ELSEVIER

Landscape and Urban Planning 56 (2001) 107–124

LANDSCAPE
AND
URBAN PLANNING

www.elsevier.com/locate/landurbplan

Challenges and opportunities for linking the modeling of forest vegetation dynamics with landscape planning models

Pete Bettinger*

Department of Forest Resources, 280 Peavy Hall, Oregon State University, Corvallis, OR 97331, USA

Received 7 November 2000; received in revised form 15 May 2001; accepted 13 July 2001

Abstract

Landscape planning and analysis, landscape simulations, and landscape projections all seek to either evaluate the current or past condition of a landscape or project future conditions. The level of spatial and computational resolution chosen should be carefully considered because it will restrict or empower future developments in large-scale, integrated landscape planning projects. In this paper, the basic challenges and opportunities associated with using forest vegetation growth and yield models and databases in large-scale, long-term forest landscape simulation projects are outlined. We pose several questions that integrated landscape modeling teams should consider when evaluating whether to use forest growth and yield data in landscape planning efforts. When managers and other professionals involved in landscape planning efforts are prepared for the challenges and opportunities inherent in modeling forest vegetation dynamics, they may then be positioned to implement a fast and smooth modeling process. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Growth and yield; Yield tables; Systems integration; Data management

1. Introduction

Within the context of forest landscape planning, few will argue that forest growth and yield data are not necessary when making management decisions at the forest stand (10–50 ha), forest (>100 ha), ownership, regional, or even national level. Growth and yield data typically consist of either tree-level estimates of forest structure, or summaries of structural conditions at the stand-level (e.g. the number of ‘‘large’’ trees, snags, or timber-harvest volume per unit area). Ditzer et al. (2000) provide an example of how forest inventory, geographic information systems (GIS), and growth models can be used in forest landscape planning. The benefits of using these data and models at a landscape scale to evaluate sustainable harvest regimes, forest recovery rates, and the potential effects of diseases, insect outbreaks, or invasive plant species on forest health are becoming increasingly clear. Assessing the effects of forest management practices on productivity is another seemingly appropriate application of these models. Two arguments in favor of using growth and yield data in landscape planning and analysis, simulations, and projections (hereafter grouped as ‘‘landscape planning’’) are that it may help to determine how activities can be allocated across a landscape, and that it may help to evaluate the effects of human-caused and natural disturbances. Using stand-level models to examine situations at the landscape level helps ensure that underlying processes are considered (Mäkelä et al., 2000).

The appropriate resolution at which the information is represented in a planning model is highly debatable

---

* Tel.: +1-541-737-8549; fax: +1-541-737-3049.
E-mail address: pete.bettinger@orst.edu (P. Bettinger).

0169-2046/01/$20.00 © 2001 Elsevier Science B.V. All rights reserved.
PII: S0169-2046(01)00178-5

within landscape planning projects, whether it is tree-level data, stand summaries, or some other gross estimate of trends in vegetation dynamics (hereafter grouped as "projections of vegetation condition") particular to an issue or planning problem. Because there is no correct answer, decisions concerning data resolution generally are negotiated by planning team members through a discussion of project goals. However, the effort of projecting vegetation conditions involves some rather cumbersome and complex technical issues. Further, there is a great need to integrate complex layers of biological information (Johnsen et al., 2001), and to address questions posed at landscape scales or resolutions higher than those at which the data was measured (Smith et al., 1998).

The focus of this discussion is on the mechanical processes used to collect, generate, and summarize projections of forest vegetation condition for forest landscape planning. We assume here that planners are not biometricians. The biological and silvicultural considerations related to the type or shape of growth and yield models are left to other, more technical research. For example, while we may examine the challenges in generating large quantities of data related to timber volume, stand structure, or other measures of forest productivity, we will not delve into the form or function of the specific equations used to make the calculations. The objective of this discussion is to help integrated planning teams understand the issues related to developing forest structure data and projecting and summarizing forest trends through time, within the context of forest landscape planning (Table 1). The discussion is divided into three parts: data development, forest condition projections, and forest condition summaries and use (Fig. 1), based on the progression of data through a modeling system.

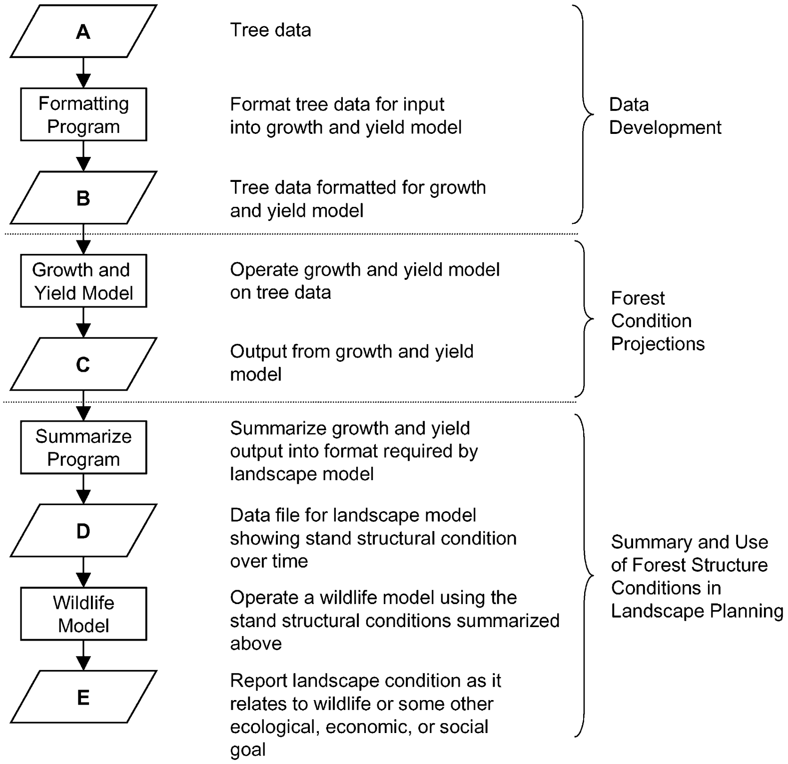

Fig. 1. Flow chart of processes associated with incorporating projections of vegetation conditions in landscape planning and associated ecological effects models.

Table 1
Issues related to data development, forest condition projections, and summaries of forest structural conditions

Data development
- Where were the forest inventory data collected?
- When were the forest inventory data collected?
- What do the forest inventory data contain?
- What do the forest inventory data not contain?
- How much data are available?
- Are other forest inventory data available?

Forest condition projections
- Which vegetation projection system should be used?
- In what area was the projection system calibrated?
- What data does it model?
- What data does it not model?
- What limitations are there to using the projection system?

Forest structural condition summary and use
- What measures of forest condition are desired?
- What processes are available to summarize the conditions?
- Have the summarization processes been verified?
- To what format should the summaries be fit?

2. Data development

Developing data for a landscape planning system may seem a trivial process, but it is one of the most important and requires careful consideration of some basic questions. To project the vegetation condition of a forested landscape, two basic elements are needed: forest inventory data and a forest growth-projection model. Forest inventory data describe the current (or recent) condition of the forest and are often related to some geographical representation of the landscape. These data may comprise a list of trees that forest technicians have sampled across the landscape, records that describe average conditions for certain types or sizes of trees, or summaries of the forest condition on a per unit area basis (e.g. conifer trees per acre or hectare). Realistic analysis of commodity production potential and management effects over time and space requires an approach that explicitly considers the heterogeneity and geographic distribution of forest conditions (Ditzer et al., 2000). Most forest industry companies update these databases every year (Fig. 2), yet the extent of this coverage reflects only a portion of the landscape, and the databases are usually considered proprietary, thus not for general audience use. For complete landscape coverage, GIS databases derived from satellite imagery are most often used, yet have limited forest inventory data associated with the landscape features. Acquiring a set of forest inventory that represents all features on a landscape equally well, then relating this data to satellite imagery, poses several challenges, many of which this paper addresses. Several basic

