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Growth Models and Their Use in Plantation Forestry

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Introduction

Sustainable management of forest resources require a large amount of supporting information. Especially when managing a forest for production of commercially valuable materials, estimation of present growth of variables (such as timber volume) are not possible to measure easily as is estimation of growth values for the future which are an essential need.

Vanclay (1994) defined stand growth models as abstractions of the natural dynamics of a forest stand, which may encompasses growth, mortality and other changes in stand composition and structure. Therefore Forest Models can be used very successfully as research and management tools. The models designed for research require many complicated data which is not readily available. Whereas models designed for management use simpler and more readily accessible data (Johnsen *et al.*, 2001).

The development of effective and accurate models to predict forest growth and products during forest rotation is essential for forest managers and planners. Growth and yield models, which rely on functions of measurement data from a sample of the forest population of interest, are the tools that have mainly been used to provide decision-support information that meets the basic operational needs for evaluating various forest management scenarios (Mohren and Burkhart, 1994).

The need for specific information for forest managers and planners is one of the reasons for the increase in demand for forest models. Questions about potential productivity, the effects of climate on forest growth, and the ability to understand and analyse the effects of silvicultural practices, such as soil preparation, weed and disease control, fertilisation and water management, can be answered using complex models in operational systems (Almeida *et al*., 2003).

Moreover, forestry models play a crucial role in forest management decision making. Over the years, a large number of models have been developed. New and improved models continue to emerge. The core essence of mimicking or representing the reality in an increasingly accurate and precise manner through the scientific modelling process fits in particularly well with a decision maker’s needs for facilitating the decision process and enhancing the quality of a decision. It appears that no decision maker today could make the right forest management decision without regular resource to some kind of forest model, although the emphasis and the levels of detail and responsibility of a model builder and a decision maker can be quite different. A sagacious balance between them can sometimes be hard to strike but such a balance needs to be continuously pursued.

Most forest growth models are constructed by several equations independently fitted to data (Soares *et al*., 1995) and these may comprise many separate but interrelated components, each of which may influence, and be influenced by other components and assumptions of the model (Vanclay, 1994). These models usually describe growth rate as a regression function of variables such as site index, basal area and stem density. In most growth and yield models, a site index is also used to determine the growth potential or maximum growth rate (Liu and Ashton, 1995).

Model Types

In the 1970's researchers started to develop mathematical and computer models in large numbers to simulate the development of stands and individual trees within the stands (Stage, 1973; Clutter and Allison, 1974; Johnstone, 1976). According to the level of predictions, complexity and use of explanatory variables, forest models can be divided into many categories. Two main classifications are: (i) empirical, process-based and hybrid and (ii) stand level, size class and single tree.

A typical empirical yield prediction model is based on data from a few management regimes and attempts to use the current information about a forest to extrapolate overall and specific growth patterns (e.g. equation 1 which was developed by Vanclay (1988a) for uneven-aged cypress pine stands in Queensland).

$$\ln \Delta G = -3.071 + 1.094 \ln G + 0.0074 G S_{h,d} - 0.2258 G \qquad \text{(Equation 1)}$$

where:

G = stand basal area

ΔG = basal area increment

$S_{h,d}$ = site index

Empirical models use the relationship with the tree's own measurable variables such as dbh, height and crown diameters and other measurable variables such as site indices, competition indices, etc. It is also common to incorporate certain assumptions into empirical models. Although the predictions are robust and precise, relationships built as empirical models cannot be biologically explained, which means, these models do not explain the process which occurs inside the tree to increase its size and volume. For instance, in the above model, basal area increment is predicted using current basal area and site index. However the model does not explain how the basal area is increased within a given time.

Under controlled conditions such empirical yield models are robust and amenable to rigorous statistical analysis and they often lead to solid, empirical relationships and tables of stand properties that have proved to be reliable tools for the forest manager (Voit and Sands, 1996).

On the other hand, process-based models simulate the biological processes that convert carbon dioxide, nutrients and moisture into biomass through photosynthesis (Sievanen and Burk, 1993; Sievanen and Burk, 1994). However, these estimates have not yet been developed to the stage where biomass and biomass growth can be identified as individual cells and cell wall thickening and aggregated into trees with detailed dimensions for the benefit of forest managers.

