A comparison of two yield forecasting methods used in Ireland

Andrew McCullagh[a]*, Michael Hawkins[a], Lance Broad[b] and Maarten Nieuwenhuis[a]

Abstract

A comparison was made between two methods for forecasting the growth and yield of five conifer species growing in even-aged stands in Ireland: the Forestry Commission (FC) Yield Tables and the dynamic yield modelling system Growfor (GF). The goal of the study was to examine and compare the outputs of each system as both are used in forest management planning and decision making in Ireland. A typical regime used in the FC yield tables was adopted and the details of this regime were used as inputs into GF. The cumulative volume was examined under a no-thin scenario and also under a scenario that involved thinning to the marginal thinning intensity (MTI). Using the GF system, volumes were significantly lower than with the FC system, for both the no-thin and the thinning scenarios, for most species. In the no-thin scenario, Norway spruce, lodgepole pine and Douglas fir showed deviations from the FC trend while Sitka spruce and Scots pine showed similar patterns to the FC volumes. Under the thinning scenario, Sitka spruce showed a similar trend to the FC volume while the GF volumes for the other species deviated from the FC ones. The MTI proved too severe and resulted in a loss in the productive capacity of the stands. Cumulative volume production was increased by reducing the thinning intensity.

Keywords: *Growfor, dynamic model, yield table, forecast, growth.*

Introduction

Yield models provide information on the future yields and assortments of stands. This information is necessary in forest management in order to make decisions on the profitability of afforestation, rotation length, thinning operations and harvests. With accurate projections of future outputs, the forester is well placed to make important management decisions to ensure optimal timber volume and value production.

The history of growth and yield modelling in even-aged plantation silviculture in Europe dates back to over 200 years ago. From the late 1700s onward, yield tables were being constructed by several German scientists such as Hartig, von Cotta and Heyer, cited in (Pretzsch et al. 2008). A yield table is a summary of the expected yields tabulated by inventory variables (Skovsgaard and Vanclay 2008). As these tables were based on estimates and limited observational data, they were known as "experience tables". Gaps in knowledge were noticed as a result of these

a UCD Forestry, School of Agriculture and Food Science, University College Dublin.
b Technical Forestry Services, New Zealand.
* Corresponding author: andrew.mccullagh@ucd.ie

and long-term experimental plots were set up, which are still maintained to the present day (Pretzsch et al. 2008).

Theoretical principles and biometric equations began to be developed. Heyer was the first to identify a correlation between height and volume in the middle of the 19th century (Skovsgaard and Vanclay 2008). In 1904, Eichhorn discovered that the standing volume production of European silver fir (*Abies alba* Mill.) is a function of stand height within limits of stand density and thinning treatment. This was confirmed for more species and then extended so that total volume production was also a function of stand height by Ernst Gerhardt in 1921, cited in (Skovsgaard and Vanclay 2008).

The Forestry Commission (FC) yield tables are based on Eichhorn's rule. A "master table" was produced by Hummel and Christie (1953) in which top height was related to the other stand characteristics: stems per ha, mean diameter, basal area and volume per ha. The models are based on yield class, which is defined as the maximum mean annual increment (MMAI) of a stand, and is measured in volume per ha per annum (Johnston and Bradley 1963). Yield class was used as an index of stand productivity but since volume is difficult to measure, top height and age were used and these were then related to volume. Growth curves were produced for each species which allowed the determination of yield class from the height and age of the stand in question. Baur was the first to include height as a site classification in a yield table in 1877, cited in (Skovsgaard and Vanclay 2008).