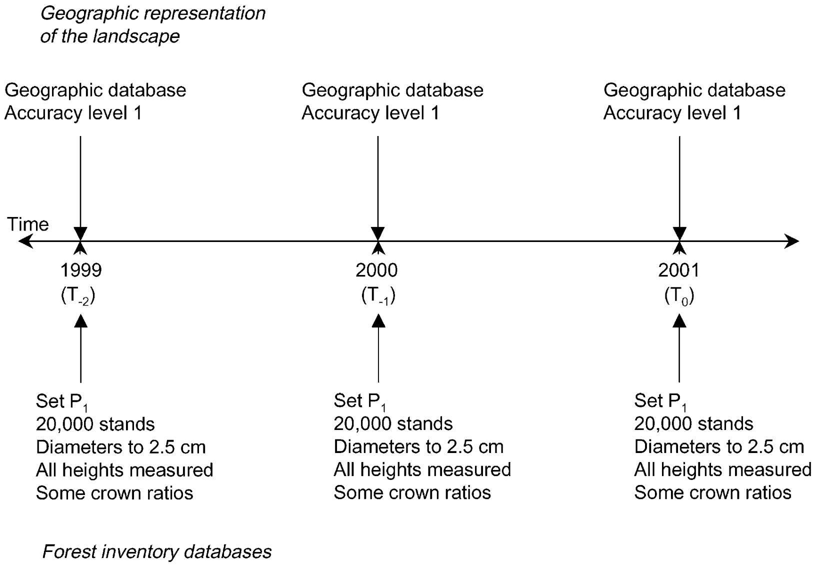

Fig. 2. Time line of forest inventory plot measurements compared with geographical database development.

questions must be asked when developing forest inventory databases, including the following: where and when was the inventory data collected, what does the inventory data contain, what does it not contain, and how much data is available?

2.1. Where were the forest inventory data collected?

Forest inventory data are expensive to collect. If one were to develop a system where forest growth trends can be estimated, a set of field plots must be adequately marked and maintained, the trees numbered and tagged, etc. and re-measured at periodic intervals. Generally, there exists a few sources of forest inventory data (public and private) for most areas in North America. However, the availability of this data is problematic, and the coverage may not be suitable for the landscape of interest.

Assuming forest inventory data are available for use in a landscape planning project, a modeler should first determine the location of each measurement plot. If they are all within the landscape of interest (L_i), this question is moot (Fig. 3). However, certain measurement plots sometimes may be located outside of L_i (in L_0), perhaps within a few kilometers of L_i, yet could represent forest conditions within L_i. For example, landscape planning in the coastal region of Oregon (L_i) might utilize forest inventory data collected in the coastal area rather than in the Cascade Mountains or southwestern part of the state. However, data for a "forest type," such as a stand of Pacific madrone (*Arbutus menziesii*), may be unavailable in certain public databases associated with L_i, but available in a database associated with the southwestern part of the state (L_0). The modeling team would have to judge the merit of using the madrone inventory of L_0 in landscape plans of L_i.

2.2. When were the forest inventory data collected?

The age of the forest inventory data poses two distinct challenges to scientists and policymakers. First, to be of value, data collected 5–10 years ago may need to be projected forward to now (assuming the landscape projection time period is from now (T_0) to some point in the future (T_1)). Growth and yield projection models may have limitations that prevent a perfect adjustment of the state of forest conditions, however. For example, assume that a growth and yield model makes projections in 5-year increments. Data collected 7 years ago could be projected forward either 5 or 10 years before it is used, but this would result in either a 2- to 3-year discrepancy from T_0, depending on the projection period. For policymakers making 100-year projections (or longer) this might not be viewed as a major problem, but it could be for scientists or managers who are interested in short-term responses or decisions associated with recent or near-term management actions.

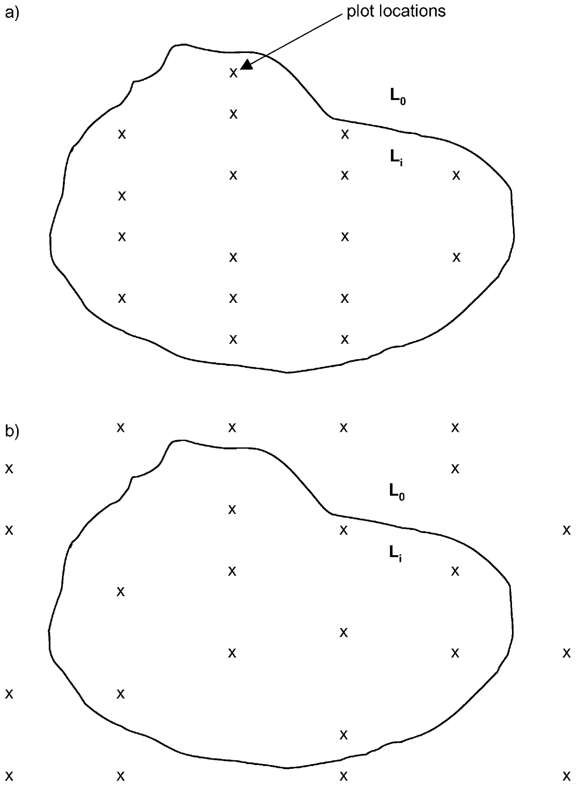

Fig. 3. Plot locations (a) within a landscape of interest and (b) within and outside a landscape of interest.

The second challenge is matching the date of forest inventory data collection to that of the geographic database with which it will be associated in the landscape planning effort (Fig. 4). Remote sensing is a valuable source of spatially comprehensive and temporally repeatable information that may be useful to

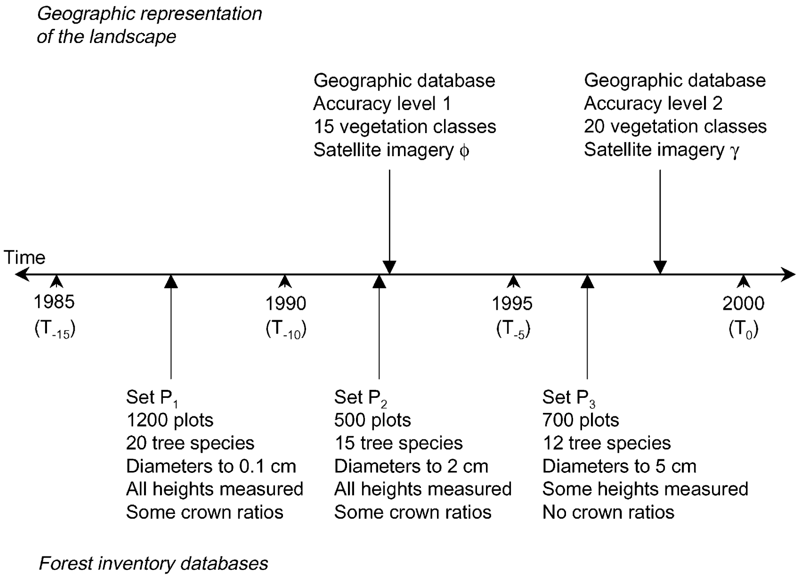

Fig. 4. Time line of forest inventory plot measurements compared with remotely sensed satellite imagery.

modelers (Plummer, 2000). Satellite imagery, for example, might be used to develop a representation of the vegetation condition of the landscape, since satellite imagery can provide a representation of the entire landscape, not just individual ownerships scattered across a landscape. If the inventory data will be associated with the imagery to represent finer detail of the structural conditions of the forests on the landscape, the timing of the inventory measurement (or subsequent projection) should be closely matched with that of the imagery. However, classified satellite imagery generally has varying degrees of accuracy and a range of represented structural conditions. Associating tree-level inventory data to these landscapes may prove quite challenging, particularly if several inventory databases are available, each with relatively better or worse qualities than the next. There is a clear need to provide an assessment of the accuracy of remotely sensed data, as well as a discussion of the range of limitations of its use. If the sensitivity of landscape model behavior to measures of forest stand structure is low, then simple indices of forest stand structure may be more appropriate than detailed measures (Plummer, 2000), and these may be more easily provided by remote sensing. However, the needs of associated ecological effects models must also be considered when deciding on the resolution of stand structure data, and in some cases this leads back to the use of tree-level forest inventory data.

