Review of tools for growth forecasting and productivity assessment in forestry in Ireland

Andrew McCullagh[a*] and Maarten Nieuwenhuis[a]

Abstract

A review is undertaken of the forecasting and productivity assessment tools used and approaches adopted in Irish forestry from the latter half of the last century up until today. Descriptions are provided for the methods and the technological or mathematical endeavours utilised alongside the necessities that led to their inception. Forecasting in Ireland has relied heavily on the Forestry Commission yield tables, though a variety of methods have been developed in order to better represent the growing conditions of Irish forests. The challenges of sustainable forest management has led to reappraisals of alternative silvicultural systems, development of which have been hampered by the difficulty in obtaining good quality data.

Keywords: *Forecasting, growth, yield, productivity, model.*

Introduction

Foresters use a variety of tools to efficiently and sustainably utilise the land and maximise yield and profit. Dramatic changes have been witnessed during the previous century – political upheaval that influenced forest policy in Ireland and technological developments which changed the tools used in forest management. The advent of computers and the increased use of mathematics have been beneficial to growth and yield forecasting. Since intensive forest management became the norm, there has been a need for accurate information on forest development. Policy shifts towards sustainable forest management, delivery of ecosystem services and carbon reporting, mean further model improvements and developments are required to improve the accuracy of forecasts and to widen the range of forest parameters included in these forecasts. The range of tools produced and adopted in Ireland for use in forest management planning and decision making are reviewed in this paper, focusing primarily on developments since the middle of the last century.

Forecasting

Efficient forest management requires estimates of stand development and productivity. These forecasts enable the manager to plan operations and arrange timber sales. The Forestry Commission (FC) Yield Tables have proven reliable for forecasting Irish stands since the first table was produced in 1953 (Hummel and Christie 1953). The yield tables are a comprehensive set of tables that allow growth projections from which a management prescription may be adopted. Used mainly for even-aged stands,

[a] School of Agriculture and Food Science, University College Dublin, Dublin 4.
[*] Corresponding author: andrew.mccullagh@ucd.ie

the FC tables are based on the yield class system. Yield class is the maximum mean annual increment of a stand and is utilised to classify stand productivity. Since the volume of a stand of trees is difficult to measure, use is made of Eichhorn's rule, which states that the volume production at a given stand height should be identical for all site types (Skovsgaard and Vanclay 2008). Top height - age curves are then produced and from these a master table is constructed that relates the top height to characteristic stand variables. From this table, the yield models for different yield classes, stocking densities and thinning regimes are derived, forecasts from which are possible while height growth remains vigorous. A comprehensive description of the FC Yield Tables was produced by Joyce (1982), outlining the stages of development from the initial beginnings of yield tables in Europe, to the tables of Edwards and Christie (1981), which are still in use today. These tables were developed using permanent sample plot data. It is accepted that their flexibility is limited since deviation from a prescribed regime reduces forecasting power. Nonetheless, yield tables have been in use throughout Europe since the 1700s, remain in use and are applicable to multitudinous prescriptions in Ireland and the UK. Outside of even-aged stands, the relationships upon which the tables are based no longer hold true (Pretzsch 2009).

The master table mentioned above was revised to account for the metric system and adopted orthogonal polynomial equations to characterise each species' growth (Christie 1972). It has been noted that the tabulation of the equations could be replaced by the use of differential equations for growth projection resulting in the removal of the static element (Broad and Lynch 2006). The PractiSFM decision support system for sustainable forest management has incorporated these equations into its system and uses them to make annual forecasts (Barrett 2009, Barrett et al. 2007).

The yield tables span a range of yield classes that vary for each species. The yield table for thinned and unthinned Sitka spruce (*Picea sitchensis* (Bong.) Carr.) may be applied to stands of YC 6 up to YC 24. However, yield classes in excess of this are not uncommon in Ireland for Sitka spruce (Joyce and OCarroll 2002, McCullagh et al. 2013). Variations in growth and yield between Irish and UK conditions motivated the production of tables developed with Irish data. In 1966, a set of tables based on 101 fully stocked, temporary sample plots for lodgepole pine (*Pinus contorta* Dougl.) was developed, using a regression of the main stand volume on top height, as described in Gallagher et al. (1987). These yield tables highlighted the differences in form between coastal and inland provenances grown in Ireland; the FC tables were based solely on inland provenances. Also highlighted was the observation that higher yield classes were being obtained by the coastal provenance, given similar height and age data (Gallagher et al. 1987). The above issues, along with the adoption of SI units, motivated the production of a revised set of thinned lodgepole pine tables by Phillips and O'Brien (1975).

