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AN ECOLOGICAL BASIS FOR PREDICTING
THE GROWTH AND STABILITY OF PLANTATION FORESTS.

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SUMMARY

The widespread establishment of even-aged forests is one further stage in the intensification of forest management which has taken place in response to a continuous increase in the demand for forest products. Two problems are foreseen in the future management of these plantations which will require further evolution in silvicultural techniques.

(1) The growth rate of plantations must be increased and accurate predictions made of likely timber yield. Where the crop cycle is long this has to be acheived against a background of continuous variation in the conditions of growth and in the response of trees. The variation due to (i) long and short term cycles in the weather; (ii) the changing response of trees with different age at different levels of amelioration, is discussed. Classical yield table techniques are not suitable as a basis for predicting plantation growth under more intensive management systems. The potential of individual tree models to predict both the total yield of the forest and the distribution of different sizes of tree within it are examined.

(2) As plantations age, the standing yield of timber is increasingly at risk from such hazards as fire and windthrow. These are not to be seen as inevitable 'catastrophies'. Their incidence is a function of species, site and silvicultural system. The potential for developing a model of the ecological basis of windthrow is examined.

It is suggested that whilst there is considerable research into the component processes of forest growth and tree:site interactions, there are few investigations into the design of new silvicultural systems for

high production or the avoidance of hazards to
production

RÉSUMÉ

La création de plus en plus étendue de forêts
équiennes   n'est   qu'une   étape   dans
l'intensification de la gestion forestière, dûe
à la demande accrue de produits forestiers. La
gestion future de ces plantations fera face à
deux   problèmes   qui   nécessiteront   un
développement   plus   grand   des   techniques
sylvicoles.
(1) Le taux de croissance des plantations doit
être augmenté et la prevision des productions
doit   devenir   plus   exacte: dans le cas d'une
longue révolution il faudra   tenir   compte des
variations   continuelles   des   conditions de
croissance des arbres et de leurs réactions.
Nous   traitons dans notre exposé des variations
dûes (i) aux cycles climatiques longs   et
courts, (ii) aux changements de réactions des
arbres selon l'âge et les différents niveaux
d'amélioration.   Les   tables   de production
classiques sont mal appropriées à la   prévision
de   la   production   d'une plantation gérée
intensivement. Nous examinons la possibilité
d'établir   des modèles-arbres permettant de
prévoir la production totale du peuplement
ainsi que les tailles des différents arbres qui
la composent.
(2) A mesure que la forêt vieillit, le bois sur
pied doit lutter de plus en plus contre les
risques d'incendie et les chablis, qu'on ne
doit pas considérer comme des 'catastrophes'.
Ces incidents sont fonction à la fois des
espèces, des   stations   et   des   systèmes
sylvicoles. Nous indiquons la possibilité de
développer un modèle basé sur le phénomène
écologique du chablis.
Nous   suggérons   que,   malgré   des   études
considérables sur les divers procédés de la
croissance d'une forêt et les interactions
arbre/station, il y a un manque de recherches
dans le domaine des modèles de sylviculture
centrés sur une haute production ou sur les
manières d'éviter les risques pour la
production.

ZUSAMMENFASSUNG

Als Reaktion auf die ständige Zunahme der

Nachfrage   nach   Waldprodukten   ist   die
verbreitete Begründung gleichaltriger Bestände
eine weitere Phase in dem Entwicklungsprozess
zu einer intensiveren Waldbewirtschaftung.
In   der   zukünftigen Bewirtschaftung dieser
Bestände lassen sich zwei Probleme voraussehen,
dei eine weitere Entwicklung von Technicken   in
der Forstkultur erfordern:
(1)   Man   muss   das   Wachstum   von   Beständen
beschleunigen und   genaue   Voraussagen   der
wahrscheinlichen Holzerträge machen. Das hat
bei   langen   Umtriebszeiten   unter
Berücksichtigung eines ständigen Wechsels in
den Wachstumsbedingungen und des   Wachstums
selbst zu geschehen. Hier wird der Wechsel
diskutiert,der bedingt ist (i) durch lang- und
kurzfristige Witterungsperioden und (ii) durch
die   mit   Alter   und   Genotyp   wechselnden
Reaktionen.   Konventionelle
Ertragstafeltechniken eignen sich nicht als
Grundlage   für   die   Prognose   des
Bestandeswachstums   unter   intensiveren
Bewirtschaftungssystemen. Wir   erfassen den
Wuchsverlauf von Einzelbäumen als Modell, um
sowohl den Gesamtertrag eines Waldes als auch
die Ertragsverteilung in Abhängigkeit von der
Baumhöhe zu erfassen.
(2) Mit zunehmendem Alter der Bestände ist die
nutzbare Holzmasse immer mehr Risken wie Feuer
und Windbruch ausgesetzt. Diese werden nicht
als unvermeidliche 'Katastrophen' betrachtet.
Ihr Auftreten ist eine Funktion der Baumart,
des Standorts und der waldbaulichen Situation.
Wir   untersuchen   die   Möglichkeit,   auf
ökologischer Basis ein Modell fur Windbruch zu
entwickeln.
Wir   behaupten,   dass   es   nur   wenige
Untersuchungen   für   die   Entwicklung   neuer
waldbaulicher   Systeme zur Ertragssteigerung
oder zur Vermeidung von Produktionsrisken gibt,
während die Faktoren des Wachstumsprozesses von
Beständen   und   die   Wechselbeziehung
Raum-Standort gründlich erforscht sind.

INTRODUCTION

Increase in the demand for timber and timber products is
not   a   new   phenomenon,   neither   is   the   evolution   of
silvicultural systems designed to meet this demand. Fifty
years ago silviculturalists felt the pressure for more wood
threatened the destruction of forests and sought ways of

managing them to cope with this.