2.3. What do the forest inventory data contain?

A wide array of vegetative attributes can be used to define the structural condition of a forest, from shrub layers to fungal communities, to both the live and dead components of a forest. For instance, to describe the snag component of a forest, one may need to know how many dead trees exist and, perhaps, the condition of those trees. To simply project the live-tree conditions of a forest through time, several basic forest attributes would be required, such as species composition, density of tree stems, and some measure of site productivity. Most forest inventory databases that are derived from measurements of field plots contain these data (Table 2). However, each forest growth and yield model may require a different set of data, and thus knowing what the available forest inventory databases contain is important in order to understand the extent and magnitude of assumptions that must be made in response to the data the inventory databases do not contain.

Unless planners collect forest inventory data with a particular growth and yield model in mind, some generalizations and assumptions are needed for fitting

Table 2
General data attributes of a forest inventory database (example inventory plot, data expanded to a per hectare basis)

No. trees	Tree species	Diameter at breast height (dbh) (cm)	Tree height (m)	Crown ratio (%)[a]	Expansion factor (trees/ha)[b]
1	Red alder	25	19	25	29
2	Red alder	33	27	45	16
3	Red alder	47	29	35	8
4	Red alder	46	25	35	8
⋮	⋮	⋮	⋮	⋮	
16	Douglas-fir	48	31	45	8
17	Douglas-fir	47	31	45	8
18	Douglas-fir	37	28	35	13
19	Douglas-fir	38	31	35	12
⋮	⋮	⋮	⋮	⋮	
37	W. hemlock	11	0	0	115
38	W. hemlock	9	0	0	115
39	W. hemlock	5	0	0	115
Total					1600

[a] Crown length/tree height.

[b] Trees per unit area that each tree record represents.

tree database data to model requirements (Fig. 5a). For example, assume that our example plot from Table 2 is represented by 39 tree records (1600 trees/ha), and that 15 of them (the red alder (*Alnus rubra*) records) are of a species not accommodated by the chosen growth and yield model. If planners are to continue using that particular inventory data and the chosen growth and yield model, either those 15 tree records (representing 435 trees/ha) must be ignored (e.g. tree species 6 in Fig. 5b), or they must be assigned a species code that *is* accommodated and that closely resembles the growth and structural characteristics of the original species (e.g. tree species 4 in Fig. 5b). Alternatively, a second growth and yield model could be used.

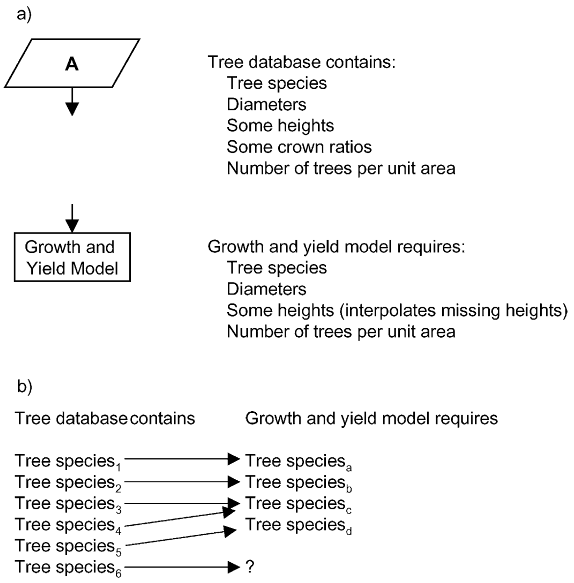

Fig. 5. Data considerations when (a) matching variables within a tree database to a growth and yield model, and (b) matching the specific measure of a variable to that modeled in a growth and yield model.

2.4. What do the forest inventory data not contain?

One of the most obvious assessments of inventory data is to determine whether all of the appropriate forest types are represented. Here, some preliminary summaries are needed to describe the extent of stand conditions represented. For example, if a 500,000 ha landscape contains 300,000 ha of plantations and 200,000 ha of naturally regenerated forests of varying conditions, one would expect more inventory data in areas where there is more heterogeneity (most likely in the naturally regenerated forests). More data, however, are usually available for the areas of the landscape for which most of the financial decisions will likely be made (i.e. the plantations). From a landscape planning perspective, one would need to ask whether there are enough data to adequately represent all landscape conditions. It is important to determine which of the landscape features are the most underrepresented and to understand the uncertainty of projecting the conditions of these resources. The landscape planning team will likely need to discuss how these determinations will affect subsequent analyses as well, factoring in the risk of under representing heterogeneity in the landscape.

More subtle determinations of possible missing information are related to the underlying forest inventory data. For example, although crown ratios (crown length/total tree height) are not required by some growth and yield models, in other models they can make forest projections more accurate. However, crown ratios are conspicuously absent from many forest inventory data sets (e.g. the western hemlock (*Tsuga heterophylla*) trees in our example inventory plot from Table 2) because of the expense involved in sampling both tree heights and crown lengths. Invariably, other data may also be missing or erroneous within an inventory database. One obvious determination of errors is to locate data outside of the normal data ranges, or in the case of categorical data, data represented by an invalid code.

Finally, modelers must understand that the type of sampling design used to collect tree data may affect the accuracy of the resulting growth and yield projections (Hann and Zumrawi, 1991). For example, data collected under a design which uses small sampling units, and used in a growth and yield model that was developed with data collected under a design that used larger sampling units, may result in inaccurate in growth predictions.

2.5. *How much data are available?*

It is quite important to discuss the trade-off between how long it takes to develop projections of vegetation conditions and the desired level of spatial and structural representation of the landscape. These discussions initially tend to focus on whether the inventory data are sufficient to adequately cover a landscape (as previously addressed), and subsequently, whether the amount of inventory data is too much to adequately manage within the time frame of the landscape planning project. Unfortunately, the potential for recognizing a vast heterogeneity of forest conditions on a landscape via hundreds of field plots may be forgone simply by a decision to reduce an planner's workload within some time frame; these compromises, however, do occur.

This trade-off might best be illustrated by assuming that a project has 1500 forest inventory plots available for its use, but only 30 days to generate the projections of vegetation condition needed for a landscape planning effort. A further assumption may be that the growth and yield model chosen requires slightly less than one minute per plot per management prescription (pathway), to generate a 100-year projection. Therefore, the total amount of time to produce growth and yield data for 1500 plots modeled under a single forest management prescription would be 25 h (1500 min) for this data set. If only one computer were available, exclusively for growth and yield modeling, only 30 management prescriptions (pathways) could be modeled in the time allotted. Variations on the assumptions indicate that the response surface is non-linear (Fig. 6). Of course, this simple example ignores the time required to format the inventory data for input into the growth and yield model as well as the time for summarizing and verifying the projections. Discussions of these matters are very enlightening, and force

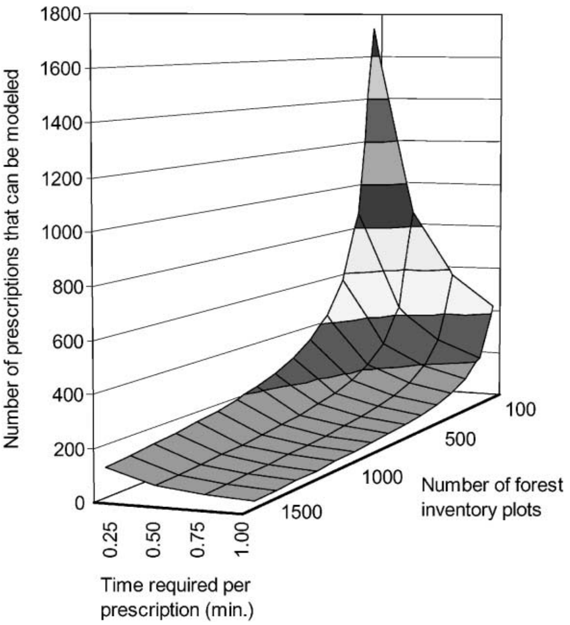

Fig. 6. Non-linear relationship between number of forest inventory plots, number of management prescriptions that can be modeled, and the time required per management prescription.

projects to focus on alternatives, compromises, and perhaps even a re-evaluation of project goals.

