THE PROSPECTS OF AN INTEGRATED FOREST PROCESS MODEL

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Summary

Though the modelling efforts on numerous forest processes have progressed considerably, a synthesis of such models has not been attempted, or alternatively, such-attempts have been unsuccessful and therefore have not been reported. Either way, it is argued that improvements upon current competition/growth models can only come about from such a synthesis.

Introduction

The main reason for developing models of forest growth is to provide the forest manager with a flexible predictive tool which will allow him to form an optimal management policy. Ek and Dudek, Dudek and Ek(1980), Loucks et al(1980), Ek and Monserud(1981), review the current state of forest competition/growth models and conclude that the most intricate models used are, for practical purposes, often little better than the most crude. Hence further refinement would seem pointless.

Another reason for developing dynamic models of the forest ecosystem is that scientific understanding of such a whole system can only be possible if the separate forest sciences are integrated to give a unified view. The whole is more than its parts! This philosophy was the "call to arms" of the IBP, (see Van Dyne 1972)) and though the output of the IBP does not represent an integration of parts (see Reichle(1980)), the holistic approach may yet provide great improvement in the predictive power of forest management models.

A representation of the forest system is shown in Fig.1. The straight edged boxes represent possible state variables of the system and the "curved" boxes are processes which operate upon these state-variables. A mention of some of the methods which have been used to model parts of this system is given, followed by a very crude mathematical outline of one integrated model formulation which attempts to reflect most aspects of Fig.1. Finally some problems in the implementation of such a "complex" model will be discussed.

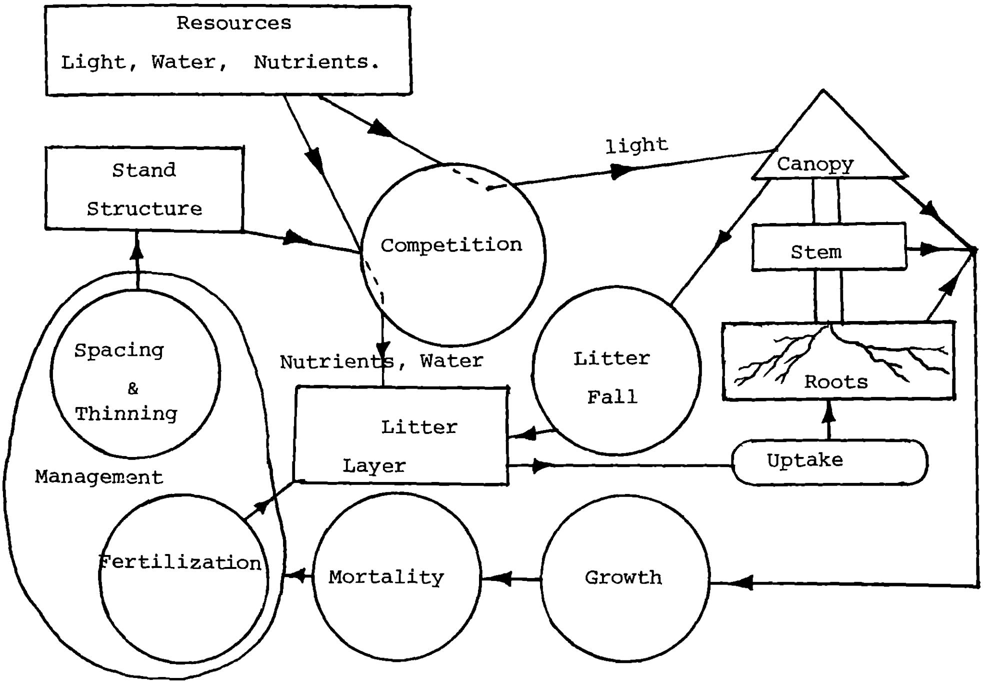

Fig.1: State variables and forest processes.

Classifications of Stand Growth Models

Munro(1974) classified growth models which had been developed up to that time into Stand Models, Individual-tree (distance independent) and Individual-tree (distance dependent). Ek and Monsurut(1981) classify modelling techniques, to date, into traditional yield table methodology, differential or difference equations, stochastic processes, distributional methods, and individual tree simulation. Here, we choose to classify competition/growth/mortality models by two factors, the first indicating the basic entity to be modelled, the second indicating whether spatial aspects are included or not. In Fig. 2 the (2x3) classification cells are termed 'types:(1)-(6)'. Models of Type (1), (2) and (3) are growth (only) models, and the introduction of a spatial factor corresponds to allowing for competition. Type (1) is the Yield Table approach, and though distributions might be estimated from population means, it is only the means which are "grown". Type (2) models (Burkhart(1974), Monserut(1979), Susuki(1971,1976,1981). Sloboda(1978), Fröhn(1978), Garcia(1976), Little & Rennolls(1982)), describe how the distributions of a stand evolve, mostly using Markovian techniques. In principle, the output from this type of model is that in which the forest manager is most interested.