For the last thirty years, foresters in Ireland have made use of Yield Models for Forest Management (Edwards and Christie 1981). This publication replaced Forest Management Tables (metric) (Hamilton and Christie 1971), which only included normal stocked plots and did not include unthinned models. Both sets of models are based on the same datasets but there is a wider variety of spacing regimes in the 1981 tables. The yield tables were derived from a set of curves which described how pure even-aged stands grow and develop over time for different species. The marginal thinning intensity (MTI) is 70% of the MMAI and it is assumed that this is the maximum amount that can be extracted annually from the stand without causing a loss of volume production (Edwards and Christie 1981). The regimes consist of a variety of initial spacings and thinning treatments. The yield models assist the forester in making decisions on when and how heavily to thin, and when to harvest. These are known as static models as it is necessary for the forester to follow the regime as deviations from the prescribed regime reduce the reliability of the forecasts. This reduces the number of options available to the forester as the management approach must be matched to the model. Notwithstanding this limitation and the fact that the models were developed in Great Britain and are based on British data, they have served Irish forestry well.

Development of a dynamical system to represent forest growth in Ireland was undertaken by Broad and Lynch (2006a). The system is based on the state-space approach as developed by García (1984). With sufficient information on the state of the system it is possible to forecast future states. The state vector and the transition function contain the necessary information required to make a forecast. The growth equation used in the system is the Bertalanffy-Richards equation (1957):

$$\frac{dx^c}{dt} = ax^c + b \qquad (1)$$

where a,b,c are parameters. It is widely used on account of its flexibility and the biological basis on which its parameters rest (Zeide 1993).

In Equation 2, the state vector x consists of the basal area (B), stocking (N) and height (H):

$$\mathbf{x} = (B, N, H)' \qquad (2)$$

where x is a vector. The growth equation is extended to a multivariate version using a power transform in which the state vector is raised to a matrix power:

$$\mathbf{x} \equiv \exp\ (\mathbf{C} \ln \mathbf{x}) \qquad (3)$$

where C denotes a 3×3 matrix. Expanding to a multivariate system:

$$\frac{d\mathbf{x}^{\mathbf{C}}}{\mathrm{dt}} = \mathbf{A}\mathbf{x}^{\mathbf{C}} + \mathbf{b} \qquad (4)$$

where b is a vector, A denotes a 3×3 matrix, allows for a system of differential equations to be used to represent forest growth. There is a sub-model to evaluate the height parameters (García 1983). Top height at a reference age (30 growing seasons since planting) is used as a measure of site productivity (also known as "site index"). Both polymorphic and anamorphic representations are possible but the polymorphic form proved to be a better fitting model in the Irish context (Broad and Lynch 2006a). The thinning function consists of a differential equation for the change in basal area against the change in stocking, which describes the change in the state of the system after a thinning. The form of the volume equation is determined using a stepwise regression. A predictor set is defined in the process and includes the following: H/√N, N.H/B, 1/H, B/H, 100/(B.H), S/B, S.S/B. Using the thinning function with the volume function produces the option to thin by volume as per the yield table approach. The only information necessary to calculate forecasts and assortments is a time slice of stand data: age, stocking, top height and basal area or DBH; importantly, details of previous silvicultural operations are not required as in the FC methodology. This results in added flexibility in that the forester is not constrained by a fixed regime such as in the yield tables. The models are contained in a graphic user-interface in the program "Growfor" (GF) which allows adjustment of thinning times and intervals as well as thinning intensity. As the models were fitted in Ireland and are based on Irish data, the expectation is that they should produce more accurate forecasts.

In an earlier study by Broad and Lynch (2006b) an assessment of the suitability of SS research data for growth modelling was undertaken. Three possible sources of bias were identified including a sampling bias that omited lower site index material, a subjective selection of larger volume sample trees, and experiment blocking which reduced randomisation. The authors argued that the volume sampling bias led to the over-estimation of volume production in plots. The authors believed this bias was present for all species in the Coillte database. Work was undertaken to mitigate this bias using independent data where possible.

The objective of the study is to compare the cumulative volume from both forecasting systems. Typical regimes from the yield tables for each species make up the input to the dynamic system and the outputs from both systems are analysed graphically and using the Mann-Whitney-Wilcoxon test.