One of the more empirical aspects of many process-based models has been the partitioning of photosynthates between leaves roots and shoots (Vanclay, 1994). West (1987) assumed that 20% of net photosynthates would be used for new leaves, 20% for stem and branch development, and 60% for root growth. West (1993) developed the model further to examine more realistic ways to model photosynthate partitioning in response to functional relationships between tree parts. He assumed that the general growth strategy of trees is to maximise leaf production subject to a few constraints.

In the 1980's and 90's, advances in forest growth modelling have indicated the high potential of process-oriented models for examining a variety of questions ranging from standard management problems to more complex issues of environmental change (Ek and Dudek, 1982; Shugart, 1984; Valentine, 1985; Voit and Sands, 1996). However, due to a number of difficulties their use has been rather limited. For example, rigorous testing of a process based model will require special measurements, such as determination of the components of stand biomass. The cost and labour intensity of obtaining such data is high. Lack of suitable data has evidently been an obstacle to testing process-based models (Sievanen and Burk, 1993; Sievanen and Burk, 1994). These models are not necessarily very complex in the context of including many explanatory variables. Such a simple model is given in equation 2 which is developed by Duursma *et al*. (2007) for estimation of photosynthesis.

$$fPH = F_v / F_{m-ref}^{-1} \sqrt[3]{-0.45 + 0.25 \ln(T_{\max,30} + 10)} \quad \text{(Equation 2)}$$

where:

F_v / F_{m-ref}^{-1} = florescence ratio

$T_{\max}$ = moving average maximum daily temperature for last 30 days

Process-based models have intellectual and scientific advantages compared with empirical models. Process-based modes are deep with scientific understanding of the considered processes and are associated with a large number of analysed processes, especially in the case of statistical models. However, despite of this, some researchers believe that process models will never be of practical use mainly due to the difficulties mentioned the early paragraphs above.

Currently the empirical models of forest growth seem to match the needs of a 'lazy evaluation' task much better than the process-based models. The preferences of silvicultural practitioners for empirical over process-based models may thus be rooted in the distinction that only the former can currently be included easily into interactive management schemes, while the latter conceptually enforces an attitude towards the forest similar to that adopted for the weather and weather predictions.

The hybrid simulation approach involves combining the above two approaches (empirical and process-based) using the major strength of each approach to compensate for the major shortcoming of the other (Kimmins *et al*., 1988). This is done mainly by improving the empirical growth models by including additional explanatory variables such as growth indices derived from process-based models (Woollans *et al*., 1997). Waterworth *et al.* (2007) built such a model to predict the plantation growth (equation 3).

$$I_a = M(\exp^{-k/a} - \exp^{-k/(a-1)})\left(\frac{P_a}{P_{avg}})\right) \quad \text{(Equation 3)}$$

where:

I_a = annual growth increment
M = above ground biomass
P_a = ratio of productivity for a particular year
P_{avg} = long-term average productivity

Although advanced technology is available for both data collection and model building, all models used in forest management are data-based or empirical. Although process-based models provide a good basis for understanding the acquired data, i.e., for understanding the physical and ecological aspects of a number of processes in forestry, empirical models are still widely used due to their simplicity when compared to the process-based models.

Whole Stand, Size Class and Single Tree Level Models

Whole stand models are often simple and robust, but may involve complexities not possible in other approaches (Vanclay, 1994). Population parameters such as stocking (number of trees per unit area), plantation age, site index, stand basal area per hectare, number of trees per hectare (Clutter *et al*., 1992) and standing volume are used to predict the growth or yield of the whole forest. No detail of individual trees in the stand are determined (Vanclay, 1994). It should be noted that some stand level models (e.g. diameter distribution models) produce tree level outputs (frequencies and average heights by dbh classes). However, they are still classified as stand level models because the inputs are stand level statistics (Clutter *et al*., 1992).

Size class models provide some information regarding the structure of the stand. Several techniques are available to model stand structure, but one of the most widely used is the method of stand table projection, which essentially produces a histogram of stem diameter (Vanclay, 1994).