"Forestry is now passing through a critical stage. The
depletion of natural forests that has taken place during the
past hundred years in many parts of the world gives genuine
cause for alarm ... if the problem of future timber supplies
is to be solved, it is (also) of the utmost importance that
the reduced forest area now available should be treated in
such a way as to produce the highest possible sustained yield
of timber ..." (Troup 1928). Also, in 1928, Toumey put forward
a basic concept which he considered should be followed in
silvicultural practice. "Forest vegetation is composed of
plant communities or units of vegetation developed and
arranged in accordance with definite biological laws and is
not an aggregation of trees and other plants brought together
by chance" (in Toumey & Korstian 1947). Toumey's view of the
forest as an ecological entity was strongly felt and he
considered that his text on the foundations of silviculture
"is not an outgrowth of plant ecology but rather plant ecology
is an outgrowth of it".

The silvicultural systems of Troup and Toumey have their
origins in tending natural forest to produce a sustained yield
without destroying the forest itself. Their considered
"ecological" basis is that yield is in balance with the site
without recourse to large scale amelioration of site
conditions. Since 1928 the demand for timber has continued to
increase. This, combined with the worldwide reduction in areas
of accessible natural forest, has led to the establishment of
substantial areas of plantations in a wide variety of climates
and frequently on land not previously forested. Plantation
forestry is subject to stringent demands requiring
intervention during the growth of the crop to maintain or
increase growth rates or to adjust the proportions of
different timber sizes to be produced. This requires a further
development in silvicultural systems which itself demands more
detailed understanding of ecological processes underlying the
growth and development of forests.

PROBLEMS OF GROWTH RATE AND THE DEVELOPMENT OF FOREST
STRUCTURE IN A PLANTATION ENTERPRISE.

The culture of forest plantations involves more than just
careful management of an existing ecosystem on conservative
ecological principles - it is an extensive investment exercise
with the following characteristics.
(i) Plantations are frequently restricted to marginal lands
with soils and climates which are poorer and more variable
than those used for agriculture - these environments do not
automatically support high yields and may present hazards such
as windthrow, frosts etc.
(ii) Timber is a bulky product, so that a large proportion of
the cost of producing it is incurred in its transport to

processing mills. The plantation enterprise should be concentrated to minimize transport and investment costs, but yet must generate sufficient production to sustain the development of an industrial infra-structure (Boardman, this volume).

In commercial plantation forests with these characteristics there are three closely related problems of forest growth and development.

Achieving a predictable, high growth rate

Plantations are costly to establish in terms of land, roads and fencing, and so generally the higher the yield/area obtained, the greater the profitability. High growth rates also mean that processing plant can be supported from a smaller area of land, again minimizing costs. However, almost as important as achieving high growth rates, is the need to predict the yield of timber which will be obtained in order to develop the associated forest industry efficiently.

Protecting the forest against hazards and predicting risk

In many cases an even-aged plantation produces a forest structure which is at risk to destruction by strong winds, fire, animals (Crooke; König; Cooper & Mutch, this volume) and pathogens (Murray, this volume). Since the incidence of such hazards is related to the structure of the forest, attempts can be made to assess risk and devise silvicultural systems to minimize it.

The development of a balanced forest structure

Conflicting requirements can arise in relation to the optimum size and spatial distribution of stands of different species and age within a forest. This topic is dealt with in some detail by Malcolm and Davies in this volume. Management options in forest design are critically affected by the capacity to increase and secure production which themselves are influenced by variations in site and topography.

ACHIEVING A PREDICTABLE, HIGH GROWTH RATE.

Traditional methods of predicting forest yields require no detailed understanding of which factors control growth rates. A 'site index' is used to classify the productive capacity of each stand based on some aspect of the growth made up to the time of observation, most frequently height (Kreutzer, this volume). Future growth is predicted from a set of empirically constructed yield tables on two assumptions, (i) the productive capacity of the stand will not change, i.e. growth will follow a pattern established from previous stands which have been similarly classified, and (ii) a particular, prescribed silviculture is followed, which determines the frequency, severity and type of thinning during the course of growth. This technique of yield prediction originates largely from the work of German foresters of the nineteenth century in long-established forests (Assmann 1970) and is based on the

precept that the removal of a timber harvest should be in
balance with the 'site'.

Over the years refinements have been made in the
parameters used to measure site indices so that they relate
more closely to productive capacity, e.g. in Britain
production classes used in conjunction with general yield
classes, to incorporate a measure of stand basal area as well
as height (Hamilton & Christie 1971). Another development has
been to stratify forest sites in relation to physiography and
various measurable site factors before constructing yield
tables. However, as Kreutzer (this volume) has pointed out,
whilst this approach has made predictions more accurate, it
has also raised many questions about the relationships between
various environmental factors and forest growth. One needs to
know which variables to chose when making yield class
stratifications. These are exactly the questions that we must
answer to understand how to increase the growth rate of
established stands.

The stage has now been reached where we should question
the extent to which this yield table technique is an
appropriate model for yield prediction in plantation forestry.

Neither of the two assumptions under which yield tables
are constructed, are applicable to modern plantation
silviculture! Plantations do not grow under uniform conditions
and intervention may be required to accelerate (Davies, this
volume) or maintain (Boardman, this volume) timber production.
The removal of yield as thinnings has now become a more
variable operation in response to the advent of new machinery
(Hamilton 1976a), fluctuations in the demand for timber of
different sizes, or the development of systems with
no-thinning (Godwin 1968) or pre-commercial thinning (Fenton &
Sutton 1968) silvicultures. We need to consider how these
characteristics of plantation forestry may be incorporated
into techniques for predicting yield.

Changes in 'site' conditions and tree response during
the plantation cycle

Plant growth is regulated by the amounts of radiation,
water and nutrients received or available and by conditions of
temperature and humidity. These are not constant over the
plantation cycle, neither is the level or type of tree
response. There are three sources of variation (i) long and
short term changes in weather patterns, (ii) continuous
developments in stand microclimate and (iii) differences in
response to environmental variation as the trees age or as the
conditions for growth alter greatly. Let us consider these
three sources of variation in turn.