Materials and methods

The tree species used in the study are the main timber species in Ireland, including Sitka spruce (*Picea sitchensis* (Bong.) Carr.), Norway spruce (*P. abies* (L.) Karsten), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), Scots pine (*Pinus sylvestris* L.) and lodgepole pine (*P. contorta* Dougl.), hereinafter respectively known as SS, NS, DF, SP and LP. Details of the development of the SS model are available in (Broad and Lynch 2006a); the same approach as used for SS was adopted for each of the species listed above. However, there is one difference in the approaches. After a period of model testing it was discovered that the volumes in the SS model were lacking an asymptote and thus required further attention to fix the upper growth limits. The models were validated using data independent of the development data.

A typical regime from the 1981 FC yield tables was used to compare the outputs from each system. This regime was one defined by the top line of each of the tables. The spacing was 2 by 2 m, a 5-year thinning schedule was adopted and an intermediate thinning was used. For each species the highest yield class (in brackets) was used: NS (22), SP (14), SS (24), LP (14) and DF (24). The regime differed for DF: 1.7 by 1.7 m spacing was used since a 2 by 2 m table was not available while a crown thinning was adopted as vigorous dominant trees with coarse branching (i.e. wolves) are common among DF trees. The rotation length was defined as the age when the mean annual increment reached a maximum. A revised set of yield tables that was developed for LP in 1975 based on data from thinned stands grown in Ireland (Phillips and O'Brien 1975) was also used.

The first line of the yield tables contains information on the age, top height, stocking and basal area, figures that are also the input to GF model. Thinnings are controlled by volume reduction and the management goal is that of maximising volume production. The output in GF follows the format of the yield tables. The data for the study consists of the outputs for the GF and FC models. This allows for direct graphical comparisons.

For each species the following scenarios were examined:

- No-thin treatment.
- MTI was used, which is 70% of the MMAI as per the yield tables.
- The effect on the cumulative volume was examined when reducing the thinning intensity by 7%, 14% and 21% from MTI.

The data were also compared with a nonparametric test, the Mann-Whitney-Wilcoxon test using the Wilcox function in the R stats library, R version 2.13.1 (R Development Core Team 2012). Separate comparisons were made for no-thin and thinned data. The model outputs for the five species constituted the samples to be compared in each case, i.e. $n_1 = n_2 = 5$.

Results

A series of graphs was produced for each species depicting cumulative volume against age for both systems which allowed comparisons of the volumes produced in the two modelling systems (Figures 1 and 2).

No-thin scenarios

For four of the species in the no-thin scenarios, the GF model produced lower cumulative volumes than the FC tables (Table 1, Figure 1). The SS volumes were similar under both models: 1,026 m^3 ha^{-1} under the FC table and 1,014 m^3 ha^{-1} under the GF model. The difference between the FC and GF values for SP was greater than that for SS but smaller than those of the other species (Figure 1). The