2.6. Are other forest inventory data available?

Landscape planning team members often suggest that project goals be delayed until other, newer (recently measured) inventory data are available. These delays must be carefully considered because, although better databases can often be obtained "in the future", opportunities to affect planning (and subsequent policy) may be lost. The challenge for planners is to obtain or develop the highest quality databases at the most reasonable cost (usually within some budget limit) in a reasonable time frame. Because databases are updated periodically, developing a system by which the new data can be assimilated rather easily and quickly into the planning system may be equally important. In addition, the verification and validation of these databases should also be considered as a time and cost item. Postponing products or extending project deadlines because newer, better databases are "soon to arrive" could be perceived as either a frustrating delay or a necessary condition for policymakers, based on the risks associated with moving forward without the new databases.

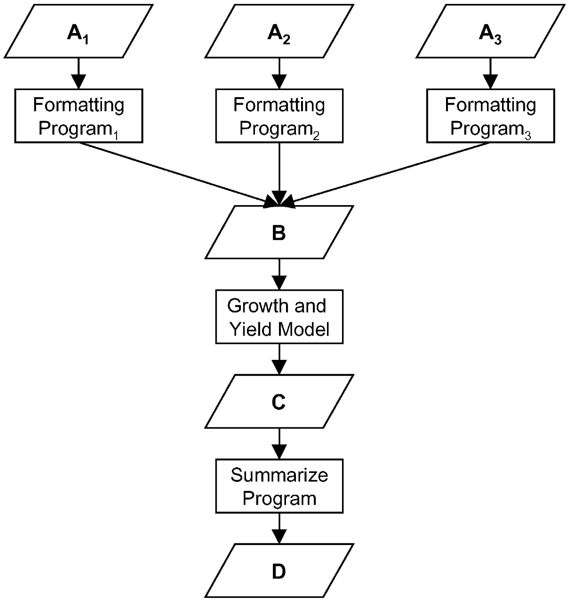

Fig. 7. Tree-level data from multiple sources may require multiple formatting programs to make the data compatible with the input requirements of a growth and yield model.

Some alternatives to traditional forest inventory databases include plot-level forest data collected under less (or more) statistically sound sampling procedures, remotely sensed data from interpretations of air photos or satellite images, or the installation and measurement of new inventory plots. All of these alternatives, as well as the available data assumed above, must be verified and perhaps validated to ensure that they reasonably represent the landscape of interest. Utilizing data from a variety of sources may also entail a variety of intermediate processes for formatting data according to the input requirements of a growth and yield model (Fig. 7). One of the most common differences is that some databases store data in metric units, and others in English units. In other cases, the protocol for identifying attributes of trees may be different. For example, our forest inventory data from Table 2 could represent tree species by their common names (e.g. "western hemlock"), which we may need to convert to a numeric code, such as "263" as used in the Organon growth and yield model (Hann et al., 1997). Suppose, however, that another source of inventory data represents western hemlock trees as "TSHE." A separate process for converting these codes to "263" are then needed if we choose to use this data. While these are simple examples, they are prevalent when using databases acquired from different sources. These other sources include Forest Inventory and Analysis plots periodically measured on private land by the US Forest Service, forest inventory plots measured on federal land by the National Forest System and Bureau of Land Management, and a variety of research plots collected by federal and university scientists. Several private organizations have also collected forest inventory data that are perhaps useful in landscape planning, yet these are generally considered proprietary, and thus generally not available for public use.

3. Forest condition projections

Once an initial landscape condition is represented by some set of forest inventory data, the next set of challenges is to describe those conditions over time for every possible combination of stand/management pathway (i.e. management prescription). Growth and yield projection models generally utilize forest inventory data as input, and apply growth and mortality functions to that data to estimate future forest conditions (e.g. trees per unit area, basal area, species mix). Other summary models, such as a snag and down log decay model, may be necessary to produce additional measures of forest structural conditions. Baldwin et al. (2001) provide a discussion on the utility of using a forest growth and yield model to provide tree-level detail for other process models. Here we present several questions related to choosing a growth and yield model.

3.1. Which vegetation projection system should be used?

Vegetation projection systems should, at a minimum, accurately model the gross growth of a forested stand as well as competition-related mortality. Likewise, they should be able to predict stand development over a range of reasonable site indices and stand conditions. Many forest vegetative models are available for areas of the world where forest research has been ongoing for several decades. In the Pacific Northwest, at least 22 computerized growth and yield models are available because no single model can satisfy all the needs of such a large and diverse landscape (Ritchie, 1999). Many of these models overlap in geographic extent. When deciding which model to use, we assume that a growth and yield model is executed on a computer, although other models of growth and yield exist as equations or yield tables (e.g. Hann and Riiters, 1982). The computerized models consist of systems of integrated mathematical relationships that attempt to mimic the dynamics of forests.

The four basic forms of growth and yield models are individual-tree, gap, whole-stand, and disaggregative. These are simulation models, i.e. simplifications of complex systems. Therefore, users should understand the advantages and limitations of each type of model (Ritchie, 1999). For example, individual-tree models utilize and track the development of trees while whole-stand models do not. Whether a stand is represented by individual trees or whether some aggregate summary statistics are important depends on the objectives of the planning process.

As their name implies, individual-tree models utilize trees to make forecasts of stand structure over time. The benefit of using this model type is its capability of producing high-resolution simulations, making it perhaps the best type for representing mixed-species or uneven-aged stands (Ritchie, 1999). Although distance-independent individual-tree models do not require the spatial location of trees in a stand, distance-dependent models do. The spatial arrangement is used to account for inter-tree competition within a stand, and may provide better estimates of thinning responses. The drawback to using distance-dependent models is that they require more data and are generally more computationally intensive than distance-independent models.

Gap models are also individual-tree models, but their distinguishing feature is that trees are modeled on a specific fixed area in a stand or gap that corresponds to the area occupied by a fully mature tree (Ritchie, 1999). The input format of these models generally is not consistent with typical sampling procedures. Thus, the tree-level inventory data must be re-formatted to the specifications of the gap model. In addition, many common measures, such as merchantable tree volume and management practices, are not available to users.

Because whole-stand growth and yield models use stand-level data to estimate forest structure through time, fine-scale, tree-level resolution is lacking. As their name implies, the output consists of stand-level measures. This type of model generally requires less data than individual-tree models, processes computations faster, and is best suited for even-aged forests (Ritchie, 1999). Disaggregative models operate in two steps: predicting stand growth with a whole-stand model, then disaggregating the results to trees that describe the stand. This model type has some of the benefits and limitations of both individual-tree and whole-stand models.

The input requirements, output products, and operating logic of growth and yield models will likely also be key in choosing the appropriate model for a planning process. Crown ratio, for example, may be an input requirement for some models, whereas others may simply impute the crown ratio from other tree data. These measured crown ratios result in growth and yield predictions that are more reasonable than when estimated. Site quality, or site index, is another input requirement that could significantly influence the results of a growth and yield simulation. Some models use site index (average height of dominant trees at some standard age) as the only measure of site productivity, whereas others require more information such as elevation, slope, aspect, and weather conditions.

Finally, the degree to which a growth and yield model (and its associated components) has been peer-reviewed may help guarantee that the form of the model is appropriate and that the projections developed are statistically appropriate within a certain range of error.

3.2. *In what area was the projection system calibrated?*

Key questions to ask of a growth and yield model are: where was the tree data obtained for developing the growth and yield equations; what range of tree sizes and site indices was measured; and how many of the tree size/site index combinations were sampled? The answers to these may lend some insight into the robustness of the growth and yield model. In addition, it is important to know the geographic regions that the model has been calibrated to work well within. The Organon growth and yield projection system (Hann et al., 1997), for example, has been calibrated for use in southwestern and northwestern Oregon, as well as the Coast Range of Oregon. Other growth and yield models, such as DFIT (Bruce et al., 1977), DFSIM (Curtis et al., 1981), FPS (Forest Biometrics Inc., 2001), FVS (Stage, 1973; Wycoff et al., 1982), PSME (Harrington et al., 1991), RVMM (Shula et al., 1998), SPS (Mason, Bruce, and Girard Inc., 2001), SYSTUM-1 (Ritchie and Powers, 1993), have been developed for portions of this same geographic area, yet the extent of the geographic boundaries vary to the north, south, and west of that specified for Organon. Extensions of particular growth and yield models to conditions outside of the range of soil and forest conditions of the calibration area most likely will require some re-calibration, which assumes users have the ability to make these adjustments (usually users do not have the ability to make these adjustments). In addition, adaptation of growth and yield models for use in modeling tree species not commonly found in a particular geographic area may require the inclusion of new ecological effects sub-models and parameters (Sands et al., 2000) into the growth and yield projection system, which again assumes users have the ability to make these adjustments.