In Northern Ireland, an unthinned Sitka spruce yield model was produced by Kilpatrick (1978) developing a basal area increment function which was used to produce the yield table. The author highlighted the benefit of non-reliance on a single variable but rather on two (basal area and height), thereby reducing the effect of measurement error. Omiyale and Joyce (1982) produced a yield table for unthinned Sitka spruce. The Bertalanffy-Richards function was used since it is based on the biological concept that the growth of an organism is the net result of the creation and breakdown of cells (von Bertalanffy 1957). Eichhorn's rule was applied and the positive relationship between top height and site productivity was exploited. Volume assortment tables were produced using data from stands of Sitka spruce growing in Irish conditions (Jordan 1992). Using a regression analysis, a master table of volumes and volume assortments was produced for single trees and stands. Results indicate that FC assortment tables were underestimating volumes. These studies have been borne out of the uncertainty of the applicability of the FC Yield Tables to Sitka spruce stands in Ireland.

Increased use of mathematical equations and, later computers, had assisted these developments and by 1995, intensive model development had begun using a new approach to forecasting: dynamic models. This approach allowed greater flexibility since the initial condition or growth history of the stand was not required for forecasts. The system was devised by Garcia (1984) and developed for Irish conditions by Lance Broad and Ted Lynch (2006).

This approach is known as the state-space approach and has been in use in Ireland since 2005. The Irish dynamic models are available in the software program Growfor. Forecasts are possible for stands with varied thinning schedules and those in which the management approach is altered or adjusted. Moreover, the models are relevant to Irish stands as they are based on Irish data and are widely applicable as they adopt stochastic processes to evaluate model parameters. Theoretically-based equations may provide safe extrapolations outside the range of the developmental data; the growth equation upon which Growfor is based, Bertalanffy-Richards, is one such equation (Vanclay 1994). Development on the Growfor system has continued with the addition of models for ash (*Fraxinus excelsior* L.) and Japanese larch (*Larix kaempfaeri* (Lamb.) Carrière) (McCullagh 2013). User-defined assortments have also been added, increasing the flexibility and practicality of the system.

The state space approach models mark a move away from yield class and instead adopt site index: the top height a stand is expected to attain at a base age, 30 years in Ireland. Though used internationally, base ages may vary from country to country depending on rotation. Top height is defined as the mean height of a fixed number of trees per unit area, the number of trees and the unit area adopted is also country specific, in Ireland it is 100 trees per hectare. The use of yield class in the yield tables assumes that thinnings are conducted on a schedule, whereas the state space model based on site index makes forecasts from any point during the rotation of a stand independently of the management or thinning schedules. Site productivity enters the dynamic model via the top height equation, the end result being a modification of the time scale. Also adopted were plot specific parameters which result in polymorphic curves. The alternative, being the less flexible anamorphic or guide curves which use global parameters across plots, can also be used, but previous studies indicate polymorphic curves provide a better fit for Irish conditions (Broad and Lynch 2006).

Research was conducted into another nonlinear methodology for growth and yield forecasting in which parameters were estimated using partial differential equations (Fekedulegn 1996). Partial derivatives are expected to produce more efficient and precise results. The study analysed the partial derivatives of biologically realistic functions which are known to produce sigmoid curves. Sigmoid curves are used to describe the general pattern of forest growth: accelerated growth in adolescence, declining with age after what is termed an inflection point in the curve. This study found the Gompertz and logistic functions to be most efficient when quantifying stand growth parameters.