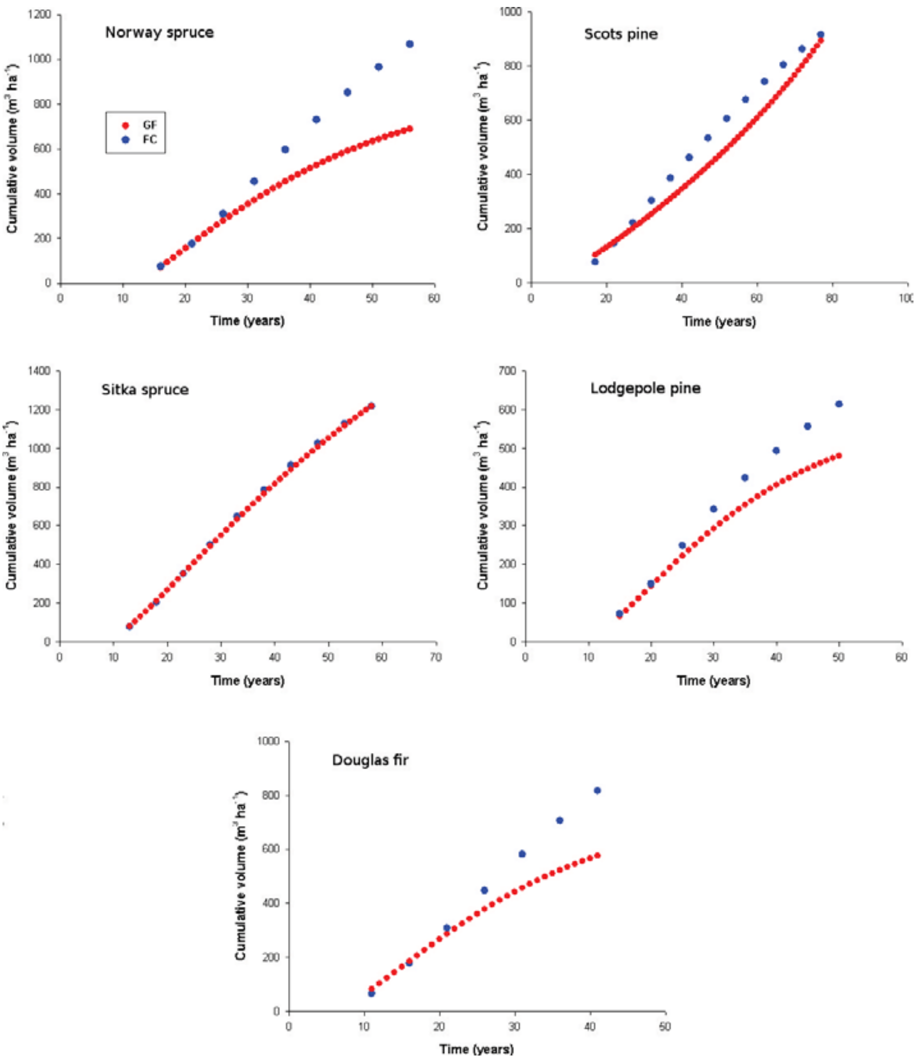

Figure 1: *Graphs of cumulative volume against time of each species under a no-thin scenario. GF = Growfor, FC = Forestry Commission yield tables.*