Table 3
Number of tree species modeled by certain projection systems designed for use in the Pacific Northwest coastal areas (USA)

Model	No. of tree species modeled
DFSIM	1
FVS[a]	42
Organon[b]	6
RVMM	9
SPS[c]	25

[a] Pacific Northwest Coast variant.
[b] Coast Range (SMC) variant.
[c] Actual number depends on variant.

3.3. *What data does it model?*

The range of modeled data varies among projection systems, as is seen in the wide variety of tree species allowed in systems for the Pacific Northwest coastal areas (Table 3). Representative site indices and stand conditions also vary with each available growth and yield model. For example, PSME (Harrington et al., 1991) is very specific about what it can model, i.e. plantation-grown Douglas-fir (*Pseudotsuga menziesii*) stands from ages 3–10. Planners must also understand the range of appropriate management treatments that can be modeled, and the available output statistics (e.g. timber volume).

As mentioned earlier, the type of model selected will also dictate the type of input data that is needed. For example, whole-stand models use less input data (a diameter distribution of the trees in the stand of interest) than do individual-tree models. Individual-tree models use tree-level data from a sample of trees in a stand. More time is usually required to use individual-tree models and to manage the input data they require and output data they generate, but the projections may be more accurate than those produced by whole-stand models.

3.4. *What data does it not model?*

As noted above, some growth and yield models have very high-level, fundamental assumptions that limit what is known about the stands they model. For example, whole-stand models do not model individual trees, so landscape planners must determine whether the individual trees are of interest for summary statistics and associated ecological or economic models. Although tree distributions can be inferred from whole-stand models, the reasonableness of these estimates for other uses (e.g. ecological effects models) should be evaluated. Other lower-level differences among the models can be determined only by studying the user's manuals associated with each model. For example, DFSIM (Curtis and others 1981) includes the following limitations (from Ritchie, 1999): stands with fewer than 750 trees/ha at establishment, that are very young or that have been pre-commercially thinned, or are less than 80% Douglas-fir, are generally outside the range of data used to develop the model. Most of the models presented in this paper have a limited range of tree species that can reasonably be modeled. FPS (Forest Biometrics Inc., 2001), FVS (Stage, 1973; Wycoff et al., 1982), and SPS (Mason, Bruce, and Girard Inc., 2001), are all able to model our example stand from Table 2, however Organon (Hann et al., 1997) does not current model red alder growth, thus a user of Organon would have to decide what to do with the red alder trees in the inventory database (ignore them, or redefine them as some other tree species), and subsequently understand the consequences of the decision. Some individual-tree models also limit the number of trees that may represent a stand. For example, Organon (Hann et al., 1997) limits the number of trees per stand to 1000.

3.5. What other limitations are associated with the projection system?

Growth and yield models differ with respect to input requirements, output products, and management options available to the user (Ritchie, 1999). No standard format, or data standard, exists for tree lists. Thus, the input requirements generally vary among growth and yield models. These growth and yield model input requirements probably also differ from the format under which the forest inventory data is organized and stored. Planners must be familiar with the input data formats for the models they utilize, and perhaps will need to develop intermediate programs to convert inventory data to a growth and yield-model format.

Some growth and yield models are available both in run-time executable, stand-alone programs, and in forms such as dynamic link libraries, which allow integration with other software. Each poses its own operational problems. Stand-alone programs generally require specific input and output formats and force landscape simulations to use pre-defined management prescriptions because the growth trends through time will usually be developed *a priori* to a landscape simulation, and stored in yield or look-up tables. Dynamic link libraries also utilize a specific input and output format. However, because they can be closely linked to a landscape simulation model, the formatting can occur within the simulation model itself. In addition, dynamic link libraries allow development of management prescriptions from a continuous set of potential prescriptions, as opposed to using a pre-defined set stored in a yield table. When linked to landscape simulation models, forest conditions can be generated "on the fly" (only when needed during a simulation), yet verification of appropriate growth and yield statistics becomes problematic because the typical output products from stand-alone programs are usually not available for planners to ponder.

How growth and yield models handle missing data and their flexibility in controlling growth is also important. In some individual-tree growth and yield models, unmeasured (missing) tree values can be estimated from empirical relationships. A good example may be in estimating the missing crown ratios on the western hemlock trees in Table 2. It is worth considering whether these estimates reflect the stand conditions of the sampled area. Likewise, the ability to control stand growth based on a measure of stand density may be important. For example, a growth and yield model might be developed for a broad area, yet will be applied to a smaller local area. Biometricians familiar with stand development in this local area may have empirical evidence indicating some control of stand density is required when applying the model there. The question is not whether controlling growth and yield by stand density is important, but whether applying that particular model is feasible.

As noted earlier, a consideration of the time required to produce growth and yield projections is important. Some stand-alone growth and yield models allow users to generate multiple simulations (in ‘‘batch’’ modes), whereas others run interactively with the user, on a stand-by-stand basis. Although the time to make a single projection may be somewhat comparable, producing multiple and, perhaps, thousands of projections is an operational issue. Therefore, modelers must determine how long it will take to perform the entire job.

Finally, the range of appropriate projections must be understood. In some ‘‘areas’’ of the potential projection ‘‘space’’, users must be aware that the resulting projections extend beyond the data collected and used for model development. For example, certain combinations of tree species, site index, and other tree and site conditions may not have been observed in data collection efforts, yet a growth and yield model may still produce projections in these areas. For example, while Organon (Hann et al., 1997) will warn users that projections beyond a stand age of 120 are outside of the range of data used to build the growth models, it allows the projections to continue. If we were to assume that our example stand described in Table 2 were currently 50 years old, and if we were interested in developing growth and yield data for a 100-year landscape simulation, we would encounter this situation, since we may need to project our example stand to the age of 150 years. The other options are to stop all forest growth at 120 years and assume the forest conditions in the remaining 30 years resembled the conditions at age of 120 years, or we could simply not track any data for ages of 120–150 years. Other growth and yield models may not cover the full range of forest change dynamics, lacking regeneration, mortality, and often certain ranges of site quality (Mäkelä et al., 2000). Therefore, planners should understand the limitations of a growth and yield model, and understand that those projections outside the recommended ‘‘projection space’’ must be reviewed for appropriateness.

4. Forest structural condition summary and use

To utilize growth and yield data for describing landscape conditions, tree-level (or stand) projections should be summarized into stand- or forest-level conditions. If a dynamically linked growth and yield model is associated with a landscape simulation model, storing and using tree-level data in a simulation model may require, for example, the quantity of $[(NTV) + (NS)]$ pieces of data to be stored and managed as needed, where N is the number of tree records, T the number of time periods recognized in the simulation model, V the number of dynamic tree-level variables to be tracked for each tree, and S is the number of static tree-level variables (stand number, plot number, tree species) that must be tracked for each tree. In our example stand of Table 2, this results in $N = 32$, $T = 20$ (assuming 20 5-year time periods), $V = 4$ (diameter, height, crown ratio, expansion factor), and $S = 3$ (stand number, plot number, tree species), which amounts to 3237 pieces of data to store and track. The amount of computer memory this requires depends on the data type specified for each variable (e.g. single precision number, double precision number, string, etc.). If the growth and yield model is not dynamically linked to a landscape simulation model, and tree-level data are stored and used as yield or look-up tables, then the required quantity is $[(NTPV) + (NS)]$ pieces of stored and managed data, where P is the number of management pathways (management prescriptions). The difference is that with a dynamically-linked process, only the current management prescription for each stand data needs to be tracked, while with a static yield table system, each potential prescription for each stand must be tracked, regardless of whether it is even used. For our example stand, assuming we had at our disposal six potential management prescriptions for each stand, thus results in 18,837 pieces of data.

