or dismissed. There are no other forest inventory, growth, mortality, silviculture, climate or genetic models known to this author that have applied (or even attempted) these two primary factors in their design or development. These factors have been applied in FPS model development for fifteen years with continued success.

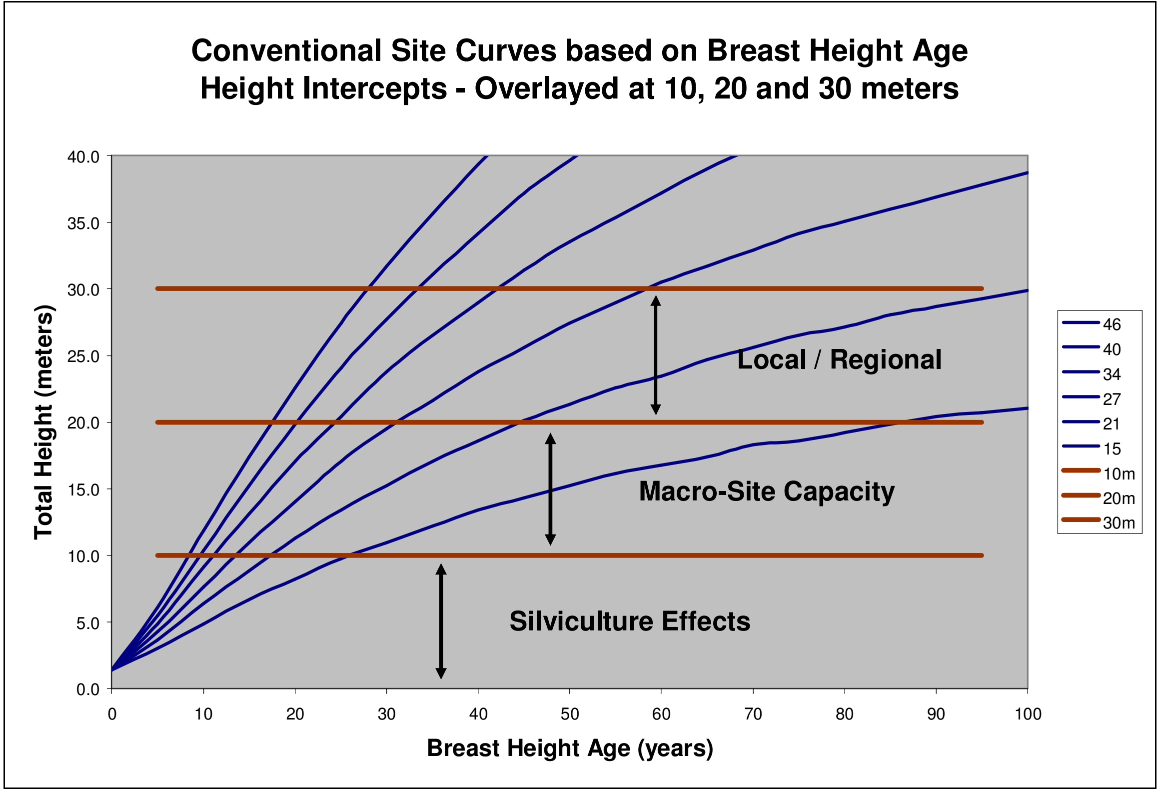
D) Model Structure & Design for the Ten Components in a Regional Library

Traditionally components (1) and (2) were provided from breast-height or total age-based height curves of site capacity. However they implicitly included past silviculture as an overriding constraint to future capacities in height-age projections. In 1978 Dr. Boris Zeide identified the commonality and differences in a wide array of height-age curves generated by various authors for many regions and species. He identified two factors important to defining height-age curves for different species and/or regions. These were site level and curve shape imbedded in each model. This imbedded level and shape defined site capacity for only one silvicultural history and the average soil-topographic-climate condition observed by the original author. It identified for the first time in forestry research that the selection of the original dataset can cause a significant impact on future uses of these equations in forest growth models. If height-age curves for a given species may vary by soil-topographic-climate conditions, then the selection of the original dataset should be based on an orthogonal sample across these primary factors.