(i) Changes in weather patterns. In extreme climates the width
of tree rings may be very closely related to variation in a
single environmental factor e.g. annual precipitation in arid
zones (Fritts 1965). In more temperate regions, climatic

variation may not be so dramatic but still has a major
influence on tree growth. Over twenty-eight sites in Colorado,
Fritts et al. (1971) found that on average some 60-65 per cent
of the variation in tree ring widths of three species was
related to variables representing the seasonal march of
climate. Different environmental variables were important on
different sites, and whilst 20 per cent of the sites showed
less than 50 per cent of the variation related to these
variables, another 20 per cent showed more than 80 per cent of
the variation so related.

Climatic cycles can have a substantial effect on growth.
In a mature plantation of Pinus sylvestris, Miller, Miller &
Binns (1977) showed that rings had varied from 0.5 mm to 1.25
mm in a regular way between the seventy-fourth and
eighty-ninth year. They detected three significant cyclical
patterns with periods of 42.0, 23.0 and 4.4 years
fertilization increased the amplitude of the variation
associated with these cycles.

The influence of short term, i.e. daily or weekly changes
in the environment on tree growth has been largely ignored.
Physiologists have tended to stress either the influence which
conditions in one year may have on a subsequent year's growth
(Kozlowski, Torrie & Marshall 1973), or the importance of
trends in the development of trees during a season (Denne
1976).

'Carry over' effects from one year to the next are
well-known in agricultural experimentation and must be taken
into account when assessing the yields of 'crops under
different treatments over a series of years (Patterson & Lowe
1970). In forests such evidence as exists suggests that these
effects can be small compared with the effects of current
season's weather. Over the twenty-eight Colorado sites
investigated by Fritts et al (1971) only 15 per cent of the
variation in ring width was 'explained' by correlation with
the previous year's ring width, compared to 60-65 per cent
variation 'explained' by current weather. For trees it has yet
to be proved that there is a direct physiological influence on
yield by one season's conditions on the next year's yield. The
influence which variation in weather in one year has on growth
in the next, seems most likely to be restricted to aspects of
shoot elongation where bud development takes place a year in
advance of extension. This may determine the number of needles
which will be produced in the following year (Cannell,
Thompson & Lines 1976), but both the size of needles and the
total length of shoot on which they are carried are influenced
by the amount of photosynthesis made during the year of growth
itself (Little 1974).

Factors controlling the duration of the growth period are
important, particularly with regard to bud development and
shoot elongation. Variation in response to these factors is a

major source of exploitable genetic variation in growth
(Perry, Cannell, this volume). However, within the limits set
by the seasonal period of development, growth fluctuates in
response to changes in the environment. In a plantation of
Sitka spruce in the Scottish uplands, cell production by the
cambium during the production of early wood varied between
zero and twelve cells per radial file of tracheids per day,
being greatest on days with high solar radiation (Ford,
Robards & Piney 1978). In the same forest, the population of
fine roots was found to decrease by up to 50 per cent over a
fifteen-day period with no rain, but after heavy rainfall the
population increased almost to its original size within five
days (Deans in press). The magnitude of these effects varied
between soil horizons and depended upon their particular
microclimates. These results suggest that fast growth requires
alternation of sunny and wet periods each with a duration of
no more than a few days. Whilst cambial activity may respond
to individual days of high radiation, long uninterrupted
sequences will lead to the development of high moisture
tension within the tree which checks cambial activity (Little
1975). The amplitude and frequency of weather changes may be
as important to the achievement of high growth rates as the
mean conditions and may explain some of the very high growth
rates in mild, temperate climates (e.g. Tottenham & Joyce
1975).
(ii) Development of stand microclimate. The extent to which
plantation growth is sensitive to changes in the environment,
will depend upon its size and structure since this has a large
influence on the microclimate of the stand. In a young
plantation height increments were found to increase slowly
until the branches from neighbouring trees overlapped.
Increments then increased rapidly from year to year until
competition between trees started (Cochrane & Ford 1978) from
which time annual height increments oscillated around a mean.
The precise environmental changes, which cause the
acceleration of height increment and those which determine the
limit of mean annual height increment are not known for this
forest. The environmental factors which determine the size a
forest canopy can attain and the size at which competition
becomes important, have been variously specified as a balance
between temperature and solar radiation (Nomoto 1964) and the
ratio between incoming rain and potential transpiration (Grier
& Running 1977). Whilst such combinations of factors may be
predominant at the extremes of wet or dry climates, some more
complex balance may be struck in intermediate zones between
water balance, temperature and nutrition (Waring et al. 1978).
Factors controlling maximum growth rate and the canopy size at
which this maximum is achieved, are important areas for future
research, since microclimate, e.g. increasing 'interception
loss' with increasing forest size, is strongly implicated and

may possibly be manipulated through silvicultural techniques. Boardman (this volume) has pointed out that little opportunity may exist for rapid acceleration of growth rate once canopy closure has occurred. Silvicultures which depend largely on maintaining a closed canopy for long periods of time and taking a substantial proportion of their yield as thinnings, i.e. anticipating mortality, may not prove as flexible as those in which the rotation is short and final yield is a large proportion of total yield.

(iii) Differences in tree response. Alterations in the physiological characteristics of trees as they age, are well-known (Moorby & Waering 1963). Many of these are easy to predict and can be counted as intrinsic properties of the crop. Such ageing effects are likely to become important to strategies of increasing and predicting yield where differences are known to exist between and particularly within species. In a progeny trial with Ponderosa pine, Namkoong & Conkle (1976) found indications of trends in height growth which differed between the phases of plantation growth, planting site and family. More research on such differences is required to determine whether they are directly due to differences in genotype or indirectly due to differences in stand structure and therefore in microclimate.

A major consequence of accelerating growth rates through a treatment such as fertilization, is the production of wide growth rings (Davies, this volume) and a possible change in wood properties. Generally, sale of timber for structural purposes is more profitable than sale for pulp and industrial processing, but such timber must meet certain specifications of strength. This is determined by the properties of knottiness, wood density, grain angle and the incidence of compression wood. Tree spacing, thinning and pruning can all influence these properties (Brazier 1977) but the silvicultural technique of most interest for its effects on quality is fertilization, since this has the general effect of increasing total growth. Little is known of the effects of fertilizing on knottiness, grain angle and the incidence of compression wood and more research is required on these aspects of growth and their importance in determining wood strength (Brazier 1977).