The main drawbacks to storing and using tree-level data within a landscape simulation model are the challenges of dynamically linking a growth and yield model or statically linking yield tables to the simulation model, the amount of storage space needed to accomplish the simulation modeling task, and the time requirements for processing the data. Alternatively, if tree-level data is not available as an outcome of a growth and yield model, yet tree-level information is needed by the simulation model, a process such as that described by Valentine et al. (2000) could be used to develop plausible model trees.

4.1. What measures of forest condition are desired?

One of the most difficult decisions each landscape planning project member must make is determining, for timely implementation of a project, the set of forest structural conditions that are needed to facilitate their analyses. The number and type of variables required by other models will depend on the complexity of those models (Plummer, 2000). While some effort is being made in the direct estimation of vegetation characteristics from remote sensing (e.g. Bergen and Dobson, 1999), data from remote sensing must be translated into information of use to other ecological effects models using some empirical or theoretical process (Plummer, 2000). Thus most measures of vegetation characteristics are usually derived from summaries of forest stand structure, which are derived from forest inventory data.

Some relatively easy measures of forest condition that can be obtained from forest inventory data or forest growth and yield projections include summarizing the number of trees per unit area with certain characteristics. For example, the number of Douglas-fir trees per unit area with diameters >50 cm, or the number of red alder trees per unit area with diameters >25 cm (Table 4). These measures, D_i, usually can be made simply by examining each tree record (or stand-table record) and deciding whether it meets the conditions of the query, then summarizing and reporting the results (Fig. 8a). Other calculations might include measures that require information or other assumptions based on professional judgment (Fig. 8b). For example, to determine the average diameter of Douglas-fir trees, a minimum diameter may be required (e.g. average of all diameters over '*x*' cm). To further explore this, assume our example stand in Table 2 had a record indicating that there were 1000 trees/ha of Douglas-fir that had no diameter, were 0.5 m tall, and a crown ratio of 90%. These obviously would represent small seedlings growing in gaps under a mature forest canopy. Should these seedlings be used in calculations of average diameter of the mature forest stand, or should they be ignored by using a minimum diameter (e.g. 10 cm) before a tree record is used in a calculation such as this?

More moderately complex measures involve examining each tree record, determining the state of the forest, then re-examining each tree record a second time. For example, reporting the average height of dominant trees would require examining each tree, storing some knowledge (e.g. tree heights) in memory, determining which trees are dominants (a subset of the

Table 4
Level of complexity in developing certain forest attributes for a time series of growth and yield projects

Forest attribute	Easy	Moderate	Difficult
Trees per unit area	X		
Basal area	X		
Volume	X[a]	X[b]	
Stand density		X	
Canopy closure		X	
Height of dominants		X	
Snags per unit area			X
Down log volume per unit area			X

[a] If available through the growth and yield model output.
[b] If not available through growth and yield model output.

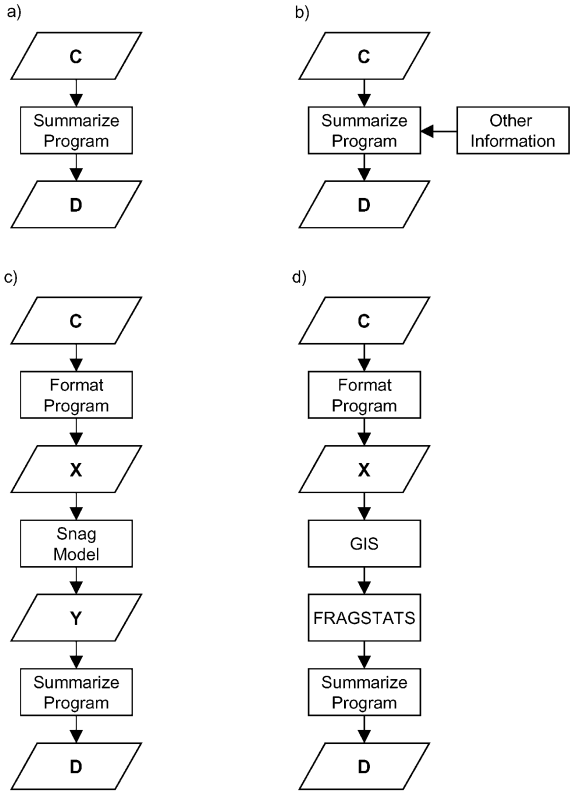

Fig. 8. Process flow for (a) an easy summarization process; (b) an easy summarization process requiring some other information; (c) a difficult summarization process requiring a complex computational summary; and (d) a difficult summarization process requiring GIS analysis.

full set of tree records), then averaging their heights. In our example stand, we may examine the full set of tree records, summing the number of trees/ha, then return to the full set of tree records and locate those that represent the tallest 25% based on the number of trees/ha each record represents. Only those records in this subset would be used to determine the average height of the dominant trees.

The most difficult summaries are those that require complex procedures (Fig. 8c and d). For example, to examine the condition of the dead tree resources (snags) in a forest, one may need to know which trees died and when, as well as the condition of each of the older dead trees, over time, which are subject to decay and fragmentation rates particular to each species and regional weather conditions. Thus for each live tree record, a corresponding mortality record may be generated each time period in a projection (as a residual of the growth and yield modeling system). Each of these mortality records may then be used in a snag decay model, which determines the residual condition of a snag based on the tree species, length of time since the tree died, regional climate, and so on. Some wildlife models may require D_i, such as fragmentation indices, or interspersion and juxtaposition measures, that are only available by passing a representation of the landscape through models such as FRAGSTATS (McGarigal and Marks, 1995). To perform this operation, the landscape may first need to be populated with the appropriate growth and yield data, such as assigning to each forested stand some structural characteristics such as stand age, tree height, and average diameter.

Determining the desirable forest structural condition measures will undoubtedly be an evolving process in which decisions are made and changed continuously. Integrated landscape planning group members must balance this indecision with the time and cost required to facilitate producing each structural condition measure. For example, a wildlife habitat suitability index model may require three D_i (Fig. 9a), whereas another ecological effects model may also require three, yet not the same three (Fig. 9b). Likewise, as the development of ecological effects models progresses, projects may find some D_i are no longer required by any models (Fig. 10). If, for example, 4 h are required to develop a procedure to summarize each D_i, and to verify that the procedure works correctly, the team must assess whether the effort of producing certain D_i is of value to the overall project. Will an additional D_i help produce more realistic results in an ecological response model? Is the desired D_i based on science, empirical evidence, or simply a hunch? If the D_i are changed often and, seemingly, capriciously, the time and cost to develop D_i may need to be considered very closely. In the coastal landscape analysis modeling study (CLAMS, Spies et al., in press), for example, 52 D_i are desired for landscape planning and ecological effects models (Table 5).

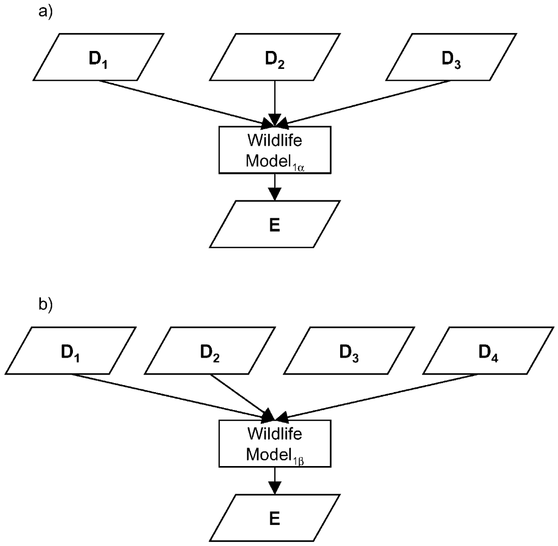

Fig. 9. An ecological effects (wildlife) model that either (a) requires three summary variables, or (b) also requires three variables but not necessarily the same three.

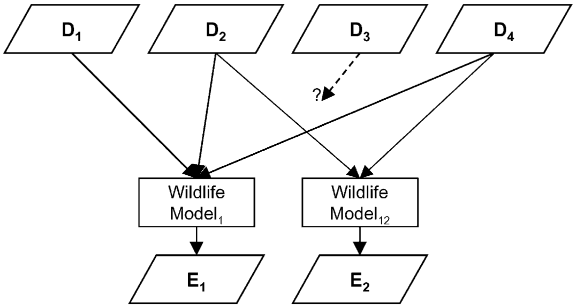

Fig. 10. Two ecological effects (wildlife) models that require three variables, yet one summary variable is no longer required.