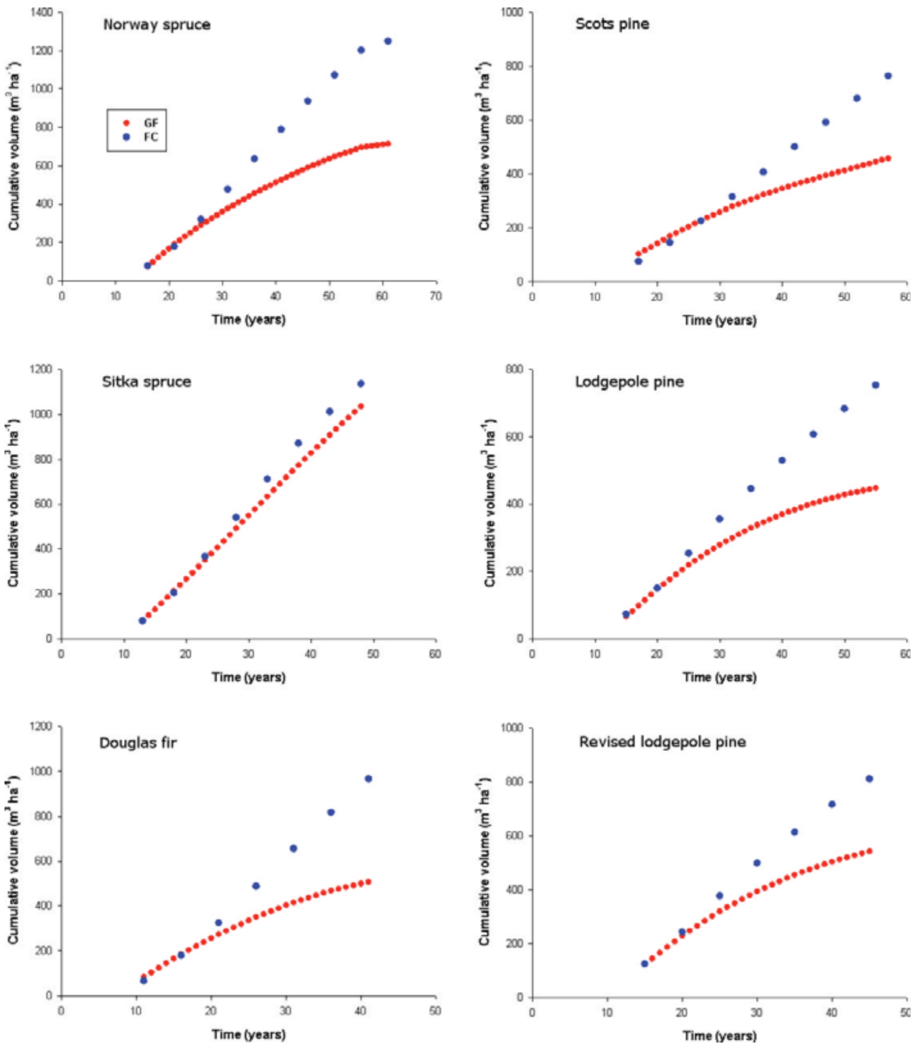

Figure 2: *Graphs of cumulative volume against time of each species under the MTI scenario. GF = Growfor, FC = Forestry Commission yield tables.*

Table 1: *Predictions of cumulative volume (m^3 ha^{-1}) production over the rotation of MMAI of each chosen species by model for the no-thin scenario; FC = Forestry Commission yield tables, GF = Growfor models.*

	Norway spruce	Scots pine	Sitka spruce	Lodgepole pine	Douglas fir
FC	1069	742	1026	613	816
Rotation (yrs)	56	62	48	40	41
GF	690	637	1007	480	576

median latencies in the groups FC and GF were 816 and 637 $m^3 ha^{-1}$ respectively; the distributions in the two groups differed significantly (Mann–Whitney $U = 20$, $n_1 = n_2 = 5$, $P < 0.05$ one-tailed).

Thin scenarios

When thinning to the MTI, the cumulative volume of each of the species was lower in GF than in FC (Table 2, Figure 2). The revised LP table also shared this trend. The volume produced for SS under the FC yield tables was 1,135 $m^3 ha^{-1}$ and 995 $m^3 ha^{-1}$ under GF (Table 2). The other species showed much greater differences. Median latencies in the groups FC and GF were 965 and 506 $m^3 ha^{-1}$ respectively; the distributions in the two groups differed significantly (Mann–Whitney $U = 22$, $n_1 = n_2 = 5$, $P < 0.05$ one-tailed).

The volume that was being extracted when thinning to the MTI was too large since the main crop was becoming depleted and the bulk of the cumulative volume was arising from the thinnings as opposed to the main crop (Figure 3).

Table 2: *Predictions of cumulative volume ($m^3 ha^{-1}$) production over the rotation of MMAI of each chosen species by model and the thinning intensity (FC 70 thinning at MTI (70% of MMAI); GF 70 thinning to MTI; GF 63 thinning to 63% of MMAI; etc.).*

	Norway spruce	Scots pine	Sitka spruce	Lodgepole pine	Revised lodgepole	Douglas fir
FC 70	1,318	840	1,135	752	810[a]	965
Rotation (yrs)	61	62	48	55	45	51
GF 70	714	500	995	447	541	506
GF 63	794	554	1,029	472	555	611
GF56	829	623	1,050	494	566	656
GF 49	854	624	1,064	514	578	681

[a] Value equates to MTI in the revised lodgepole table.