Brazier (1977) reviewed a number of reports indicating that fertilization decreased wood density, which, by implication, would be expected to decrease timber strength Exceptions to this are very slow growing trees which were initially producing 'starvation wood'. Fertilization increases the proportion of early wood, the cells of which have a high lumen area:wall thickness ratio. Smith, Wellwood & Elliot (1977) also reported this general result but suggested that climatic differences were important and could interact with fertilization to affect wood density. They also reported

differences in response to fertilization between trees.
Finally, fertilization sometimes alters the form of trunks and
hence the 'form factor' used in prediction (Flewelling & Yong
1976).

This examination of 'site' conditions and tree response
leads to the following conclusions:

(i) Trees respond to variation in weather over a range of
frequencies and ameliorative treatments may amplify the
effects of such variation.

(ii) In temperate regions, unless irrigation is used or
large reservoirs of soil moisture exist, the highest
growth rates are likely to be achieved in conditions
where there are rapid short term fluctuations in the
weather.

(iii) Where the growth process is largely controlled by
the supply of a necessary resource, e.g. water,
radiation, or nutrients, then forest growth rates will
change markedly with age as the stand structure
influences the microclimate. Ameliorative treatments,
such as fertilization or drainage may accelerate these
effects.

(iv) Low input silvicultural systems, may neither respond
adequately to 'ameliorative' treatments or if they do,
may not produce timber of the same quality as originally
intended.

The essential character of forest growth is that it is
variable and intensification of management is likely to make
it more so. Current mensurational techniques for predicting
yield assume that the largest part of variation can be
expressed in terms of a growth curve, either empirically
constructed from the growth records of previous stands
(Hamilton & Christie 1974a) or by attempting to fit various
types of growth curves, e.g. logarithmic (Kilpatrick 1978) or
the Richards growth function (Rawat & Franz 1974). Variation
is treated as error. Neither approach provides a satisfactory
basis for yield prediction of intensively managed plantation.
Rather we should consider forest growth as being produced by a
series of impulses under changing conditions and the
appropriate mathematical structure for this is multivariate
time series analysis (e.g. Box & Jenkins 1970). Growth can be
analysed by time series techniques (Ford & Robbards 1976;
Ford, Robbards & Piney 1978) and models for prediction using
such techniques are increasingly in use in economics.

Manipulating and predicting the distribution of yield
by adjusting stand structure

The distribution of yield from a plantation, both in time
and in terms of the assortments of stem sizes, can be
influenced by initial spacing (Hamilton & Christie 1974b) and
by the thinning regime adopted (Assmann 1970). When yield
tables are constructed by an empirical site index technique,

e.g. Hamilton & Christie (1974a), it is necessary to specify quite closely the particular thinning regime to be used and most frequently this has been some form of selective thinning. However, increasing interest in mechanical thinning (Hamilton 1976a), no-thinning (Godwin 1968), often combined with more intensive forest management and a range of harvesting techniques, have together stimulated attempts to model the competition process between individual trees with the object of providing more flexible predictions of growth and yield (Arney 1974; Munro 1974).

A number of curve fitting techniques have been applied to provide descriptions of stem size distributions in even-aged plantations, e.g. Baily & Dell (1973). However, a more fundamental approach, modelling the influence that a tree's neighbours may have on its growth, has recently been quite widely adapted. By concentrating on the growth of the individual, this approach offers a framework whereby all the major direct influences on growth may ultimately be incorporated into one model. It is intended that individual tree models which simulate the mechanisms of growth and competition will provide flexible predictive models, beyond the scope of conventional yield tables (Munro 1974).

Competition occurs for the resources used in growth and can be defined as a process. "When the immediate supply of a single factor necessary (for growth) falls below the combined demands of the individual plants, competition begins" (Clements quoted in Donald 1963). These resources, viz. light, water and nutrients, exist in finite concentrations so competition is a spatial process and its onset in a plant community depends upon the relative growth rates of the plants themselves. Thus, fertilization increases growth and accelerates the competition process (Yoda et al. 1963). The competition process has five characteristics which must be considered when a model is being constructed.

(i) Two plants of the same size may not have the same status in a community. If one has bigger neighbours than itself, whilst the other has smaller neighbours, the two individuals would not be expected to achieve the same growth in future. 'Success' in competition is a matter of probabilities - it depends upon the relative sizes of neighbours - so competition should be regarded as a stochastic process.

(ii) Competition in a plant monoculture can only be assessed by observing the distribution of relative growth rates, RGR, e.g. for basal area, square cm/square cm/yr. We must ask: "Has there been a change in the efficiency at which the growth machinery of the individual plant operates?" Little can be judged from the distribution of plant size in a community. This can take many forms (Ford 1975; Diggle & Ford, unpublished) as a community ages.