Table 5
Type of forest attributes required for CLAMS project simulations and associated ecological effects models

Forest attribute
Average diameter — all trees >5 cm diameter
Average height — (1) dominant trees; (2) dominant conifers
Basal area — (1) total; (2) conifers; (3) hardwoods; (4) alder; (5) very large shade intolerant conifers; (6) small and medium shade-tolerant conifers
Canopy closure — (1) all trees; (2) trees <2.5 cm diameter; (3) trees 2.5–24 cm diameter; (4) trees 25–37 cm diameter; (5) trees 38–49 cm diameter; (6) trees 50–75 cm diameter; (7) trees >75 cm diameter
Canopy height index
CLAMS vegetation classes
Diameter diversity index
Down log volume — (1) all logs; (2) all logs 30–50 cm diameter (large end); (3) all logs >50 cm diameter (large end)
Oregon Department of Forestry Structural Stages
Quadratic mean diameter — (1) all trees; (2) all conifers; (3) dominant conifers
Stand age
Trees per unit area — (1) total; (2) 10–25 cm diameter; (3) 25–50 cm diameter; (4) 50–75 cm diameter; (5) >10 cm diameter; (6) >50 cm diameter; (7) >75 cm diameter; (8) >100 cm diameter; (9) conifer; (10) conifer 50–75 cm diameter; (12) conifer >75 cm diameter; (13) hardwood; (14) Douglas-fir 50–75 cm diameter; (15) Douglas-fir >50 cm diameter; (16) Douglas-fir >75 cm diameter; (17) western hemlock 50–75 cm diameter
Volume — (1) softwood standing volume (thousand board feet per unit area [MBF]); (2) softwood thinning volume (MBF); (3) hardwood standing volume (MBF); (4) hardwood thinning volume (MBF)
Snags — (1) 10–25 cm diameter, >5 m tall; (2) 25–50 cm diameter, >5 m tall; (3) 50–75 cm diameter, >5 m tall; (4) >75 cm diameter, >5 m tall; (5) >50 cm diameter, >15 m tall

4.2. What processes are available to summarize the conditions?

Programs to summarize D_i from growth and yield projections, and to place the resulting data in a format compatible with a landscape simulation model or ecological effects model, usually are developed specifically for each project. Too many uncertainties (i.e. changes in the number of D_i desired, number of growth and yield models being used) can hinder accommodating the development of summarization programs in a commercial manner. In fact, a separate compiling program may be required to bring together summaries of a single D_i from two or more sources of growth and yield data (Fig. 11). If no compiling program is available, one needs to be developed. For example, in the CLAMS project, with 52 D_i desired and changing periodically, a special summarization program had to be developed to extract from growth and yield data each D_i. Devising summarization programs is perhaps the most under appreciated task when developing data for landscape simulation models. Project managers who are sensitive to this may be more effective in quickly facilitating the allocation of people, time, and other resources to meet project goals.

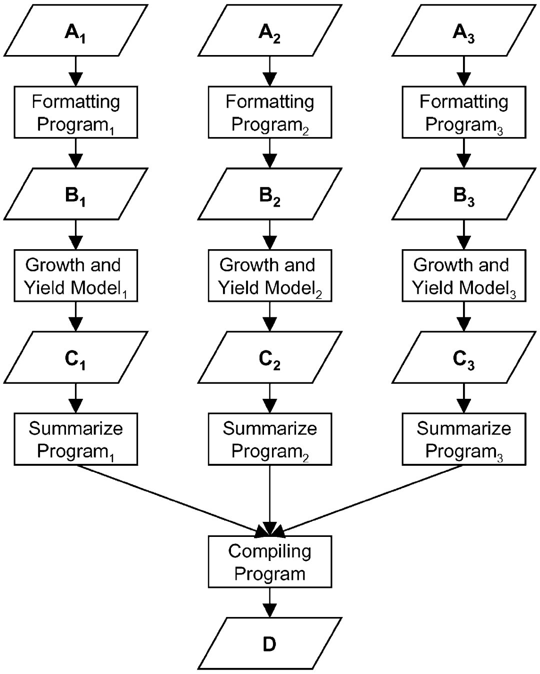

Fig. 11. Tree-level data from multiple sources, utilized in multiple growth and yield models requires a variety of formatting and summarization processes specific to the input and output formats of each growth and yield model.

4.3. Have the summarization processes been verified?

When developing forest growth and yield data for use in landscape planning efforts, a verification process should be developed for each data processing step (Fig. 12). Confirming that the correct mechanical or mathematical processes have been performed often involves manually comparing input and output data or checking certain calculations. Comparing the output from a summarization process to some other available process is beneficial, especially if one process seeks to emulate the results of the other.

For example, consider two snag models: (A) commercially available, yet allows consideration of only one stand at a time, and (B) a similar model constructed by your programmer to emulate A, yet can process multiple stands. If several stands were processed using both A and B, the results from B could be verified against those from A. Matched results would help ensure that the results from the new summarization program (B) were similar, if not identical, to those produced by the other available process (A). Furthermore, if multiple stands were processed simultaneously in B, verification of the first, last, and one intermediate stand would be reasonable choices. In addition, if a range of forest types were determined at this point, verification that the summaries for disparate forest types were correct would also provide a meaningful assessment of the robustness of the summarization program.

Verification during one step of the larger modeling process may also help locate errors at one or more previous steps (Fig. 13). For example, applying the summary data to a wildlife model and, subsequently, verifying the wildlife results, may indicate some rather subtle problems not recognized earlier in the forest inventory data summarization process. Development

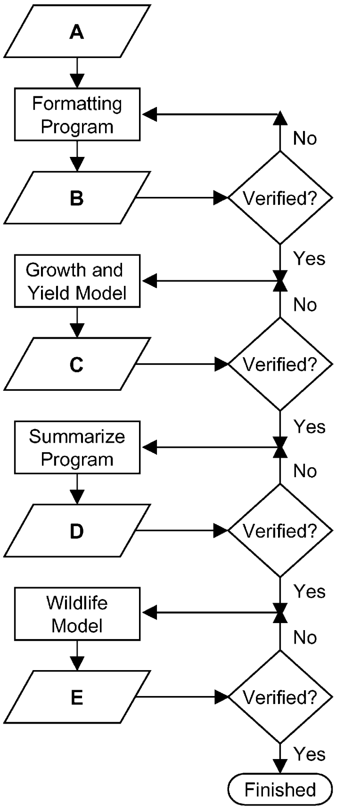

Fig. 12. A verification process for the vegetation-modeling process.

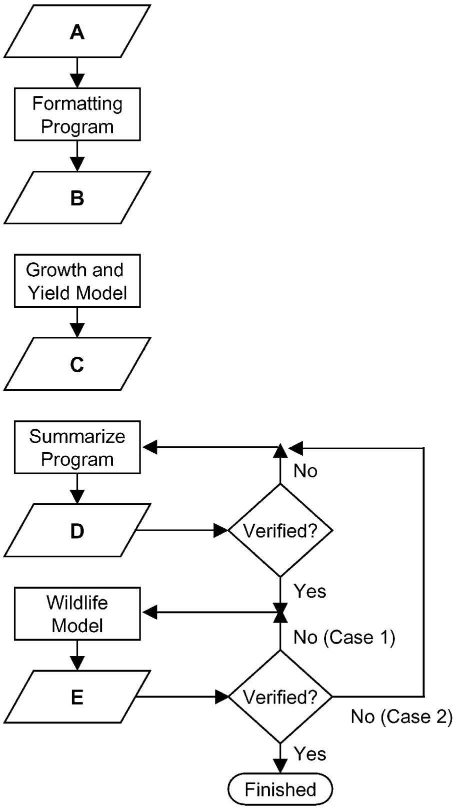

Fig. 13. Verification may require that the vegetation-modeling process move back more than one step, depending on the type of error that has been located.

and verification would then be moved a step or two backward (Case 2 of Fig. 13) before continuing.

