Top-down growth modelling: a prototype for poplar plantations in Italy

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Abstract

Hybrid poplar plantations are one of the most important sources of timber and wood fibres in Italy and represent a significant alternative as sustainable use of agricultural land. Effective management of such plantations requires adequate growth and yield models. In light of this, the paper presents the fundamentals of a top-down growth and yield model for hybrid poplar (I-214 clone) plantations in Italy. In the top-down approach, standing volume, basal area, or other characteristics are the primary quantities predicted and these quantities are disaggregated into size class, and, eventually, into individual tree information. The basic element of the proposed prototype is the stand basal area growth equation. Stand age, current stand basal area, and site index are considered as predictors. If the current DBH distribution is also known, a second function estimates the size-class distribution of overall stand growth, projecting the DBH distribution to the end of the considered growth period. Individual competition indices do not contribute to the explanation of the growth variation at the tree level. Prototype predictions prove to be quite accurate: they are based on readily available forest inventory data, thus extracting knowledge from the wealth of accumulated long-term observations usually carried out in forestry. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Short rotation tree cropping, like hybrid poplar clone plantations, is an important source of valuable wood assortments and fibres. Furthermore, this kind of land-use represents a sound opportunity as sustainable use of agricultural land. Adequate growth and yield models are required for effective management of these plantations. Yield tables currently available in Italy

provide only stand-level values estimating few pre-defined wood assortments.

Forestry growth-and-yield modelling is usually management-based and management-oriented, aiming to extrapolate useful predictions for management purposes on the basis of a limited set of field observations. A wide variety of growth and yield models have been developed (see Corona, 1996). The most common approach is that of pragmatic prediction using empirical models like regression equations. This is achieved mainly through field measurement of relevant variables such as height, stocking, stem volume, and increments fitted using more or less elaborate regression

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models evidencing the essential characteristics of the field data set. Empirical model building refers to a mindset that lends itself to constructing practical models useful in describing and coping with real-world situations (Thompson, 1989). However, as with plot data, empirical models provide only a description of the given set of data. They are widely applied as means to produce required operational results as quickly as possible (Zeide, 1999).

On the contrary, the so-called process modelling is considered a more scientifically defensible, meaningful, and robust approach towards which forest modellers should be oriented (Mohren and Burkhardt, 1994). This follows the more or less implicit axiom that each process considered, if effectively understood, can be described recomposing its constituent sub-processes. Indeed, existing process-based models produce growth and yield estimates by summing up the outcomes of particular physiological processes in various tree compartments (branches, roots, etc.). However, models based on such a bottom-up mindset have found little use for long-term observations of commonly inventoried forest attributes like tree DBH or height (Goulding, 1994; Corona and Scotti, 1998). Furthermore, these models usually require sophisticated and rarely available information (so that many input values have to be 'estimated'), and when occasionally such information is measured, the errors are likely large. Zeide (1999) stresses also that such models may even be seen as inherently/basicly incomplete, because the actual number of physiological processes is too large to model and some of them are still unknown.

Deficiencies of physiological models do not mean that we should revert to empirical data-based models. In situations where predictions are required for a very broad range of management decisions, it would be desirable to have a system of growth and yield models capable of providing logical and consistent estimates for varying degrees of detail (whole stand, size class, individual tree, tree component, etc.), thus allowing users to efficiently compute estimates with a level of detail appropriate to the intended use of the information (Burkhardt, 1999). On the other hand, after many decades of research in the field of forest growth-and-yield modelling, only limited advantage has been achieved integrating studies on different scales, despite the considerable on-going effort to merge process

and empirical models (Corona and Scotti, 1998). In fact, as Zeide (1999) highlights the choice may be framed not so much as between empirical and process models, but rather as between bottom-up and top-down process models.

A top-down modelling approach is here discussed within the experimental framework of the development of a growth model prototype for commercial hybrid poplar plantations in Italy. In this country, such plantations are one of the most important sources of timber and wood fibres (3 million cubic meters harvested per year). They are managed mainly to produce plywood by short rotations (9–12 years) with planting densities between 300 and 400 stems per hectare and no thinning (Corona et al., 1992).

2. The top-down approach

The top-down approach starts where bottom-up models end: with the aggregated measured outcome (tree size/number). Landsberg (1986) discussed the top-down approach to growth modeling at length, considering it as a temporary stopgap for physiological bottom-up models: as he acknowledged at the end of his book, his discussion was purely hypothetical, since there were no models based on the top-down approach at that time.

As proposed by Zeide (1999), the processes leading to the generation of the measured yield form a multilayered hierarchy that is first described on the most general level and successively, whenever possible, efforts are devoted to get down to more specific processes. Such a disaggregation approach has the advantage that timber/wood masses at all levels are conditioned to the whole stand value which is mathematically/statistically more tractable than size class or individual tree masses. On the other hand, it may cause the disadvantage that management treatment effects may not be readily incorporated at the whole stand level (Burkhardt, 1999). However, this seems to be a minor problem in the case of the commercial poplar plantations in Italy, where management usually neither includes thinning, nor does self-thinning take place during the rotation.