Additionally, the early height-age development of individual trees in forest stands (component (3)) have been found to be highly influenced by early silvicultural practices of site preparation, nursery stock, planting techniques, non-tree vegetation control and browsing from insects and animals. These influences have confounded many traditional analyses to define height-age curves for site index classification independent of silvicultural history.
Figure 3 displays a traditional set of height-age curves from a published model (King, 1966) which provides estimates of site capacity but as a result assume a fixed silvicultural history and an average soil-topography-climate from the region sampled. Forty years of forestry research has identified a wide range of early height growth capacities depending on the kind and intensity of silvicultural treatments applied. These early silvicultural influences become secondary to macro-site influences by the time the trees have developed to heights of six to ten meters (20 to 30 feet). However, height growth rates may be from 30% - 150% of traditional site curve

predictions when the trees are in the one to five meter height range of growth. This is extremely significant in the use of growth models to evaluate and justify early silviculture investments.

Figure 3. The 10-meter site capacity method compared to traditional site curves.



In the past three years, the FBRI research team has conducted twelve regional field studies in six western States using balanced orthogonal sample designs for classifying site capacity by soil, topography and climate. The method is identified as the 10-meter site index approach. Site is defined by the number of years required for trees to grow from 10 to 20 meters in height. Primary factors defining site capacity in all regions include length of growing season (days above 10 degrees C), elevation, soil depth, soil drainage and annual precipitation. In every project these models have explained 75 to 85 percent of the variation in site capacity. This has never been achieved using traditional site curve methods. There is every reason to expect similar results in every forested region. The methods are non-parametric and orthogonal.

Additionally, this method provides a robust technique which may be used to quantify the rate of change in site growth capacity due to climate change by sampling the same orthogonal matrix using trees which grew through the 10 to 20-meter height interval in sequential decades. Components (4), (5) and (6) characterize individual tree dynamics (diameter, height and mortality) under all conditions of site, size and competitive stress. Traditionally these have been modeled using complex equations and transformations of site, density, age and initial size. Each model is based on a statistical fit to some specific dataset of known silvicultural history. These models become obsolete as soon as some alternative silvicultural treatment regime is proposed. This is especially important since most traditional growth models are based on even-aged silvicultural treatment regimes. Current trends are forcing evaluation and acceptance of all-aged silvicultural as alternatives to clearcutting, seed-tree or shelterwood regimes. Traditional permanent research field plots only sampled a minor portion of tagged trees for height and often no trees below some minimum size threshold (such as a 2-inch minimum diameter at breast height). These research trials are ill-equipped to answer questions about the growth dynamics of all-aged stands in a selection-harvest only silvicultural system. Traditionally this would imply a whole series of new field trials representing every conceivable silvicultural treatment alternative. This would be extremely time consuming (decades) and expensive to implement.

However, using existing research trials where all heights were measured on all trees and all trees were stem-mapped provides a population from which an orthogonal sample may be obtained. Since 1973 Dr. Arney has been measuring heights on all tagged trees on a sample of research installations across the West. These installations have been systematically stem-mapped and accumulated in an ever expanding research database. For each tree species, all plot measurement intervals were standardized on a fixed increment in height (20-feet) rather than a fixed increment in age (e.g., 5 or 10-years). All observed increments of diameter (breast height) and total height were divided by the observed increment in site capacity height. Figure 4 displays the diameter increment range in relative diameter and height scale of a single species of any height, diameter or stand density (competitive stress level, Arney 1973).