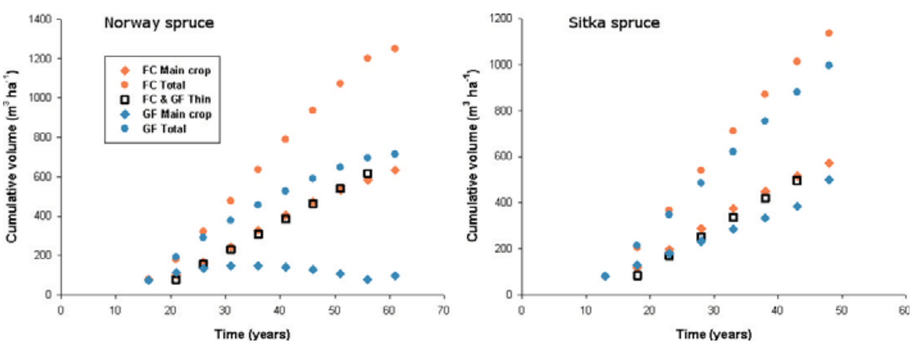

Figure 3: *Graphs of the main crop, the thinning and total volume for Norway spruce and Sitka spruce under both modelling systems FC = Forestry Commission yield tables, GF = Growfor.*

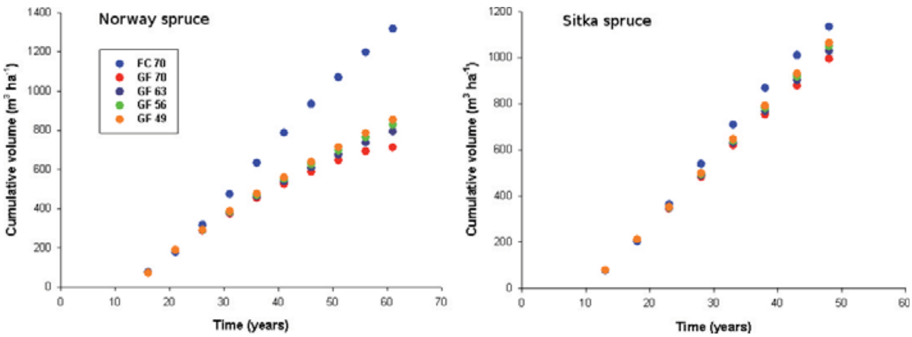

Figure 4: *Graphs of volume against time under varying thinning intensities for Norway spruce and Sitka spruce under both modelling systems. FC 70 thinning at MTI (70% of MMAI); GF 70 thinning to MTI; GF 63 thinning to 63% of MMAI; etc; FC = Forestry Commission yield tables, GF = Growfor.*

Thinning intensity reductions

For each of the species, the cumulative volume production was progressively increased by reducing the thinning intensity by 7%, 14% and 21% of the MMAI. At the greatest reduction, cumulative volume production still remained much lower than using the MTI with the FC models. The trend is shown for NS but a similar pattern was produced for each of the other species with the exception of SS (Figure 4).

Discussion

The volume outputs for each modelling system are different as each system is based on a different approach. GF is based on the state-space approach and makes use of site index whereas FC uses yield class. The functions within each of the forecasting systems are different. In GF the volume and thinning values are evaluated as per the functions described in the Introduction. The FC volume values are derived from the master table and the thinning values are determined using the yield class and the desired thinning intensity once a stand becomes fully stocked. Mortality is treated differently too.

In the FC tables mortality is only considered up to the first thinning. Subsequent mortality is considered recoverable, whereas in GF mortality is recorded as it occurs (Broad and Lynch 2006a). A major factor is that the systems are not based on the same dataset. The climate in Ireland is not identical to that of Britain, but more importantly, the treatments in each country's respective research plots would not have been the same.