The most detailed approach is that of single tree models which use the individual tree as the basic unit of modelling. The minimum data input required is a list specifying the characteristics of each tree in the stand. Some models also require the relative spatial position of the tree or tree height and crown class. Single tree models may be very complex, modelling branches and internal stem characteristics and may be linked to harvesting and conversion simulators (Vanclay, 1988). Single tree growth has been found to be a better measure of stand growth than alternatives based on averages and predicting growth on a stand basis.

The use of individual-based models in ecology has gained considerable acceptance in recent years, and individual-tree models have been developed for a number of forest types. While individual-tree models offer a great deal of flexibility in describing stand structure and simulating silvicultural operations such as thinnings, they may not estimate overall stand values (volumes and basal area per hectare) as accurately as whole stand equations.

Role of Forest Models

Growth estimation of living trees and stands is needed by managers for many purposes including:

a. yield prediction,
b. health monitoring,
c. long term productivity monitoring,
d. socio-economic analysis of forest influences,
e. marketing,
f. planning harvesting and
g planning long term machinery requirements.

Yield Prediction

Yield prediction is an essential activity in forest management especially for the production of commercially important outputs such as fuelwood and sawn timber. Sometimes it is necessary to predict the future growth and structure at the very early stages or even before the establishment of plantation. The results of such estimations will be used for planning purposes and necessary calculations such as expenses and profits, etc. Mathematical models play a vital role in predicting those values in order that effective planning can be done.

Health Monitoring

Management of forest plantations is similar to that of long-term agricultural crops such as rubber. The growth of such plantations can be hindered by many factors. Main constraints can be fire, diseases and insect pest damage. In Sri Lanka, fire is a common hazard in dry zone teak plantations which can also sometimes be seen in eucalyptus plantations of the upcountry. Insect damage by skeletonizers and defoliators are common in teak plantations in the early stages of the establishment. The shoot borer is the main problem in mahogany monocultures in the wet zone of the country. Natural fire and insect damage may be seasonal or periodical and therefore the relevant models can be used to calculate the damage and thereby understand the destruction with different intensities of the problem concerned. Moreover, the history of damage and its intensities can be modelled with time or period to identify the specific critical time of the damage and hence the preventive methods that can be effectively applied.

Long -term Productivity Monitoring

Typical forest management is a business which does not end after the completion of one cycle. Therefore planning ahead and implementation of activities such as replanting for the second generation after the previous harvest, maintenance or improvement of the quality of the site where the forest is grown are vital to maintain the similar or increased growth rates to that of the previous cycle. If the quality of the site decreases, steps should be taken to improve the quality in order to obtain a higher yield in the particular forest. For this reason, there should be a mechanism of identifying the change of site quality with the time even with a single cycle. In order to fulfil this requirement, modelling the site quality indicators with time has become a common practice. Mainly height indices are used such as indicators which are developed using a selected height (top height, dominant height, average height of dominants and co-dominants) and age.

Socio Economic Analysis of Forest Influences

Modelling is important when a particular forest is managed as a multi-purpose resource with the association of sustainable management. If non-wood forest production such as fuelwood, medicinal plants and grazing are expected in a particular forest, the sustainable harvesting quota should be calculated using forest models in order to collect such products without over-exploiting the resource. Since multi-purpose management is common even with forest plantations, those particular models address the issue of "how much?" to be harvested within a particular area or within the entire forest in a defined time frame. Using the results, the appropriate allocations can be divided among the forest users.

Marketing

If forest products cannot be sold for a reasonable price, profits cannot be obtained even though the most intensive management practices are used. The price of the products is decided by market demand. Therefore models generating "demand curves" are essential in the forestry business aimed at earning profit. Those models will allow the forest mangers or practitioners to identify the high demand periods, for e.g., summer in temperate countries where most of the outdoor furniture is purchased. Therefore the forest managers can couple the thinnings and final harvests with the time when the demand is predicted as high in order to sell the products at a higher price.

Planning the Harvest

Forest harvesting must be planned for many reasons. Some of these, such as demand have been described in previous paragraphs. At the harvesting time, the managers should answer the questions of "how much to cut?", "how to cut?", "where to cut?" and "when to cut?" for better planning. If clear cutting of the entire forest is not an objective, the amount harvested should be determined. This may depend on an exploitable size or a certain number/volume of trees. Only after deciding on the amount of harvest can the managers plan for the required machinery, transport, labour and potential profits. The answer to the question "how to cut?", i.e., felling techniques depends on the tree size and end product. If a specific area is to be harvested due to higher growth rates or poor growth rates, those areas will be identified by answering the question of "where to cut?" and the harvesting time is determined by "when to cut?" to eliminate operations during undesirable periods. Usually harvesting operations are conducted in dry periods to increase the cost efficiency and to protect the site. Therefore meteorological models will help to determine such periods.