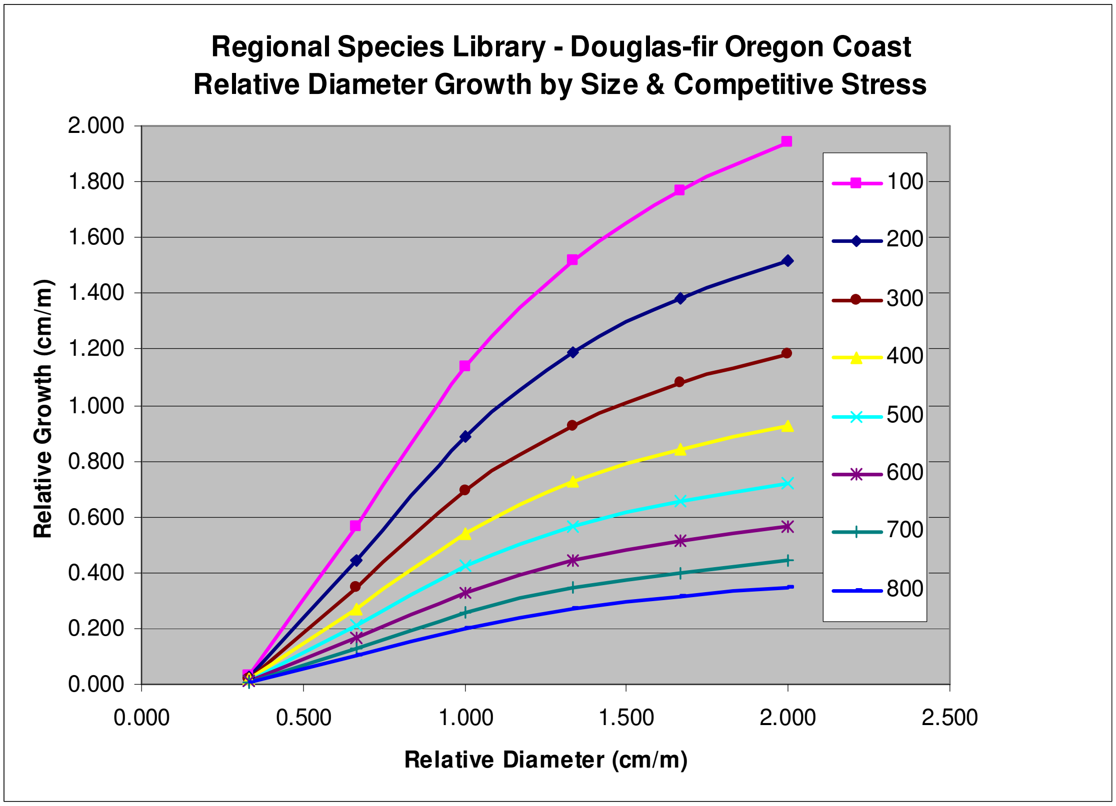
On a relative scale Figure 4 represents the diameter (breast height) growth potential for any tree size, age, density or site index level. The tree observations used to generate this figure were drawn as orthogonal samples from the range of size and density found in each research installation. The growth profiles in Figure 4 are the averages of the individual tree measurements. Installations are drawn from an orthogonal matrix by soil-climate site capacities.

This same relative transformation was done for individual tree height growth and for individual tree mortality by species and region.

The Regional Species Library then contains the actual average observations of diameter, height and mortality in a series of non-parametric tables by species and region. The growth model then simply interpolates across the size / density surface for an estimate of growth or mortality for each tree in the growth model. This growth model design is structured to interpolate the dynamics of all ten principal components drawn from the Regional Species Library regardless of species or region of interest. This integrated system of databases and software is extremely robust with regard to its ability to apply to any species or region.

This FPS growth model architecture is defined by Monro (1973) as an Individual-tree, distance-dependent growth model. In other words, each tree grows or dies depending on the local site, silviculture, size, vigor and tree-specific density at that point in time. The growth model is structured independently of any assumption of even-aged or all-aged structures or species composition.

Figure 4. Example relative diameter increment model in FPS Regional Species Library.