The fact that SS deviates from the main trend, that of GF forecasting volumes significantly lower than FC volumes, leads to the question – does SS in Ireland actually grow similarly to that in GB? A study in 1972 showed that the volume in unthinned Irish SS stands was greater than the figures displayed in the yield tables (Hamilton and Christie 1971) and that Irish stands could achieve yield class values greater than 24 $m^3\ ha^{-1}\ yr^{-1}$ (Gallagher 1972). Although the results of that study contradict our findings, it does highlight the fact that SS volumes are close to those in GB thereby explaining some of the deviation of SS from the trend. It is also possible is the greater quantity of older age data available that was available for SS than for the other species might cause this deviation. However theoretical equations such as the Bertalanffy-Richards growth equation are known to extrapolate well outside the range of development data (Vanclay 1994) which would suggest that extra data should not produce such a dramatic effect. An additional limitation associated with the development of the SP GF model was the availability of only a small dataset and caution is required when drawing conclusions based on its use.

Purser et al. (2004) discussed the possible impacts that climate change may have on Irish forestry. Rising CO_2 levels could stimulate forest growth, while increasing temperatures have the effect of speeding up chemical and biological processes in plants and could cause an increase in primary production. However, extreme events such as summer drought may reduce growth rates of common species (Broadmeadow and Ray 2005). Dynamic models are based on repeated measures of stand level data with the goal to forecast production values. Unlike ecosystem process-based models, there is no facility to model the effect of climate change. Re-parameterisation based on new data which is assumed to incorporate the effects of a changing environment under climate change is a feasible but impractical approach. Indeed the data used to produce the dynamic models includes the impact of climate change over the measurement periods. García et al. (2011) depicted a framework in which the state-space approach may be extended to simulate biomass, carbon and nutrient cycling in order to model the effects of climate change.

The FC tables extract thinning volumes which, when adopted in GF, generally resulted in too much volume being removed in the thinnings. The main crop that remains is not producing the maximum or even a sustainable, volume increment and damaging the stand's productivity potential. It is possible that the MTI is too high or that there are significant incompatibilities when thinning to the MTI under the GF system. Indeed, the views expressed by practitioners attending a recent COFORD seminar (COFORD 2011) support the view that there is awareness among Irish foresters that the FC thinning models overestimate the main crop volume increment. For this reason, several foresters indicated that, even though they use the FC models, they do not thin to MTI, especially at younger stand ages. Reducing the thinning intensity demonstrated that the cumulative volume production under GF could be increased and that more appropriate results are obtained when a lower intensity is adopted.

The main crop that remains after thinning to the MTI was small as the bulk of the cumulative volume was in the thinnings. There may be situations where this is planned, but usually this is not the management objective. The most valuable stems would be the largest ones that live for a full rotation, so it would be in the forester's interest to maximise the volume of the final harvest. In reality, most forests are managed in order to yield the greatest profit or rate of return and the development of a user-defined assortment component for GF, which is currently under way, will allow the user to analyse the financial return of different thinning and rotation choices. An optimisation routine, which determines the financial optimal thinning and rotation parameters, given user-specified assortments and timber prices, can then be developed using dynamic programming or network methodologies (Nieuwenhuis 1989). Currently, data included for model development has mainly included stands which have had low thinnings. However, should data from stands which have had crown thinnings become available, then specifying the material to be removed in a thinning would become a possibility. This feature would be of particular interest to foresters looking into alternative silvicultural practices.

The dynamic model GF is based on the site index system. Site index is the top height a stand is expected to have once it reaches the base age. It is used as an indication of site productivity; a higher site index indicates a more productive site. Unlike the use of yield class in the yield tables, site index is generally independent of management and is therefore a more general and robust site productivity indicator and is used worldwide. As these site index models are not based on the yield class system, it is to be expected that the concept of MTI does not really apply and a different method of defining the thinning intensity is required.