The exploitable size is usually defined by a specific diameter which is always an easy measurement to be made. Therefore the tree growth models will allow the managers to project the current tree growth to the future and thereby to determine the number of trees to be harvested after a certain period of time. The method of felling will then be determined by the projected tree size. Future growth differences will also be identified by projecting the current growth using growth models.

Planning Long-term Machinery Requirements

Large-scale forest operations require planning of machinery and labour costs. These machineries may be hired from outsources or may have to be purchased. Therefore it is essential to determine the magnitude of forest operations before leasing or purchasing such high cost equipment because it should be capable of completing the task within a certain time.

Whether one should model at tree level and aggregate for stand estimates or model an aggregated level depends on the scientific objectives of modelling. The use for which a growth model is intended, it is generally argued, should determine the resolution level at which one should operate.

Since forest modelling can be anything from a simple to a complex procedure, there are many methods of constructing models for the same purpose. The complexity depends on the modelling objectives, the required accuracy, quality of data and the resources available. However, one of the norms used by the modellers is to build simple but robust models especially if the purpose is effective field use. Thus the following models describe the ability of using different structures for the prediction of the same variable. Since modelling became popular since the middle of the last century, all the selected models given below were constructed in that era.

The common feature of all the given models (equations 4 to 9) is the similarity of the explanatory variables. These are *dbh* and total height (*h*). However, ways of including these two explanatory variables into the models and the way the parameters were assigned are different from one model to the other.

$v = 0.00229 dbh^2 h$ to predict stem volume for a composite of species in the Lake States (Gevorkiantz and Olsen, 1955)
(Equation 4)

$v = -1.045389 + 0.00271 dbh^2 h$ to predict merchantable stem volume for old field slash pine plantations in the Georgia middle coastal plain and the Carolina sandhills (Bennett et al., 1959)
(Equation 5)

$v = -3.291 + 0.0696 dbh^2 + 0.0576 h + 0.00126 dbh^2 h$ to predict total stem volume of plantation-grown loblolly pine in the lower Piedmont of Georgia (Romancier, 1961) (Equation 6)

$v = 0.002198 dbh^{1.7399} h^{1.13319}$ to predict total stem volume for Douglas-fir in British Columbia (Brackett, 1973) (Equation 7)

$v = 0.284 + 0.00224 dbh^{1.8627} h^{1.1031}$ to predict total stem volume for red pine in eastern Canada (Newnham, 1967)
(Equation 8)

$v = dbh / (0.691 + 363.676 h^{-1})$ to predict total stem volume for red pine in Canada (Honer, 1965)
(Equation 9)

Growth and Yield modelling

Modelling is not only a method to bridge the gap between science and management, it can also help to understand the cause for this gap. In any modelling project, several aspects of the problem posed need to be recognised; conceptual, mathematical, engineering and ecological aspects. Historically, whether prediction mainly rested on an empirical (and local) basis. Predictions were derived from past experiences rather than the solution of well-understood equations describing non-linear atmospheric transport processes. These days such equations can be fed with sufficiently actual data and solved computationally so that the corresponding predictions now out-compete the crude empirical models of the past in most cases. Limits in the time horizon of whether periodically are understood as an inevitable feature of a complex dynamic system (Hauhs *et al.*, 2003).

According to Barkhart (2003), the typical approach taken in past growth and yield studies was to define a population of interest, obtain a sample from the defined population (the sample could consist of temporary plots, permanent plots or both), and estimate coefficients (usually with least squares) in specified equation forms. This approach produces satisfactory prediction tools for many purposes, but it may not be adequate in circumstances where forest management practices and objectives are changing rapidly. Given that growth and yield models are used to project the present forest resource and to evaluate treatment effects, data both of the inventory type (which describe operational stands of interest) and of the experimental or research type (which describe response to treatment) are needed. The amount of effort that should be devoted to each type of data collection is not immediately obvious.