Absolute growth rate, e.g. for basal area, square
centimeters/year, may not be a sensitive indicator of
competition since it is greatly influenced by plant size.
The necessity for observing RGR was illustrated by
examining growth rates and RGRs of individual trees in a
young Sitka spruce plantation in Scotland just reaching
the stage when its annual production of needles was
constant (Fig. 1). Ninety percent of the trees, i.e.
those with basal area between 53 and 240 square
centimeters, had the same relative growth rates, although
there were considerable differences between them in size
and in growth rate. Only the smallest 4 per cent and the
largest 6 per cent had substantially different RGRs and
showed the effects of competition. In an unthinned
plantation, differences in mean RGR between size classes
accentuated as the stand grew (Ford 1975).
(iii) The intensity of competition changes as a stand
develops. In its simplest form this can be seen in
differences found between young and old stands in
calculated competition coefficients. These coefficients
decrease with increasing age (Thomas & Stevens 1977).
(iv) The importance of competition in determining the
distribution of final plant size may depend on the degree
of site heterogeneity (Cannell et al. 1977) and genetic
variability (Diggle & Ford unpublished).
(v) The competition process can influence the total
amount of growth that a stand makes. Differences exist
between trees within a stand in the amount of timber
produced per unit of crown volume or crown surface area.
In general, dominants and sub-dominants are more
efficient than dominants, e.g. Hamilton (1969). But there
are some suggestions that the largest trees in a stand
can be less efficient than those slightly smaller. Some
indication of this effect can be seen in Fig. 1 where the
mean RGR of trees in the category of second largest basal
area is higher than those of the largest basal area.
Similar effects can be seen in some older unthinned
plantations (Ford 1975). Differences in crown efficiency
can also be produced by thinning treatments. In a series
of experiments where selective thinning was maintained to
remove increasing numbers of small trees (Krammer 1966),
the mean individual crown volume was largest in the most
severely thinned stands but timber production per unit of
crown volume was lowest.
Competition models for even-aged forest stands are at an early
stage of development. There are two important problems which
must be faced, (i) relative tree status must be represented
accurately and (ii) descriptions of the total amount of growth
to be 'shared' amongst trees must be made flexible if the
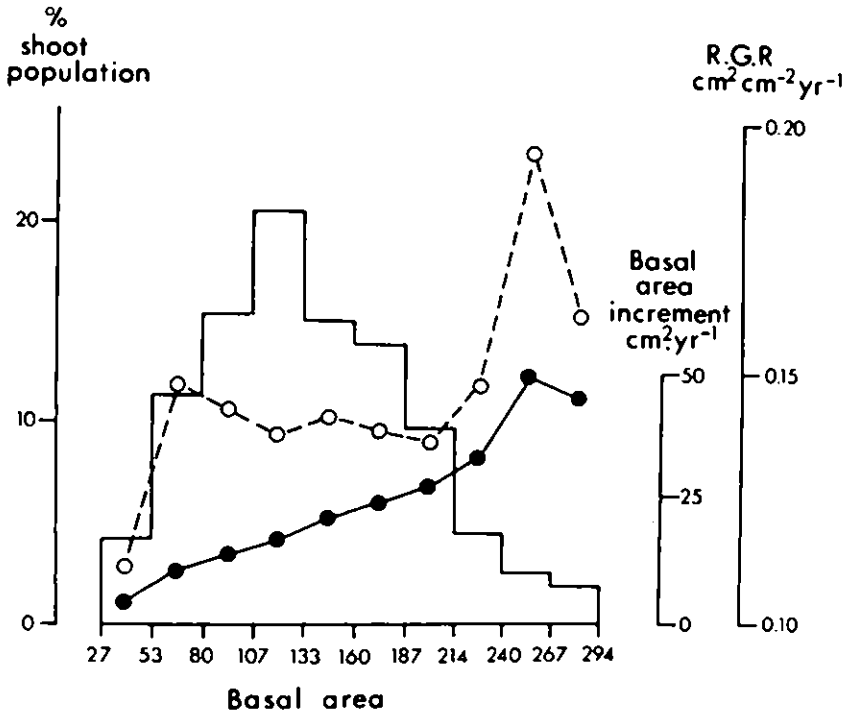effects of different environmental factors are to be assessed.

Fig.1. Frequency distribution of trees by basal area and the
mean basal area growth rate (closed circles) and basal
area relative growth rate (open circles) for each basal
area category in a 14yr plantation of Sitka spruce.

Some techniques for describing relative tree status are
described in Fig. 2, but rarely has more than 60 per cent of
the variation in growth between individuals been accounted
for.   Parameters are required to express the degree of
influence which a plant may have on its neighbours. In some
models a zone of influence is estimated for each tree as a
function of its diameter (Bella 1971; Hegyi 1974) and
interaction with other trees is calculated either as a
function of the distance between neighbours or by estimating a
zone of influence and calculating interaction as the summation
of intersections, with a weighted influence in favour of large
trees (Bella 1971) (Fig. 2). Neither tree diameter nor basal
area are sufficiently accurate representations of tree size to

be used in competition models. They are integrated values of all growth made by the tree over the history of the stand and can only describe general differences between individuals; a more suitable measure would be basal area increment over the last year as this would give a better indication of the changing status of individuals. Basal area or diameter can not be directly related to the competition process as can measures such as height or crown size.

More functional measures of tree status have been used in stand simulations. Newnham & Smith (1964) modelled competition as the extent to which a tree crown was intersected by neighbours; Ek & Monserud (1974) used tree height in conjunction with an estimated crown radius (Fig. 2), whilst Mitchell (1969) simulated crown development directly as dependent upon branch growth which was in turn related to the proximity of neighbouring crowns. However, these three models, in common with many others, use the form and size of open grown trees as a base line for estimating growth and development. They do not simulate competition at the process level in terms of the relative distribution of resources for growth and this they would have to do in order to predict the effects of treatments such as fertilization on the distribution of tree sizes within the stand.

A strategy for modelling forest growth

Difficulties have been encountered with models designed to predict both the distribution of yield and growth in relation to site factors. Frequently this has been because the requirements of management have been kept too closely in view when formulating model structures. Accuracy requires an effective simulation of physiological and ecological processes but for ease of use, models must not be too complicated. I suggest a three level modelling strategy for producing a more reliable yield prediction technique for forest plantations.

(1) Basic growth models

Two are required, a physiologically based model of plant response to environmental variation and a population dynamics model of the competition process. The former should be modelled at the level of carbohydrate, water and nutrient balance of trees and should be able to predict the factors limiting growth as conditions vary. It should provide information on growth rate to a population model describing competition as a stochastic process. This second model should determine the rate of change of competition intensity as stands develop and the extent to which relative growth rates are determined by factors other than competition, particularly genetic variation.