Recommendation

The results of this study support the view that Irish foresters should move away from the use of static yield tables. The lack of options available when adopting a prescription restricts the forester and prevents any investigation into alternative silvicultural practices. Since deviating from a prescribed regime reduces the reliability of the projections and, taking the differences highlighted above into consideration, it is recommended that the dynamic approach is adopted. GF has been developed using Irish stands and thus projections should be more accurate and relevant to the Irish forester. Moreover, the wide range of options with regard to thinning times and intensity provides a flexibility that is not available with the static approach.

Acknowledgments

This paper is based upon a presentation given at the COFORD Seminar "Forest growth assessment and modelling in Ireland" on December 15th 2011. The authors would like to thank the participants for their useful comments.

This research was funded by COFORD, a division of the Department of Agriculture, Food and the Marine.

References

Broad, L. and Lynch, T. 2006a. Growth models for Sitka spruce in Ireland. *Irish Forestry* 63: 53–79.

Broad, L. and Lynch, T. 2006b. Panel data validation using cross-sectional methods. *Irish Forestry* 63: 80–95.

Broadmeadow, M.S.J. and Ray, D. 2005. *Climate Change and British Woodland*. For. Comm. Information Note 69: 1–16.

COFORD. 2011. *Forest Growth Assessment and Modelling in Ireland* http://www.coford.ie/eventspresentations/2011events/acofordseminar-forestgrowthassessmentandmodellinginireland/ [Accessed June 2013].

Edwards, P.M. and Christie, J.N. 1981. *Yield Models for Forest Management*. Forestry Commission Booklet 48.

Gallagher, G. 1972. Some patterns of crop structure and productivity for unthinned sitka spruce. *Irish Forestry* 29: 33–52.

García, O. 1983. A Stochastic Differential Equation model for the Height growth of forest stands. *Biometrics* 39: 1059–1072.

García, O. 1984. New class of growth models for even-aged stands – Pinus radiata in Golden Downs forest. *New Zealand Journal of Forestry Science* 14: 65–88.

García, O., Burkhart, H.E. and Amateis, R.L. 2011. A biologically-consistent stand growth model for loblolly pine in the Piedmont physiographic region, USA. *Forest Ecology and Management* 262: 2035–2041.

Hamilton, G.J. and Christie, J.N. 1971. *Forest Management Tables* (Metric). Forestry Commission Booklet 34.

Hummel, F. and Christie, J. 1953. *Revised Yield Table for Conifers in Great Britain*. Forestry Commission Forest Record 24.

Johnston, D. and Bradley, R. 1963. *Forest Management Tables*. Commonwealth Forestry Review 42: 217–227.

Nieuwenhuis, M. 1989. Operations research in forestry. *Irish Forestry* 46: 51–58.

Phillips, H. and O'Brien, D. 1975. *Revised Yield Tables for Coastal Lodgepole Pine*. Forest and Wildlife Service, Ireland. Research Communication 16.

Pretzsch, H., Grote, R., Reineking, B., Roetzer, T. and Seifert, S. 2008. Models for forest ecosystem management: A European perspective. *Annals of Botany* 101: 1065–1087.

Purser, P.M., Byrne, K.A., Farrell, E.P. and Sweeney, J. 2004. The potential impact of climate change on Irish forestry. *Irish Forestry* 61: 16–34.

R Development Core Team. 2012. *A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing. Vienna, Austria.

Skovsgaard, J.P. and Vanclay, J.K. 2008. Forest site productivity: a review of the evolution of dendrometric concepts for even-aged stands. *Forestry* 81:13–31.

Vanclay, J.K. 1994. *Modelling Forest Growth and Yield*. Wallingford, UK: CAB International.

von Bertalanffy, L. 1957. Quantitative laws in metabolism and growth. *The Quarterly Review of Biology* 32: 217–231.

Zeide, B. 1993. Analysis of growth equations. *Forest Science* 39: 594–616.