		Competition	
		N (Non-spatial)	Y (Spatial)
Basic Model Entities	Population Means	(1)	(4)
	Frequency Distributions	(2)	(5)
	Individual Trees	(3)	(6)

Fig.2 Competition/Growth/Mortality Model Classification.

For, if the rules of distribution evolution could be elaborated sufficiently, then changes in the distributions of heights, diameters, volumes, form, etc. in response to any management action might be predicted. The model types ((3)-(6)) may be regarded as attempts to obtain a suitable "Rule of evolution". Exact sizes of individuals are needed in type (3) models, as in type (6), and since such data is not normally available to the forest manager, the literal use of such models is not realistic.

Types (4), (5), (6) essentially take into account the presence of competition. In Type (4) models the spatial factor is only indicated by a mean stocking density (numer of trees/ha) whilst in type (6) models a complete map of the forest is required.

Type (5) possibly represents the level of a convenient compromise, where the distance distributions arising from the spatial structure of the stand would allow real competition modelling (in comparison to type (4)) but would not require the enumerative data of type (6). Theoretical work on competition (Matern(1960), Mead (1973,1969), Gates and Westcott(1978), Gates(1980), Diggle(1977), Rennolls(1978), Ford and Diggle(1981), Besag(1974), Ripley(1976) might have some impact on the implementation of a type (5) model.

Resource Allocation Models

The competition models mentioned above are mostly concerned with the battle for the light resource. However, the control of the three dimensional structure of the stand, by spacing and thinning, is not the only management option. The forester may also fertilise and/or drain his crop. Hence, if growth models are to be flexible enough to cope predictively with these alternative management options then it is likely that nutrient cycling and water input/outputs (plus their interactions) must be represented.

Kimmins(1982) has developed a very detailed deterministic model of nutrient cycling in crops and has related it to the growth of the stand. However since he adopts a growth model of type (1) his predictions are correspondingly limited. Thornley(1975), Sweeney et al(1981), describe the growth process in terms of state variables which relate to the nutritional status of the plant; ie permanent structural material and temporary storage material. There would seem to be much scope for a stand competition/growth model which includes some of the nutrient status, (but no all that Kimmens includes!), in such a way that the formulation of the growth process arises naturally from this status.

Jarvis(1981) reviews the way in which water processes and stress can affect a tree's growth. However he does so on a daily (even hourly!) basis and such a highly resolved model clearly does not match the requirements of a forest management model. Also, it is thought that, in Britain, water stress is hardly ever directly limiting to tree growth, (Dr W O Binns, Dr J Roberts, pers. comm.). Still, it is possible that water may be directly limiting. There may be insufficient water, due to drought, to mediate nutrient uptake from fertile soil horizons. There is also some argument as to whether competition from weed species might put the tree under water stress.

Finally, in this section, we exclude from consideration attempts to model the meristemal growth processes in the canopy, stem and roots. Though these processes are fundamental it would be overoptimistic (particularly in view of the results arising from the IBP) to expect such a degree of reductionism to be successful, (see Thornley(1982) on reductionism).

A mathematical formulation

The following model should only be regarded as a very crude first approximation to the model which might, one day, be successful, (Adams(1980)).

Tree 'Anatomy'

Let X(t,u) be a state variable representing the temporary storage material of age u, available at time t, (assumed discrete). We might loosely think of X as the total available nutrient supply in the canopy, though not all of it can become available in one year. The tree is planted at t=0. If λ_u is the rate of convertion of this temporary storage then we have

$$X_1(t) = \sum_{u=1}^{t} \lambda_u X(t,u)$$

as the total 'X-contribution' towards growth from internal cycling.

Suppose the proportional litter fall is δ_u then the new (and hence assumed to be unavailable) litter at time t is given by

$$Ƶ(t,o) = \sum_{u=1}^{t} \delta_u X(t,u)$$

If δ_u is the rate of conversion from litter (age-u) to an 'X-equivalent' available nutrient pool then,

$$Ƶ(t,i) = Ƶ(t-i,o)\prod_{u=1}^{i} (1-\delta_u)$$

Hence, the available nutrient 'X-contribution' from the litter is given by

$$X_2(t) = \sum_{i=1}^{t} \delta_i Ƶ(t,i)$$

If S(t) and F(t) are the nutrients directly available from the soil and fertilizer treatments and the leaching rate of available nutrients is θ, then

$$X(t,o) = X_1(t)+(1-\theta)\left[X_2(t)+S(t)+F(t)\right]$$

We also have

$$X(t,u) = 1-\left\{\lambda_{u-1}+\gamma_{u-1}\right\} X(t-1,u-1)$$

Let us now define $Y(t)$ to be the total permanent structural material of the tree (stemwood?); $\Delta Y(t)$ its increment in year t. Since the nutrient resources are normally allocated to the crown, roots and stem in order, suppose that if

$$X(t,0) < qX_{crit}(t) \qquad 0<q<1$$

then $\Delta Y(t)=0$

$X_{crit}(t)$ might be the amount of resource diverted to the new crown in resource unlimited growth at time t. If $X(t,0) > qX_{crit}(t)$ then there will be growth, but the amount will depend on the competitive status of the tree.