Based on this framework, the present study was targeted to the elaboration of a prototype approach for poplar plantation growth modelling. Basic objects of

the top-down prototype are easily measurable variables such as stem DBH and number of trees per unit area. These variables are the outcome of many and often conflicting ecobiological forces and can serve as a proxy for each of them (Zeide, 1999). The top-down model prototype describes these processes by difference equations.

The prototype presented in this paper is based on basal area growth modelling. Three successive steps implement the top-down procedure in this case.

1. Stand-level basal area growth (ΔG) is modelled as an aggregated value identifying the main biological factors.
2. Distribution of basal area growth among DBH-classes is modelled as second step $\Delta g(\text{DBH}) = f(\text{DBH}, \Delta G, \text{var}_1, \text{var}_2, \dots, \text{var}_n)$.
3. Growth differences within each DBH-class are examined in relation with the competitive status of individual trees.

For each step, specific methodological aspects depend on the results of the preceding analysis. Hence, following materials paragraph, methods and results are presented step by step.

3. Materials

The study was carried out on four permanent experimental plots set up within hybrid poplar (*Populus x euroamericana*) plantations established in 1981 in central Italy (43°34'N, 11°22'E). The plantations were constituted by the I-214 clone, the most widespread in Italy, and widely used also in many countries all over the world (France, China, etc.). Marziliano (1998) describes environmental and management features of the examined plantations. Conventional site preparation was carried out, planting density was 400

stems per hectare, spaced on a 5 m × 5 m grid; no thinning was applied; the trees were moderately pruned twice according to a conventional schedule. The four plots represent different site-index conditions. Experimental plots area measures 0.18 ha each. Measurements started 5 years after planting and were repeated every 3 years until the age of 14. A last measurement was carried out at age 16 (1997). Statistics of the main dendrometric variables recorded in each plot are reported in Table 1. Considering increments as dependent variable, correlation among observations along the time line is greatly reduced. Averaging increments over a 3 years period greatly attenuated the year effect.

4. Stand-level basal area growth function

The function estimating yearly increment of stand-level basal area was developed based on a well known model (Assmann, 1970):

$$\Delta G_t = f(\text{SI}, A_t, G_t)$$

where SI is the site index, A_t stand age, G_t stand basal area at age A_t , ΔG_t stand basal area increment between age A_t and age A_{t+1} .

Detailed definition of equation structure should reflect biological characteristics of the growth phenomenon modelled, yet preserve sufficient fitting flexibility. Two difference forms distilled from existing growth equations represent both expansion and restraining biological trends subtended to tree growth. As age and tree size increase, the expansion module brings the increment up, while the decline module pushes it down. The expansion module accounts for aspects of the biotic potential like photosynthetic activity, absorption of nutrients, constructive metabolism and anabolism. As evidenced by Zeide

Table 1
Statistics of the main dendrometric variables recorded in the experimental plots^a

Variable	Mean	Minimum	Maximum	S.D.
Site index (m)	21.4	18.5	24.1	2.3
Stand basal area (m ² per ha)	22.12	17.31	28.22	4.54
Stand basal area increment (m ² per ha per year)	1.04	0.80	1.32	0.21
Average tree basal area increment (cm ² per year)	0.0030	0.0007	0.0070	0.0011

^a Values referred to the last measurement year (1997).

(1993), in all major equations except Weibull's, the expansion module presents increment as a power function of size. The decline module is driven by age and changes in the same direction as does the corresponding restraining processes. This module, therefore, encapsulates growth restraints. The decline module has two forms: exponential and power. This may be explained by a greater number of factors that hinder growth: scarcity of resources, competition, reproduction, ageing, diseases, herbivory, disturbances, etc.

The success of theoretical growth equations in forest modelling is not accidental. Their structure supports some confidence that the identified general processes are more than figments of researchers' imagination. Developed mainly to mimic the dynamics of tree/stand growth, these equations express two basic processes of growth. Their coefficients have relevant ecobiological interpretations, and at least their signs can be predicted. While the processes infuse meaning into empirical equations, the equations give shape to the processes, making them if not tangible, at least operational (Zeide, 1999).

As an exploratory analysis, the performances of the differential forms of four well-known theoretical growth equations were compared. The first three are examples of the 'exponential decline' form, while the last one is referred to the 'power decline' form.