A top height model was produced for Sitka spruce using nonlinear quantile regression (Lekwadi et al. 2012). Quantiles were used as surrogates to classify the spruce data into polymorphic site classes and. The Chapman-Richards growth function was fitted to the quantiles using nonlinear regression. The nonlinear quantile regression approach was compared to anamorphic curves and proved better and more robust than them.

The models described so far are stand level models which implies input and output variables and forecasts are made at the stand level. In 2007, development of the single tree model Carbware began, in which data is processed at the individual tree level. One of the main benefits of this approach is its applicability to stands in which age is indeterminate, i.e., uneven-aged or mixed stands. As each tree is to be measured, data costs are higher and computing time can be significantly greater than that of stand model approaches. Systems of equations model the behaviour of the tree in relation to the environmental conditions and stand dynamics during a growth period are evaluated tree by tree (Pretzsch 2009). Stand level variables are obtained by aggregating the individual tree measurements. Porté and Bartelink (2002) concluded that these are the best models for mixed species stands, while Peng (2000) claimed they are best for uneven-aged stands. These models allow for great flexibility in relation to species combinations and stand structures, management regimes and regeneration methods (Pretzsch 2009). Competition is modelled through competition indices which are classified by the utility or not of a tree's spatial coordinates. A single tree model is distance dependent if the locations of the subject tree and its neighbours are utilised. Single tree growth models have been in development for at least five decades (Liu and Ashton 1995). The area of influence is a widely used competition index; defined as a circular horizontal projection around a tree in which the tree competes for resources. Should the area of influence of one tree overlap with that of another tree, it is assumed that the trees are in competition, the amount of which depends on the area of overlap. Ek and Monserud (1974) developed an individual tree, distance dependent growth simulator called FOREST. As well as using the approach above, the authors used the potential modifier approach in which the maximum growth of a tree is assumed to be reducible by competition. An open grown tree is an example of a tree that is assumed to be growing to its maximum potential.

Carbware is a single tree growth model that simulates carbon dynamics in the forest and between forests and the atmosphere, developed by Black et al. (2012). Carbware is a distance independent model and competition indices used include the basal area of trees larger than the subject tree, the crown ratio and the crown competition factor. It is based on National Forest Inventory data (NFI 2007) and is used in carbon reporting under the terms of the Kyoto Protocol. It simulates the diameter increment of individual trees for species cohorts and is capable of making forecasts for single species even-aged stands, as well as mixed and uneven-aged stands by aggregating data for single trees.

Site productivity

Traditionally site classification had been focused on matching the most appropriate tree species to a site. Cajander (1926) devised vegetation site types in which climax vegetation is classified into habitat or site types. In Ireland, there has been considerable research conducted on the topic of site classification since correct matching of the species to the site is intended to ensure the landowner obtains the highest possible level of productivity. O'Carroll (1993) examined the yield prediction of conifers on peat, identifying physical site factors that influence production. Farrelly (2009) examined the expanded role played by site classification in recent years, specifically, multifactor classifications and the wider concerns related to sustainable forest management, carbon sequestration and environmental issues (Farrelly et al. 2011a, Farrelly et al. 2011b, Farrelly et al. 2011c).

The decision support system Climadapt is a web based application that can differentiate the effect of climate variables, allowing future projections of climate change scenarios under which analysis of species suitability to site may be undertaken (Ray et al. 2009). Climadapt is based on the multifactor system from the UK, the Ecological Site Classification developed by Ray (2001), which is a knowledge-based system that combines observations, experimental results and professional expertise of FC scientists. The system was scaled and calibrated for Irish conditions under the CLIMADAPT project.

Current challenges

Model performance is evaluated by the accuracy and precision of its forecasts (Soares et al. 1995). Hence, good quality data are a prerequisite to model development. The NFI is an important data source, recording changes in the national forest estate between the years 2006 and 2012. It is expected that successive rounds of measurements will take place, on a five year cycle, into the future and add to this resource. Use of the NFI for growth modelling purposes is challenging due to its concentric sampling design. Trees are measured and counted based on different minimum diameter thresholds in each circle. Ingrowth is the term used to describe trees that are not recorded in the first cycle but are recorded in the second cycle as their diameter has then reached the minimum diameter threshold for that circle. These trees confound growth increment values required in growth modelling. Another issue is that measurements for top height are not taken in the NFI. Methods to estimate top height are available, but their performance has not yet been evaluated.