However, modelling process should clearly be linked with the theoretical knowledge which allows one to select the most important candidate variables, explanations of the model structures and estimated procedures. Parameter estimation is a dynamic task: reality is changing and the knowledge of the reality is also changing. All the priority research topics in this area have the same objective: reducing uncertainty in the ultimate model predictions.
After parameter estimation and model construction, the next step consists of the process of verifying the model. The use of simple or more complex tools in order to verify statistical assumptions and evaluation is essential to test the models adherence to reality and the coherency of its results. A very important contribution to this process is the analysis of the biological interpretation of the parameters.

An existing model needs some updating after some time, because it will need to be re-evaluated and modified: knowledge of the system involves the tract that and the true situation may change. To accomplish this task, there are two main possibilities: (i) to start from the beginning (adding new data, re-evaluating the possibility of having new functional forms, new structures, new methods), or (ii) to develop and use tools to support model updating. In the intervening time, it may be more efficient to re-fit the existing model, develop a completely new model, or use newly developed estimation techniques on existing model forms that were not known at the last calibration.

Modelling methods are commonly assessed based on their properties of unbiasedness, asymptotic unbiasedness, consistency and efficiency (as related to standard). They are also assessed for their ability to hold properties under different types and distributions of data. Properties of fitting methods are affected by several variables, including sample size, number of parameters to be estimated, the distribution of the model errors and the fitting method.

Requirement of Data

At present, even with the developed techniques, one of the main limiting factors for model building is the lack of availability of data. Therefore the level at which forest stands can be modelled is often dictated by the data available. If, for instance, individual trees are not numbered and identified, individual tree-based approaches are not possible. Without sound data, especially that measured from permanent sample plots over a long period of time, it is very difficult to build "perfect" models. Further, it is essential to collect the data covering all geographical regions and site types to build such a model. That type of data is useful in two ways, i.e., to build new models and to calibrate already available models.

There are contrasts between the data used for modelling and the data available for using the model, especially when the models are included in decision-support systems (Amaro, *et al*., 2003). It is very important to define the data characteristics. Often the models are good, as are the decision tools, but the decisions may still not be as good as they should be due to lack of specific quality in the data.

Sri Lanka Context

In 1998, the hectares of plantation forests belonging to the Sri Lanka Forest Department was 135,525.67 (Bandaratillake, 1998). However, all those plantations are not managed due to the reasons such as encroachment, elephant problems, fire hazards etc. In addition, the private sector, especially the regional plantation companies also manage a large amount of forest plantations for fuelwood and timber. The interest in establishing forest plantations especially in tea growing areas has been boosted in recent years, because profits earned by tea has declined due to introduction of many regulations on production by European countries and Japan, due to high production costs and due to competition from countries like India and Kenya.

The main problem faced by the private sector in forest plantation establishment and management is the lack of growth records, intensive management guidelines and the lack of growth projection systems. Yield tables are the foundation of plantation forest management since they give information from initial planting density to the final harvest with all the treatments such as thinning. Moreover, it provides information on growth rates at regular intervals. At present, the Sri Lanka Forest Department has published yield tables for teak, eucalyptus, pine and cypress. Other than for teak, the growth variations due to different site qualities were not taken into account. Only teak has three different yield tables for three site classes. Moreover, growth differences between different species were considered as being similar for certain yield tables. For example, a single table has been constructed for both *Eucalyptus grandis* and *E. robusta* for sawn log production.
Although the yield tables are built using mathematical relationships between output and input variables, those models are not directly revealed to the users. However, there are advantages in the direct use of growth and yield equations over the yield tables because the current growth rates can be used to predict the future growth or the present growth of some other variables. Therefore in such situations, growth models are more realistic than yield tables. The latter are mostly considered as management guidelines and growth monitoring methods. Some of the growth models (equations 10, 11 and 12) that can be used to predict the tree volume for different species in Sri Lanka are given below (source: Forest inventory manual for Sri Lanka, 1996) models use dbh and height as explanatory variables.