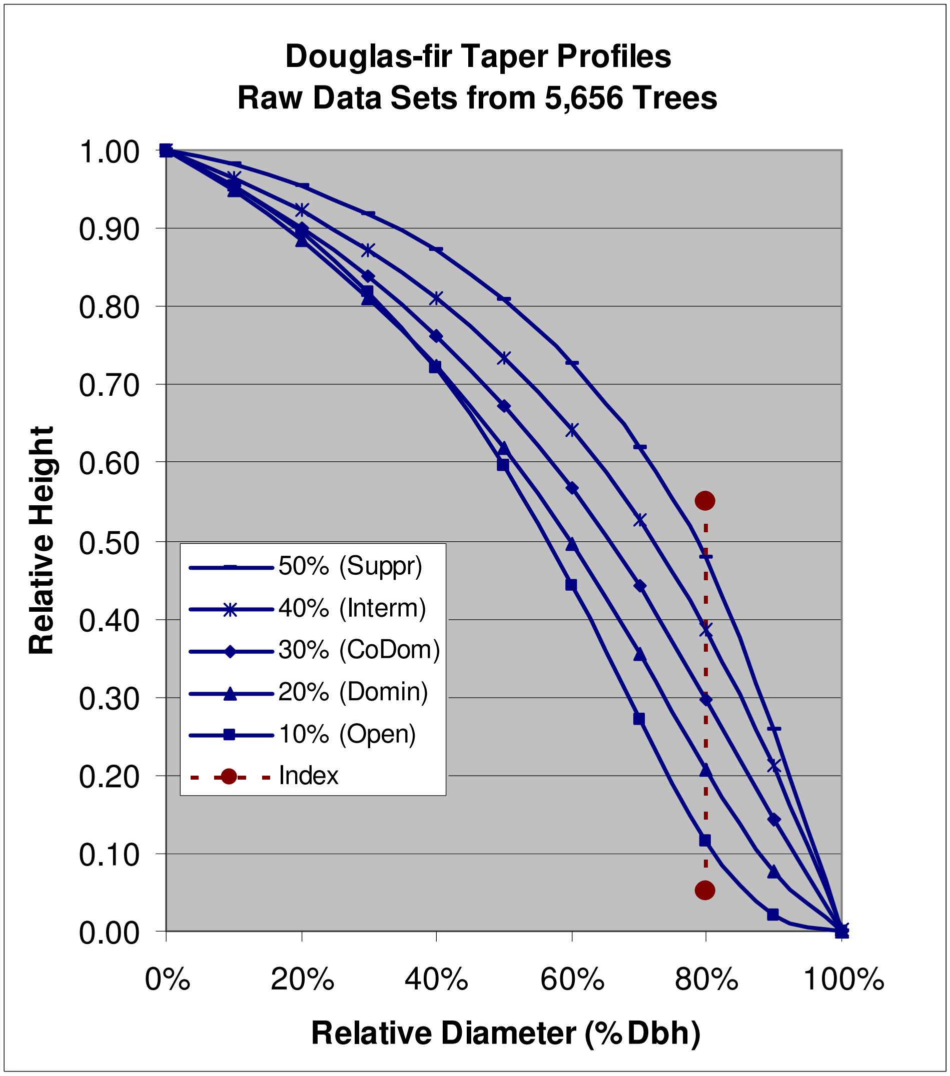
Similar to the relative transformation of diameter and height growth profiles, the tree taper profiles are displayed and applied in scales of relative dimensions. The objective in the taper profiles was to draw out the essential differences due to tree form in order to optimize the computations for volume, merchantability, biomass and carbon distributions.

The same tree diameter (breast height) over total height provides a robust scale to display and rank tree taper profiles as it did for tree growth profiles. Figure 5 is a display of the actual averages of tree diameters and heights as obtained from felled-trees after sorting and ranking by taper class. Every diameter observation is displayed as ratio to the diameter at breast height. Every height observation (minus 4.5-feet) is displayed as a ratio to total height (minus 4.5-feet). This provides the ability to aggregate all sample trees on the same chart regardless of total height or diameter.

This series of taper profiles are represented in the Regional Species Library as a table for each species. These taper profiles have been developed for every species and region in thirteen States using the same non-parametric architecture and orthogonal sampling approach.