4.4. To what format should the summaries be fit?

The output, or summaries, of growth and yield projections may be required in various forms for a landscape simulation model and associated ecological effects models. For example, depending on the development stage of a simulation model, the summaries of growth and yield projections must conform to the requirements of the landscape model or vice versa. Negotiating the interdependencies can be difficult, especially if the summary data format seems to change continuously. Requiring data to be formatted to certain specifications, at certain stages of the project, means that these data standards can help control inconsistencies in the formats. Likewise, intermediate processes may be needed to convert data to a more desirable format. Although text-formatted tables and ASCII files are the most rudimentary, they are also the least worrisome, particularly when compatibility issues are encountered with newer or older versions of commercial database-management programs.

5. Conclusions

The dynamics of long-term forest vegetative change are becoming a more important aspect of forest landscape simulation and analysis efforts. Simulation models gain credibility when vegetation conditions are substantively considered over time. For these models, the level of resolution of the resulting structural conditions will either facilitate or hinder future development of landscape modeling projects. Do all forest landscape planning efforts need to model forest vegetation dynamics as finely (at the tree-level) as we have often described here? Probably not. The answer to this question is project-specific and depends on the project goals, project personnel, data availability, and so on. A more interesting dilemma is whether one should build a landscape planning model around the limitations of a growth and yield model, or adapt the characteristics of a growth and yield model to the characteristics of a landscape planning model. More than likely a portion of both ideas will shape the evolution of a landscape modeling effort.

On a more technical level, planners should be aware that relatively minor alterations in assumptions and data can affect the processing (time and cost) of vegetation data for simulation and analysis efforts. These effects depend on the stage in the vegetation-modeling process (Fig. 1) at which the changes must occur, and the level to which data management has progressed. Each change undoubtedly requires re-verification of the subsequent data management processes. Detailing the vegetation modeling process should provide insight into the technical challenges of linking projections of vegetation conditions with landscape planning efforts. The specific challenges and opportunities will likely vary from one project to the next, yet those planners who are prepared will likely experience a faster and smoother implementation of the vegetation-modeling process in landscape planning efforts.

References

Baldwin Jr., V.C., Burkhart, H.E., Westfall, J.A., Peterson, K.D., 2001. Linking growth and yield process models to estimate impact of environmental changes on growth of loblolly pine. For. Sci. 47, 77–82.

Bergen, K.M., Dobson, M.C., 1999. Integration of remotely sensed radar imagery in modeling and mapping forest biomass and net primary production. Ecol. Model. 122, 257–274.

Bruce, D., Demars, D.J., Reukema, D.L., 1977. Douglas-fir managed yield simulator DFIT user's guide. USDA Forest Service, General Technical Report PNW-57, Pacific Northwest Forest and Range Experiment Station, Portland, OR, 26 pp.

Curtis, R.O., Clenenden, G.W., DeMars, D.J., 1981. A new stand simulator for coast Douglas-fir: DFSIM user's guide. General Technical Report PNW-128. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR, 79 pp.

Ditzer, T., Glauner, R., Förster, M., Köhler, P., Huth, A., 2000. The process-based stand growth model Formix 3-Q applied in a GIS environment for growth and yield analysis in a tropical rain forest. Tree Physiol. 20, 367–381.

Forest Biometrics Inc., 2001. FPS Version 6.0. www.forestbiometrics.com (accessed by author 5 February 2001).

Hann, D.W., Hester, A.S., Olsen, C.L., 1997. Organon User's Manual, Edition 6.0. Department of Forest Resources, Oregon State University, Corvallis, OR, 133 pp.

Hann, D.W., Riiters, K., 1982. A key to the literature of forest growth and yield in the Pacific Northwest: 1910–1981. Research Bulletin 39. Oregon State University Forest Research Laboratory, Corvallis, OR, 77 pp.

Hann, D.W., Zumrawi, A.A., 1991. Growth model predictions as affected by alternative sampling-unit designs. For. Sci. 37, 1641–1655.

Harrington, T.B., Tappeiner II, J.C., Hughes, T.F., Hester, A.D., 1991. Planning with PSME: a growth and yield model for young Douglas-fir and hardwood stands in Southwest Oregon. Special Publication 21. Oregon State University Forest Research Laboratory, Corvallis, OR, 14 pp.

Johnsen, K., Samuelson, L., Teskey, R., McNulty, S., Fox, T., 2001. Process models as tools in forestry research and management. For. Sci. 47, 2–8.

Mäkelä, A., Landsberg, J., Ek, A.R., Burk, T.E., Ter-Mikaelian, M., Ågren, G.I., Oliver, C.D., Puttonen, P., 2000. Process-based models for forest ecosystem management: current state of the art and challenges for practical implementation. Tree Physiol. 20, 289–298.

Mason, Bruce, and Girard Inc., 2001. SIS — The stand inventory system (featuring the use of the SPS growth model). www.masonbruce.com (accessed by author 5 February 2001).

McGarigal, K., Marks, B.J., 1995. FRAGSTATS: Spatial pattern analysis program for quantifying landscape structure. USDA Forest Service, Pacific Northwest Research Station, Portland, OR. General Technical Report PNW-351, p. 122.

Plummer, S.E., 2000. Perspectives on combining ecological process models and remotely sensed data. Ecol. Model. 129, 169–186.

Ritchie, M.W., 1999. A compendium of forest growth and yield simulators for the Pacific Coast states. General technical report PSW-GTR-174. USDA Forest Service, Pacific Southwest Research Station, Albany, CA, 59 pp.

Ritchie, M.W., Powers, R.F., 1993. User's Guide for SYSTUM-1, Version 2.0, A Simulator of Growth Trends in Young Stands under Management in California and Oregon, General Technical Report PSW-147. USDA Forest Service, Pacific Southwest Research Station, Albany, CA, 45 pp.

Sands, P.J., Battaglia, M., Mummery, D., 2000. Application of process-based models to forest management: experience with PROMOD, a simple plantation productivity model. Tree Physiol. 20, 383–392.

Shula, R.G., Knowe, S.A., Radosevich, S.R., 1998. Regional Vegetation Management Model (RVMM) version for the Coast Range Mountains of Oregon and Washington. Department of Forest Science, Oregon State University, Corvallis, OR. http://www.cof.orst.edu/cof/fr/research/organon/rvmm/rvmm_it.htm (accessed by author 5 February 2001).

Smith, J.E., Woodbury, P.B., Weinstein, D.A., Laurence, J.A., 1998. Integrating research on climate change effects on loblolly pine: a probabilistic regional modeling approach. In: Mickler, R.A., Fox, S. (Eds.), The Productivity and Sustainability of Southern Forest Ecosystems in a Changing Environment, Springer, New York, pp. 429–451.

Spies, T.A., Reeves, G.H., Burnett, K.M., McComb, W.C., Johnson, K.N., Grant, G., Ohmann, J.L., Garman, S.L., Bettinger, P., in press. Assessing the ecological consequences of forest policies in a multi-ownership province in Oregon. In: Liu, J., Taylor, W.W. (Eds.), Integrating Landscape Ecology into Natural Resource Management. Cambridge Univ. Press.

Stage, A.R., 1973. A prognosis model for stand development. USDA Forest Service, Intermountain Forest and Range Experiment Station, Research Paper INT-137. Ogden, UT, 32 pp.

Valentine, H.T., Herman, D.A., Gove, J.H., Hollinger, D.Y., Soloman, D.S., 2000. Initializing a model stand for process-based projection. Tree Physiol. 20, 393–394.

Wycoff, W.R., Crookston, N.L., Stage, A.R., 1982. User's Guide to the Stand Prognosis Model. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-133. Ogden, UT, 112 pp.

Pete Bettinger is an assistant professor in the Department of Forest Resources at Oregon State University. He is a forester who mainly performs research in the area of forest landscape planning and harvest scheduling, but also teaches GIS applications in natural resources. His research interests are in heuristic programming techniques for multi-objective forest planning problems and in the integration of GIS techniques into forest operations. Pete has worked as a forester in the forest industry in Virginia, Florida, and Washington, and as an economist for the USDA Forest Service's Pacific Northwest Research Station. He received a PhD from Oregon State University, developing a land management planning system that acknowledges aquatic habitat goals as well as commodity production goals.