$v_5 = [0.337 + (5.575 \div \pi dbh)] \times (\pi dbh^2 h \div 40000)$ to predict under-bark volume upto 5 cm cut-off for *Cupressus macrocarpa* (Equation 10)

$v_5 = [0.337 - (0.151 \div \pi dbh)] \times (\pi dbh^2 h \div 40000)$ to predict under-bark volume upto 5 cm cut-off for *Eucalyptus grandis* and *E. robusta* (Equation 11)

$v_{20} = v_5[1.0 - (6.307 \exp(-0.0955 \pi dbh))]$ to predict under-bark volume upto 20 cm cut-off for *Eucalyptus grandis* and *E. robusta*
(Equation 12)

Useful Models in Plantation Forestry

The requirement of the models depends on the objectives of the management of the forest plantations. If the management objective is to supply fuelwood or pulp, prediction of weight becomes more important since the sales are based on wood weight. However, if a particular forest is managed for sawn timber, volume becomes the most important variable. The reason is that all calculations are based on the volume to be attained in that particular forest. Other than volume, growth of dbh and height over a given period is also important. Therefore prediction of dbh, height and volume (over bark or under bark) is the most common objective among the modellers in commercially important forests. In such situations, modelling the other variables such as crown height, crown mass or tree biomass are comparatively less important. Some of the models constructed for commercial species growing in Sri Lanka are given from equation 13 to 15 (for *Eucalyptus grandis* growing in all sites types in Sri Lanka) and 16 (for *Tectona grandis* growing in all site types in Sri Lanka).

$$\sqrt{v} = 0.5946 \times \sqrt{gh} + 0.0356 \times G / h_{top} \qquad \text{(Equation 13)}$$

$$dbh = (51.470 / (1 + \exp - 0.0140 \times (a - 18.798))) \times (0.988 \times \sqrt{h_{top} / a} \qquad \text{(Equation 14)}$$

$$h = (46.772 / (1 + \exp - 0.114 \times (a - 17.085))) \times (0.908 \times \sqrt{h_{top} / a} \qquad \text{(Equation 15)}$$

$$\sqrt{v} = 0.5730 \times \sqrt{gh} + 0.0253 \times [1 / (h_{top} / a)] \qquad \text{(Equation 16)}$$

where:

a = plantation age
dbh = diameter at breast height
g = tree basal area
G = stand basal area
h = total height
h_{top} = top height

Equation 13 (source: Subasinghe 2001), 14 and 15 (source: Subasinghe, 2008) were constructed for *Eucalyptus grandis* growing in all site types in Sri Lanka. Equation 14 is a model constructed by Subasinghe (2004) for *Tectona grandis* in all site types of Sri Lanka.

Discussion

It is inevitable that modelling objectives is one of the most important considerations when determining forest strategies. The importance of user interactions and the definition of modelling objectives allow the identification of the three main types of users with whom the modelling interact: scientists, forestry practitioners and managers, 'Administration' and society (Amaro *et al.*, 2003). It is essential to expand the scope of modelling to address the need of these varied users.

Due to the increased use of models in decision making, model credibility is becoming increasingly important in forest management. This is particularly true when forest managers and decision makers legitimize their decisions based on models. More recently reliance on valid models for making critical decisions regarding sustainable resource management has placed model credibility on a more prominent footing. Therefore it is essential to conduct continuous validations of models as this is the most effective way to enhance model credibility.

While recognising that models for understanding is important, many forest models emphasise modelling for prediction instead of modelling for understanding. This may be the reason for constructing mostly empirical models for production forests. Forestry modelling as a profession has placed too much emphasis on finding the "perfect" model that did not serve a decision maker's needs and was rarely useful in the real world. Modellers are called on to develop models that address more of the operational concerns that forest practitioners face in day-to-day management of forest resources, than to build models that can really be used to solve real world problems.

Until recent times, most of the forestry models were constructed to predict the production of man-made forests. However, in addition, it is necessary to have new approaches such as modelling natural forests, modelling the evolution of the sustainability of the systems, modelling deadwood, modelling wildlife habitats and modelling unusual events (e.g., catastrophes, diseases). Modelling biomass and carbon pool fluxus at the landscape scale allows one to estimate the ecosystem carbon carrying capacity which provides a baseline for evaluating the effects due to disturbance and climate change. Moreover, incorporation of uncertainties and the effects of catastrophic events are crucial for the existing models so that more useful information can be generated.

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