(2) Growth-yield Linking models

Two models are required to link simulated growth of processes with yield prediction techniques. One to describe the distribution of yield over individual trees and how this

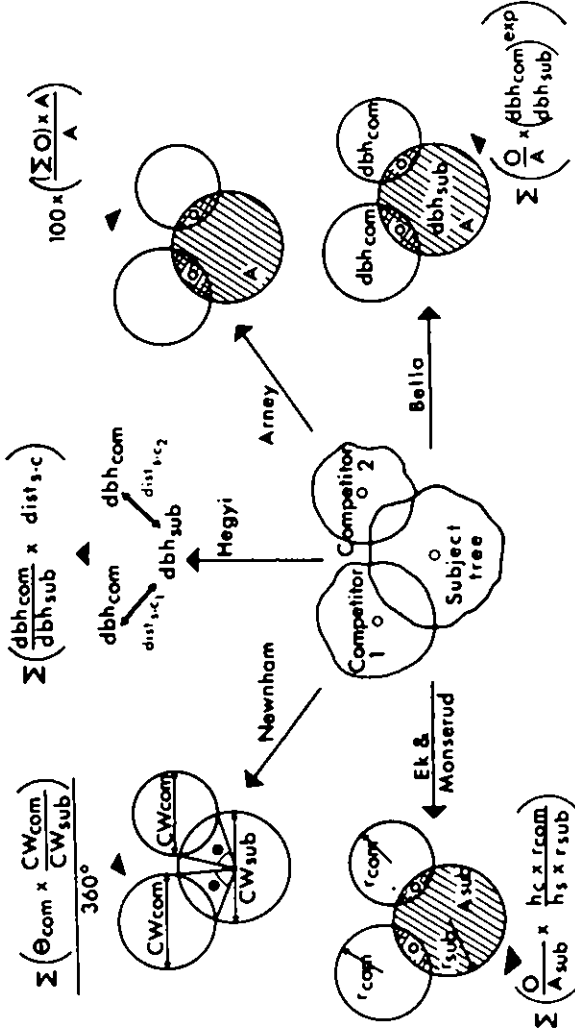Fig. 2. Techniques for calculating relative tree status or competition coefficient suggested by various workers (references in text).

Subscripts: sub or s = subject tree, com or c = competitor tree.
Area A = crown size estimated from open grown trees of same trunk size
O = area of overlapping crowns, θ = angle of crown intersections
CW = crown width, r = crown radius
dbh = diameter at breast height, h = tree height

may vary under a range of conditions. Such a model would link
physiological   and   competition   models   with   the   actual
production of timber in terms of both total yield and quality.
The second to describe the changes which can occur in stand
microclimate as stand structure is manipulated. The object of
this   would   be   to   provide   the   link   between   proposed
silvicultural treatments and their effect on growth. Models in
this category are the most neglected aspect of the science of
yield prediction.
(3) Yield models
        The prime object of these should be to estimate the
'error' in prediction. They should be capable of examining the
likely   fate   of   a   proposed   silvicultural treatment under a
range of future weather patterns and management options.

HAZARDS TO PLANTATION DEVELOPMENT.
        The fate of many forests is   regeneration   through
destruction, by wind or fire (Malcolm; Adlard, this volume).
When such a process occurs in a plantation.it is considered to
be a catastrophe and whilst this is certainly so as far as
management is concerned,   such catastrophies have ecological
reasons and are not purely random events. The study of their
ecology can provide insight leading to both control and
prediction. Fire is a major hazard in dry climates, and
attempts have been made to predict its occurrence in both
scrub, e.g. Rothermel (1972) and forest, e.g. Davis & Irwin
(1976), Cunningham & Martel (1973). Windthrow is a major
hazard to plantation development in the United Kingdom (James
& Dier 1968), the Irish Republic (Gallagher 1974), New Zealand
(Irvine 1970; Wilson 1976), Australia (Cremer et al. 1978) and
Germany (Hutte 1968).
        Three groups of factors influence the occurrence of
windthrow:
        (i)   the frequency and strength of the wind,
        (ii)   the interception of wind by the tree crown to create
               a drag force,
       ·(iii)   the resistance to windthrow offered by soil and
               roots.
        Our knowledge of how these interact is limited. Published
studies have either analysed either a single factor, for
example, resistance offered to windthrow by soil and roots
(Fraser & Gardiner 1967) or the incidence of windthrow over a
forest in relation to site and management factors after a gale
has taken place. Unfortunately the latter type of analysis is
complicated by methodological problems. In most plantations
the distribution of species and soil types are confounded and
certainly in the British Isles, soil type is confounded with
topography. Most important of all, the cultural techniques
used during establishment are confounded with age of crop.
Consequently, the analysis of gale damage can be of very

limited   value,   even   to   predict future windthrow, let alone
advance understanding   of   the   mechanism   itself.   A   further
drawback   is   that the conditions which operate in major gales
may not be closely related to those   which   are   important   in
smaller   but   more   frequent   storms.   The   latter   may   cause
substantial loss of timber (Gallagher 1974; Irvine   1970)   and
it   is protection against them which is more frequently sought
by forest managers (Booth 1974b).

(i) The frequency and strength of the wind

        The   arrival   of   wind   storms   cannot   be   predicted
accurately, but, like other weather phenomena, must be treated
as a stochastic process. However, wind has a complex structure
(Allen   1968; Meroney 1968) and we need to know more about the
combinations of factors which produce windthrow, such   as   the
relationship between the duration of high mean wind speeds and
the   incidence   of   strong   gusts   and   between wind speed and
rainfall.   Without this information detailed analysis of   wind
as   a stochastic process in an attempt to predict risk may not
be fruitful.