The Natforex database (www.natforex.ie) is an alternative data source which comprises 140 historic experiments and trials dating back to 1957. This data source has the potential to be used for model development, analysis and validation. A limitation of these data is that for uneven-aged or mixed species models, coordinates of the measured trees and crown measures are often required for completion indices and these were not typically collected as part of these experiments.

Current research

Current modelling endeavours include research into determining if the dynamic modelling approach Growfor can be used for mixed species stands. One approach being investigated is a doubling up of the three variable single species method, using three variables per species for a two species stand. The argument is that one may use as many variables as necessary to fully represent the state of the system, though this creates a further challenge in that one may potentially have too many parameters and not enough data with which to undertake parameter estimation. Competition is not defined in the state space approach, though its effect will be contained in the growth trajectories of the two species and, therefore, its simulation is deemed unnecessary.

The use of NFI data to evaluate the Carbware and Growfor models and identify any potential refinements is also being investigated. The NFI can provide an indication of the performance of both models against the national forest estate. Carbware was developed using Coillte permanent sample plot (PSP) data while Growfor used a combination of PSP and temporary sample plot data. For Carbware, site factors are to be included in the diameter increment function and the stem profile models recently developed in the Treemodel project will be used to evaluate the assortment functions. This research will also give an indication of model suitability for the forecast of tree and stand development under alternative silvicultural systems.

Conclusions

Industry has adopted the current models as they have met their objectives. However, their applicability to mixtures and alternative silvicultural systems remains to be determined. The Irish dynamic models were born out of necessity and the need for relevance and accuracy in relation to timber production. Site classification now encompasses the wider environment, as opposed to just matching the species to the site and, similarly, alternative modelling systems will be produced when they are most required by users or when policy changes. Until then, the current approach of adapting existing models is appropriate. Moreover, alternative modelling systems require good quality data, comprising requisite variables in consecutive measurement cycles and the establishment and maintenance of new experiments to collect such data (e.g. the establishment and measurement of permanent sample plots to provide data to construct and or calibrate empirical or process-based models) require a constant supply of funds.

References

Barrett, F. 2009. The PractiSFM multi-resource inventory protocol and Decision Support System. A model to address the private forest resource information gap in Ireland. *Irish Forestry* 66: 5-21.

Barrett, F., Somers, M. and Nieuwenhuis, M. 2007. PractiSFM - an operational multi-resource inventory protocol for sustainable forest management. In *Sustainable Forestry: from Monitoring and Modelling to Knowledge Management and Policy Science*. Eds. Reynolds, K, Thomson, A., Shannon, M., Kohl, M., Ray, D., Rennolls K., CABI. pp.224-237.

Black, K., Hendrick, E., Gallagher, G. and Farrington, P. 2012. Establishment of a national projected reference level for forest management for the period 2013 - 2020 under Article 3.4 of the Kyoto Protocol. *Irish Forestry* 69: 7-32.

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

Cajander, A.K. 1926. The theory of forest types. *Acta Forestalia Fennica* 29: 108.

Christie, J.M. 1972. The characterisation of the relationships between basic crop parameters in yield table construction. Presented at the *3rd Conference Advisory Group of Forest Statisticians*, 7-11 September 1970, Jouy-en-Josas, France.

Edwards, P.M. and Christie, J.M. 1981. Yield models for forest management. *Forestry Commission Booklet* 48.

Ek, A.R. and Monserud, R.A. 1974. Trials with program FOREST: growth and reproduction simulation for mixed species even- or uneven-aged forest stands. In *Growth Models for Tree and Stand Simulation*, Ed. Fries, J., Stockholm, Royal College of Forestry. pp.56-69.

Farrelly, N. 2009. The use of site factors and site classification methods for the assessment of site quality and forest productivity in Ireland. *Irish Forestry* 66: 21-38.

Farrelly, N., Ní Dhubháin, Á. and Nieuwenhuis, M. 2011a. Modelling and mapping the potential productivity of Sitka spruce from site factors in Ireland. *Irish Forestry* 68: 23-40.