This approach provides the FPS cruise compiler, re-merchandiser, growth model and harvest scheduler to access the same Library reference when computing volume, biomass or carbon. There is no other set of integrated forest management tools available where all components of the system access the same volume functions. This is an extremely important benefit when a forest management organization is attempting to produce year-end inventory reports compatible with year-end growth estimates. A cruise compiler from one source and a growth model from a different source have always produced different yields when loaded using a common tree list. We overcome this difficulty by all forestry components calling on a common set of Libraries.

Figure 5. Display of average profiles by taper class from 5,656 Douglas-fir trees.



All ten principal components of this forest management system use the Regional Species Library as the source of localized, regional species-specific parameters. This Library is easily updated and available for third-party evaluations and verifications.

Integration of research analytical techniques with non-parametric models and orthogonal sample designs has resulted in a robust approach to move forward across many regions and species with a common design. This approach greatly reduces total time and expense to build forestry decision-support tools for alternative forest management goals. It is no longer necessary for a research team or graduate student to build an entire growth model from scratch just to evaluate a species, silvicultural effect, genetic impact or climate trend. Past research in growth models were exploratory in nature and highly driven by individual initiative of each author. The material presented in this paper is the summation of those trials and experiences over the past forty years. Due to the nature of this history of fragmented research, much of the understanding about modeling has not been aggregated, summarized and documented. That goal is now underway at the Forest Biometrics Research Institute with the objective of providing a robust basis for moving forward in the development and use of models for forest management and planning.

The current 340-page textbook describing this Forest Projection and Planning System (FPS) is being re-written in 2010 and 2011 to accomplish two missions. The first is a complete tutorial of the approach and methods to: (a) build, maintain and update a stand-based forest inventory; (b) project individual forest stands under any silvicultural regime of treatments including planting, spacing, site preparation, brush control, pest control, fertilization, pruning and commercial thinning; and (c) provide complete detail for short and long-term forest planning analyses of alternative silvicultural regimes, riparian buffers, wildlife corridors, green-up constraints, harvest size restrictions, and various Habitat Conservation Plan constraints. The second mission is the complete documentation of the biometric methods behind these non-parametric models and their balanced orthogonal sampling strategies which were applied. This second mission will likely take the form of a series of publications about each of the ten principal components. They will be available from the FBRI web site for download if no other form of publication is more appropriate.

These two missions of providing documentation of the current capacity in forest modeling will provide working documents for staff in operational forest management organizations, a basis for undergraduate forestry education sufficient to manage a working forest and a foundation for future research and development in forest biometrics – inventory, growth and planning.

E) Identify a single forestry education program in each major region of the continent.

Currently there are many SAF-accredited undergraduate forestry programs across the United States. Few if any of these provide an in-depth education about a working forest and the methods and tools to manage that forest upon graduation. As a result many forestry consultants are fully employed assisting major forest land management organizations in developing good inventories, year-end reports and long-term forest management plans. This is partially due to limited staff constraints, but it is also due to the fact that younger college graduates do not have the skill sets demonstrated by the older existing professional forestry consulting teams. This author has been heavily involved in continuing education programs for working foresters for over thirty years. The short courses are being taught at ever declining levels of education because current forestry graduates are demonstrating lower levels of understanding about basic forestry principles than their predecessors. This trend must be reversed if this industry is to grow.

The National Research Council recommended focused programs in education. One forestry “center of excellence” could provide the critical mass if it includes:

1) **A University undergraduate and graduate educational program and staff** in the foundation sciences of forest management using current inventories from a working research experimental forest;