        Hutte (1968), Irvine (1970) and O Cinneide   (1974)   have
all   suggested   that   storm damage is greatest in places where
turbulence   and   wind   speed   are   increased   by   relief,
particularly on lee slopes. Measurements of variation in wind
speed over a landscape were made with   anemometers   and   were
found   to   be   related   to   topographic features (Hutte 1968).
However, it is difficult to   characterize   the   components   of
topography   which   effect wind microclimates.   Flow round many
regular objects can be predicted   mathematically   (Schlichting
1968), but flow over a specific natural topography cannot.   In
the U.K. attempts have been made to assess variations in   wind
speed in relation to topography by (a) using simple integrated
measurements   of   wind run, e.g. tatter flags, (b) calculating
'topographic shelter', the sum of the horizon   angles   to   the
eight   major   compass points (Howell & Neustein 1966), and (c)
constructing models of   forest   topography   for   use   in   wind
tunnels.   However,   Booth (1974a) concluded that a combination
of these techniques had not been proved helpful   in   stability
zoning   although   recent   work   has   proved   more   encouraging
(Booth, personal communication). Measurements of wind speed at
different points over   model   forests   in   wind   tunnels   have
correlated   well   with anemometer data from the forest itself,
although tatter flags and anemometer data did   not   correlate.
The   scale   models   incorporated   either   an   exaggeration   of
vertical height or a roughened surface.

(ii) The interaction of wind with tree crowns

        Susceptibility to windthrow has been related to   increase
in   tree   height   (e.g.   O Cinneide   1974) and, under   U.K.
silviculture, to   increased   thinning   intensity   (e.g.   Booth
1974b).   However, some evidence (Irvine 1970; O Cinneide 1974)
suggests that windthrow risk peaks in   plantations   of   middle

age when thinnings are frequent and that older stands are more
stable. The disruption which thinning causes to the surface of
the   crop is generally considered to produce an uneven
distribution of drag forces between the crowns (Mitcherlich
1974; Cremer et al. 1978). Two silvicultural techniques have
been suggested to combat this problem and to produce a
plantation   with   an   undisturbed   canopy   as crop height
approaches that of greatest windthrow risk. (a) No thinning
throughout the life of the crop (Godwin 1968) combined with an
early   final   felling;   (b)   early non-commercial thinning,
designed to produce a short rotation crop which has an
undisturbed   canopy   as   the 'critical height' approaches and
produces a final yield of sawlogs (Fenton & Sutton 1968 as
applied in Irvine 1970; Moore 1976). Neither technique is
fully tested and there is need for fundamental studies on
these systems of the relationship between stand structure, the
distribution of drag forces and windthrow.

    Over the past decade a number of micrometereologists have
measured   wind profiles over and within forest canopies
(Jarvis, James & Landsberg 1976). Most usually their objective
has been to assess the importance of ventilation of the canopy
in the transfer of heat, water vapour and carbon dioxide
between the atmosphere and the crop. The logarithmic wind
speed profile has usually been assumed, which for tall
vegetation is

$$U_{(z)} = \frac{U_*}{k} \ln \frac{z-d}{z_o}$$

where $U(z)$ is the wind speed at height z,
U_* is the 'friction' velocity or 'eddy' velocity and
represents the rapidity with which momentum finds its way
to the surface.
k is a constant
d is the zero plane displacement
z_o is the 'roughness length' of the surface.

    d and z_o are parameters which give some indication of
the   aerodynamic characteristics of a surface. d indicates the
mean level of action at which momentum is absorbed by the
individual elements of the plant community: the level of
action of the bulk aerodynamic drag on the community. The size
of z_o specifies the bulk effectiveness of the canopy as a
momentum absorber.

    However, although variation in d/h and z_o/h have been
found for crops with different structures, the potential of
such parameters for analysing susceptibility to windthrow
seems limited for the following reasons. (a) Large uniform
areas of forest are required to determine z_o and d
accurately. (b) d and z_o can be determined only for wind
profiles obtained under the limited conditions of no exchange
of heat between the canopy and the atmosphere (but see Jarvis,

James & Landsberg 1976). (c) The use of the logarithmic
profile to describe momentum exchange for vegetation greater
than 2m high is being increasingly questioned. The
three-dimensional structure of tall crops (Ford 1976) may
influence momentum transfer (Mulhearn & Finnigan 1978). From a
theoretical analysis, Perrier et al. (1972) considered that
the logarithmic profile could only be applied to a tall row
crop when the inter-row cavities were completely filled with
foliage. For other crop structures they described the wind
profile in terms of the different degrees of mixing of the
wakes and vortices which develop behind individual roughness
elements.

Papesch (1974) emphasised that more attention must be
paid to the structure of the wind when considering the forces
which act to produce windthrow. Wind does not provide a
constant force but one which occurs in gusts. A wind can be
described in terms of its turbulence structure, i.e. the
relative amounts of energy which it contains as little gusts,
high frequency energy, and large gusts, low frequency energy.
Observations made across a forest edge showed a reduction in
total energy as the wind passed from a grassland over the
forest, but a relative concentration of energy at higher
frequencies close to the natural sway period of the trees.
This was due to interaction with the tree crowns.

Papesch (1974) developed a mathematical formulation for
the relationship between the wind, tree crown and the movement
of the tree combining both static parameters, such as mean
wind speed, and dynamic description, such as the oscillation
in wind amplitude. One interesting prediction from
calculations with this model was that, under the same general
conditions, when edge trees required a mean wind speed of 80
mph to blow them down, trees within the forest required a mean
wind speed of only 62 mph. It is indeed a common occurrence
that edge trees are the only ones left standing after
windblow. A greater fluctuation of the forces acting on trees
just behind the forest edge was predicted from wind tunnel
studies with static forest models by Fraser (1964).

Testing the analysis developed by Papesch requires (a)
more comprehensive measurements of the frequency distribution
of wind energy over forest canopies of different types (Bull &
Reynolds 1968), (b) more detailed analyses of the dynamic
response of tree crowns to increase in wind speed (Mayhead
1973), and (c) the development of methods to describe the
configuration of the canopy surface (Ford 1976) and to apply
these to the changes in shape which occur as the wind blows.
With this information experiments to investigate the
distribution of drag forces could be conducted in windtunnels
(see Marshall 1971 for an agricultural application) with more
'realistic' forests than have been used to-date.