Competition

We might conveniently define the competitive status of plant k at time t to be a mixture of competitive statuses that might be obtained from different competition models. For example,

$$p_k(t) = \lambda p_k^{(1)}(t) + (1-\lambda)p_k^{(2)}(t) \qquad 0\leq\lambda\leq1$$

where

$$p_k^{(1)}(t) = \prod_{j\in\mathcal{N}_k} \begin{cases} 1 \text{ if } \beta_{kj} \equiv \tan^{-1}\left[\delta_{kj}/K|D_k(t)-D_j(t)|\right] \geq \alpha(t) \\ \beta_{kj}(t)/\alpha(t) \text{ otherwise} \end{cases}$$

where $\mathcal{N}_k$ is the "neighbour set" of 'k', $\alpha(t)$ is a function onto $(0,\pi/2)$, δ_{kj} is the distance between 'k' and 'j', and D is a size related variable (such as dbh), (See Ford & Diggle(1980)). and where

$$p_k^{(2)}(t) = \frac{C^{-1}(C(D_k) - \sum_{j\in\mathcal{N}_k} f(C_k,C_j,V_{kj})}{D_k}$$

where $c(D_k)$ ($\equiv C_k$) is the 'zone of influence' of a tree size D_k, V_{kj} is the region of overlap of C_k and C_j and f is the 'apportioning rule', (See Gates(1975)).

If we now define a photosynthetic potential $P_k(t)$ of the k^{th} tree by

$$P_k(t) = p_k(t) \sum_{i=0}^{t} \mu_i X(t,i)$$

μ_i representing the relative photosynthetic efficiencies of 'needles' of differing ages, then we might adopt the following logistic 'stem' growth model.

$$\frac{\Delta Y_k(t)}{\Delta t} = \varphi P_k(t) \left(1 - \frac{Y_k(t)}{Y_k(t)+\xi P_k(t)}\right) + \varepsilon(t)$$

$$\frac{\xi\varphi P_k^{\,2}(t)}{Y_k(t)+\xi P_k(t)} + \varepsilon(t) \qquad \varepsilon(t) \text{ an error term}$$

a form closely related to the growth model of Thornley(1975). The growth rate parameter φ might be limited by setting,

$$\varphi_k(t) = 1-\left\{1-\left(\frac{X_k(t,0)}{X_{crit(t)}}\right)^{r_1}\right\}\left\{1-\left(1-\frac{W_k(t)}{W_{crit}(t)}\right)^{r_2}\right\}$$

where 'W' indicates a water resource variable. Similarly with ξ.

Finally, we might let the probability of death of tree k at time t (given it was alive at (t-1)) be given by

$$\rho_k(t) = \exp\left[-\left[P_k(t)\right]^2/\sigma^2\right]$$

Hence the total probability of death at time t is

$$\rho_k(t) \prod_{\tau=1}^{t-1} \left(1-\rho_k(t)\right)$$

Estimation, Initialization and Telescoping

This model, besides not being meant to be taken literally, is highly over-parameterized. Any attempt to estimate all the parameters, as given, would inevitably yield meaningless estimates for at least some of the parameters, in so far as they will be outside the bounds we know they must be within, as formulated in the model. This could be overcome by inserting parameter constraints, (possibly by reparameterizing), but many of the parameter sets may be known, or found, for the special/locality under consideration, by specialist analysis, (eg litter layer analysis, canopy solarimeters, etc.......). Hence they may be inserted as constants in the model. Furthermore some of the parameter sequences, eg$\{\gamma_u\}$, might be realistically replaced by a single parameter. If this is not strictly valid the remaining parameter estimates will compensate for this "model error". The whole model has to be fitted to trajectories of growth/mortality data. Since the model is couched in stochastic terms, a pseudo-likelihood estimation procedure may be used, (see Besag(1976) for explanation of the "pseudo").

When the model has been calibrated (ie the parameters have been estimated or determined) for a particular crop on a particular site we will wish to use it to predict the future growth pattern, given the current crop state and proposed management strategy. In order to avoid the impractical data requirements of type-(6) models it will be necessary to characterize the spatial structure either from its management history or from simple measurements. Predictions (plus standard errors) could then be obtained by using a small dummy type-(6) simulation model.

Finally, it is desirable that the model should be constructed so that it may 'telescope' on itself, thus enabling it to be used as a simple type-(1) model, if desired, and that the results should then be consistent. Similarly it should be possible to 'turn off' the action of any process by the choice of particular parameter sets (see Burkhart(1981)).

Prototype programs are under construction and test but have not progressed sufficiently far, as yet, to tell us if the hope expressed in the introduction of this paper, (that is, the hope that holistic models might represent a significant step forward), has any justification.

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