Farrelly, N., Ní Dhubháin, Á. and Nieuwenhuis, M. 2011b. Site index of Sitka spruce *(Picea sitchensis)* in relation to different measures of site quality in Ireland. *Canadian Journal of Forest Research* 41: 265-278.

Farrelly, N., Ní Dhubháin, Á. and Nieuwenhuis, M. 2011c. Sitka spruce site index in response to varying soils moisture and nutrients in three different climate regions in Ireland. *Forest Ecology and Management* 262: 2199-2206.

Fekedulegn, D. 1996. *Theoretical Nonlinear Mathematical Models in Forest Growth and Yield Modelling*. MSc (Forestry) Thesis. National University of Ireland.

Gallagher, G.J., Lynch, T.J. and Fitzsimons, B. 1987. Lodgepole pine in the Republic of Ireland II. Yield and management of coastal lodgepole pine. *Forest Ecology and Management* 22: 185-203.

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.

Hummel, F. and Christie, J.M. 1953. Revised yield table for conifers in Great Britain. *Forestry Commission Forest Record* 24.

Jordan, P. 1992. *Production of Provisional Volume Assortment Tables for Sitka spruce (Picea sitchensis (Bong.) Carr.)*. PhD (Department of Crop Science, Horticulture and Forestry) Thesis. University College Dublin.

Joyce, P. 1982. Development of yield tables. *Irish Forestry* 39: 65-74.

Joyce, P. and OCarroll, N. 2002. *Sitka spruce in Ireland*. Dublin. COFORD, National Council for Forest Research and Development.

Kilpatrick, D.J. 1978. Growth models for unthinned stands of Sitka spruce in Northern Ireland. *Forestry* 51: 47-56.

Lekwadi, S., Nemesova, A., Lynch, T., Phillips, H., Hunter, A. and MacSiurtain, M. 2012. Site classification and growth models for Sitka spruce plantations in Ireland. *Forest Ecology and Management* 283: 56-65.

Liu, J. and Ashton, P. 1995. Individual-based simulation models for forest succession and management. *Forest Ecology and Management* 73: 157-175.

McCullagh, A. 2013. *Development of dynamic yield models for conifers, broadleaves and mixtures in Ireland*. PhD (Forestry) Thesis. University College Dublin.

McCullagh, A., Hawkins, M., Broad, L. and Nieuwenhuis, M. 2013. A comparison of two yield forecasting methods in Ireland. *Irish Forestry* 70: 7-17.

NFI. 2007. *The National Forest Inventory - Republic of Ireland*. Forest Service, Dublin, Ireland.

O'Carroll, C. 1993. *Yield prediction and nutrional requirements of conifers on milled cutaway peatland*. PhD (Forestry) Thesis. University College Dublin.

Omiyale, O. and Joyce, P. 1982. A yield model for unthinned Sitka spruce plantations in Ireland. *Irish Forestry* 39: 75-93.

Peng, C. 2000. Growth and yield models for uneven-aged stands: past, present and future. *Forest Ecology and Management* 132: 259-279.

Phillips, H. and O'Brien, D. 1975. Revised yield tables for coastal lodgepole pine. *Forest and Wildlife Service, Ireland. Research Communication* 16.

Porté, A. and Bartelink, H.H. 2002. Modelling mixed forest growth: a review of models for forest management. *Ecological Modelling* 150: 141-188.

Pretzsch, H. 2009. *Forest Dynamics, Growth and Yield From Measurement to Model*. Berlin, Heidelberg. Springer-Verlag Berlin Heidelberg.

Ray, D. 2001. Ecological Site Classification Decision Support System V1.7 Edinburgh. Forestry Commission.

Ray, D., Xenakis, G., Tene, A. and Black, K. 2009. Developing a site classification system to assess the impact of climate change on species selection in Ireland. *Irish Forestry* 66: 101-122.

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.

Soares, P., Tomé, M., Skovsgaard, J.P. and Vanclay, J.K. 1995. Evaluating a growth model for forest management using continuous forest inventory data. *Forest Ecology and Management* 71: 251-265.

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.