(iii) The resistance to windthrow produced by soil and roots

Early studies in the plantations of upland Britain indicated that windthrow occurred principally on shallow rooted crops growing in soils with impeded drainage, most typically peaty gleys (Fraser & Gardiner 1967; Pyatt 1968). On gleyed soils closely spaced deep ditches were ploughed to dry the soil and enhance transplant growth (Taylor 1970). This technique has now been revised since tree pulling experiments on gleyed soils indicated that lateral spread of roots between widely spaced ploughing ditches (4.27 m) was more effective in promoting stability than the small increase in rooting depth which could be achieved with closely spaced (1.22 m) ploughing ditches (Booth 1974b).

The relationship between root growth, soil conditions and stability is complex. Cremer et al. (1978) measured soil sheer strength on well-drained and poorly drained soils in a Pinus radiata plantation near Canberra, Australia, shortly after a destructive gale. The mean relative sheer strength of the undisturbed poorly drained soils was 1.0 compared with 2.0 for undisturbed well-drained soils. However, within the root balls of blown trees the relative sheer strengths were respectively 5.3 and 3.2 for poorly and well-drained sites. On the intrinsically mechanically weaker soils the root balls had grown firmer and to a larger diameter with better lateral attachment but poorer vertical hold. Cremer et al. (1978) did not identify the mechanically weaker soil as being more prone to windthrow.

Shallow root growth is frequently attributed to the occurrence of some impenetrable zone in the soil or to waterlogging. However, concentration of roots at the surface of forest soils is the rule rather than the exception (e.g. Eis 1974). Following a destructive gale in New Zealand, Irvine (1970) concluded that shallow rooting was prevalent among uprooted Pinus radiata but that this was a response to the distribution of nutrients in the soil since these were located in the surface soil horizons. Ford & Deans (1977) analysed the growth of fine roots in an eleven year old plantation of Picea sitchensis on a peaty gley in Scotland. A distinctive and more active root population was found in the surface soil and those soil horizons formed beneath turf upturned during ploughing. Most fine roots were found in soil with the largest concentrations of available nutrients. The importance of the upturned turf ribbon as a source of nutrients on gleyed sites and its role in root development has also been stressed by Savill (1976). Increasing the available nutrient to a stand by fertilizing increases the total amount of root (Paavilainen 1967) and root thickening is also increased by increased nutrient concentration (Coutts & Phillipson (1976). Further work is required to determine the effect which cultural techniques may have on the mineralisation process and how this

may vary with soils of different basic nutrient status and
physical characteristics.

Mineralization requires specific physical conditions
(Heal, this volume) and may not proceed at a uniform rate in
all parts of the forest soil and this could affect the
distribution of root growth. Deans (in press) has shown that
in a young plantation of Picea sitchensis in the southern
uplands of Scotland with an annual rainfall 1800 mm/yr, root
mortality can occur during the summer months and is associated
with drying out of the soil. The distribution of water to the
soil of this plantation is very localized, some 40 percent of
water received during the summer months flows down stems (Ford
& Deans 1978), a phenomenon which may have a direct influence
on root growth and may also influence the mineralization
process in the soil. McColl (1973) has demonstrated that
mineralization is enhanced by the passage of a wetting front
through a soil horizon.

Before a silviculture can be specifically designed for
windy areas, further research is necessary into all three of
these factors:

(i) to define the frequency and spatial variability of
risk,

(ii) to search for variability which may exist between
canopies of different structure in the dissipation of
momentum,

(iii) to formulate the relative importance of soil
moisture, nutrient concentration and physical impediment
to the lateral and vertical spread of roots and to
examine more precisely the influence which different root
structures may have on stability.

Some interesting silvicultures for windy areas have been
proposed. From different regions both Irvine (1970) in New
Zealand and Moore (1976) in Ireland have suggested that widely
spaced crops could be grown over short rotations without
production thinning. Mitcherlich (1974) has suggested that on
gentle terrain planting in strips with the youngest trees
up-wind can improve stability and both Fraser (1964) and
Mitcherlich (1974) have suggested high pruning or early
thinning of edge trees to reduce turbulence above the canopy
just interior to the edge. Hengst & Schulz (1976) have
suggested that specific silvicultures be applied to match
topography in a wind damaged forest, including the creation of
a new network of forest roads with specially structured stand
margins and conversion of uniform stands to mosaics of
different species and ages. Following a comprehensive
description of the linked catastrophies of windthrow and fire
which occur in Lower Saxony Otto (1976) described
silvicultures for a range of soil types which would minimize
risk. He particular stressed the advantages of wide spacing
and species mixtures.

CONCLUSIONS

The intensification of forest management with a general trend towards higher growth rates and realisation of yield, secure against wind and other hazards, have continuously produced research problems. In some cases the solutions to a number of these problems imply a need to change the silvicultural system. For instance, a suggestion has been made in both the British Isles and New Zealand to increase spacing, shorten the rotation and abandon commercial thinning in conifer plantations. This silvicultural system has been proposed both to minimize risk from windthrow and to shorten the time in which saw timber can be obtained. In implementation it is not a single alternative to high density crops which require thinning; interactions between spacing, quality of planting stock and pre-commercial thinnings must all be considerd (Bunn 1974).

When such radical proposals are made, it is profitable to consider them as a 'new' silviculture and to question other aspects of the cultural technique. Dawson (1975) emphasized that "intensive culture is concerned with a number of culture treatments applied to the same stand, not just one or two practices as generally in 'timber stand improvement'". The large gains made in agricultural productivity have been through the application of not one, but a number of improvements working together. In this respect it is important to appreciate that from the economic viewpoint "the extremes of intense culture are quite expensive and are, in this sense, high risk" (Bentley 1975). This makes it all the more important to define the objectives of a plantation enterprise more closely than 'maximum sustained yield' (Elliott 1977). The opportunities for devising high yield silvicultures are greater when a range of specific objectives can be given rather than one general objective. Not only can the physiologist, breeder and ecologist work towards more closely defined endpoints, but particular advantage can be taken of natural variations which occur both in the biological and the physical resources (Patterson 1975). Attempts to design silvicultures to meet specific management objectives in specific climates and on specific soils would provide a stimulus to the further incorporation of plant physiological and ecological knowledge into the forest industry.

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