   a. **Sophomore program**
      i. Forest sampling (stands), Stand sampling (Plots), Sub-sampling (Trees, shrubs, snags)
      ii. Inventory maintenance (MS-Access), PC-based GIS, Acreage adjustments for roads and buffers, depletion updates
      iii. Annual forest sampling frequency and intensity
      iv. Site distribution and means to classify and validate
      v. Habitat classification and update methods
   b. **Junior program**
      i. Inventory growth projection methods
         1. Applications, Constraints, Validation
      ii. Silvicultural systems and yield differences
         1. Clearcut regimes, preferred species & densities
         2. Seed Tree regimes, regeneration systems
         3. Shelterwood regimes, habitat implications
         4. Selection regimes, single-tree versus group
      iii. Forest health, vigor, regeneration, tolerance
         1. Species selection, vigor, plantation culture
   c. **Senior program**
      i. Harvest scheduling methods linked to GIS
         1. Hydro, Wildlife, Watershed & Neighbors
      ii. Planning horizons for 100 years versus 5 or 50 years
      iii. Impact and silviculture of 2nd & 3rd rotations
      iv. Standards of merchandising and valuation
      v. Regulation by Area, Volume, Value or NPV
      vi. Harvest unit polygons versus Stand polygons
   d. **Graduate program**
      i. Solid foundation in forest measurements and sample statistics
      ii. Review and research major biometric principals
      iii. Develop foundation in GIS and computer skills
      iv. Exercise scientific method through independent research.

2) **A Research Institute** as a center of research and development maintaining and enhancing:
   a. standard forest inventory methods, tools and documentation
   b. standard forest growth and decline models and documentation
   c. standard forest planning models, spatial reporting and methods
   d. standard libraries by region and species of growth capacities, genetics, structure (form, bark, crown) and vigor (tolerance, resistance)
   e. permanent databases of all regional research trials both historical and current programs including vegetation, soils and climate parameters;
3) **A Research Experimental Forest** containing a self-sustaining, active forest management plan of harvest and renewal (approximately 4,000 acres) interspersed with research trials on species regeneration and silviculture (1,000 acres). This working forest will provide direct public demonstration of sustainable forest management (forest, wildlife,

ecosystem, financial), maintenance of long-term research, and university student firsthand experience; and,

4) **A Continuing Educational Program** for operational forestry organizations which facilitates technology transfer from research to education to practice. A series of short courses should be established at each experimental forest including field and laboratory exercises incorporating all ongoing and new technologies from all forest management-related sources. These include species selection, nursery practices, silviculture, wildlife, edaphic, climatic, regulatory and society influences on forest practices. This suggests a full-time program in continuing education at each experimental forest including facilities and staff. If society expects to encourage successful industries; then these industries will require the best technologies and training to remain successful. It is the successful industries of our communities which provide long-term employment, stability and basis of public funding (taxation) for schools, roads and community services. Personal health and wellbeing is based on community health; and community health is based on the source of support which maintains that community. It is critical to protect and enhance those sources of community support. University education is a foundation, but continuing education provides maintenance of health and vigor within our profession.

The Forest Biometrics Research Institute has identified itself as a focal point for forest biometrics research, development, education and service. It is structured and functioning to fulfill Item (2) in the previous series of recommendations. FBRI is attempting to locate and incorporate existing regional field research trials and experimental forests (Item 3). The FBRI has also been conducting annual continuing education professional workshops in inventory, growth projection and harvest planning (Item 4). The Western Forestry & Conservation Association (WFCA) has evolved to a status in 2009 where its sole purpose is to provide ongoing short-courses for professional foresters. Apparently no research or educational organization (beyond FBRI and WFCA) has taken up this banner and that is a concern.

This review and forecast is <u>not</u> about any individual person or organization. It is simply a view into what has transpired in our recent past and the view of the future as shared by this author and thoroughly presented in the National Science Council report (Cubbage et al, 2002).

Undergraduate education programs are incomplete and ill-designed to equip the graduating forester for the current requirements of the practicing forestry profession. Existing slates of coursework are redundant and incomplete. They have fallen below an acceptable level to provide fully-enabled forestry professionals as outlined in the previous sophomore to senior depth of understanding. It appears that practicing professional foresters must speak up publically to help change the current lack of focus and direction in forestry education.

Forest "research, development and education" is indeed at a crossroads, it is time to make critical decisions for the future. Past research in forest modeling has identified a robust architecture for future application, evaluation of alternative silvicultural systems and ongoing research development. The forestry profession has evolved beyond the one model – one researcher approach to research. It is at the point of incorporating more robust integrated systems to fully understand and present management alternatives and their consequences into the future. We have the tools and we need to fortify the sustainability of our professional skill sets to succeed.

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