- Chapman–Richards $\Delta G_t = \phi \gamma (\alpha^{1/\gamma} G_t^{(\gamma-1)/\gamma} - G_t)$
- Gompertz $\Delta G_t = \gamma G_t (\ln(\alpha) - \ln(G_t))$
- Logistics $\Delta G_t = \phi G_t (1 - (1/\alpha) G_t)$
- Korf $\Delta G_t = \gamma (G_t/A_t) (\ln(\alpha) - \ln(G_t))$

The non-linear regression procedure that estimated equation coefficients used Gauss–Newton approximation method. Table 2 presents some statistics for each model; the function based on Korf equation appears to perform the best.

In Korf equation, coefficient α represents the asymptotic value of the integral function for age approaching infinity. As applied in the present context, α represents maximum stand basal area. Since examined plots present different site quality, the coefficient representing maximum stand basal area was expressed as function of site index, using a power transformation: $\ln(\alpha) \propto SI^\theta$.

$$\Delta G_t = \gamma \frac{G_t}{A_t} (SI^\theta - \ln(G_t)) \quad (1)$$

Obtained fit statistics and coefficients of model (1) are as follows: RMSE = 0.24869 m² per ha per year; adjusted $R^2 = 0.7051$; $\gamma = 0.628299$ (asymptotic S.E. = 0.101366); $\theta = 0.465025$ (asymptotic S.E. = 0.020293). Fig. 1 evidences satisfactory fitting results compared to experimental values. Residuals are well distributed (Fig. 2) with no conditioning outlier.

5. Distribution of basal area growth among DBH-classes

Theoretical models like Eq. (1) attempt to provide a picture of growth in a single step. As highlighted by De Wit (1993), explanatory models demand that research is carried out for at least two integration levels; the lower level will then be the explanatory level and the upper level is the one to be explained. In such a perspective, the processes below the stand level will be now considered.

In evenaged stands, size and average growth within the size-class are evidently related: smaller trees are smaller, because they grow less and vice versa. The difference $s_{i_t} = g_{i_t} - \bar{g}_t$ between individual basal area g_{i_t} , corresponding to DBH-class i , and stand average basal area $\bar{g}_t$, represents the size-class level independent variable. Suppose we can assume that growth (Δg_{i_t}

Table 2

Comparison of statistical performance of stand-level basal area differential growth equations

Theoretical growth equation	Sum of squared residuals (m ² per ha per year)	Mean residual (m ² per ha per year)	S.D. (m ² per ha per year)
Korf	1.2797	0.0135	0.2918
Champan–Richards	1.7463	0.0197	0.3424
Gompertz	4.5623	0.0436	0.5488
Logistics	6.3847	0.1003	0.6441

Fig. 1. Observed and estimated basal area values in the experimental stands.

is the individual basal area increment between age t and age $t + 1$) and size (s_{it}) are linearly related.

$$\Delta g_{it} = \lambda_t + \beta_t s_{it} \quad (2)$$

In this case, to model the distribution of growth among size-classes, only one parameter, the slope term β_t , is required since the constant term λ_t , representing average increment, is determined at the higher-level as a ratio of stand growth and number of individuals (N): $\lambda_t = \Delta G_t / N_t$.

Including four plots measured five times each, the experimental data present a total of 16 cases. Linearity of the growth-size relation was verified for each case. No systematic deviation could be observed; allowing for a third degree polynomial as the most extended model, the stepwise selection procedure always includes only the first degree term. Regression results,

synthesised in Table 3, display constantly high R^2 levels with average around 0.7 and a single value as low as 0.3. Regression slope β represents growth difference for trees with unit size difference. As expected, all values are positive although between case variability is relatively high; the ratio of standard deviation to the average is over 70%.

Many stand variables are significantly correlated with β (Table 4). Fig. 3a shows that β decreases with age, particularly at initial stages, and Fig. 3b displays a slight curvature plotting values against site index. Best fit was obtained by the following model.

$$\beta_t = \beta_1 + \beta_2 \times SI^2 \times A_t^{-2} \quad (3)$$

Obtained fit statistics and coefficients of Eq. (3) are as follows: RMSE = 0.03402 m²; adjusted R^2 = 0.8810; β_1 = 0.026953 (S.E. = 0.013338);

Fig. 2. Residuals from stand level estimation (model (1)).

Table 3

Coefficients and R^2 values of Eq. (2) estimated for the each plot at each measurement

Plot	Age	λ (m ²)	β (m ² cm ⁻²)	R^2
1	5	0.005020	0.300076	0.90
1	8	0.003175	0.110605	0.71
1	11	0.003403	0.091537	0.69
1	14	0.002914	0.056283	0.49
2	5	0.003967	0.315120	0.70
2	8	0.002673	0.096811	0.70
2	11	0.002739	0.093521	0.52
2	14	0.002392	0.046689	0.29
3	5	0.006581	0.327279	0.81
3	8	0.003918	0.132708	0.82
3	11	0.004763	0.114450	0.81
3	14	0.003774	0.051645	0.39
4	5	0.004673	0.226674	0.82
4	8	0.002843	0.084103	0.78
4	11	0.003292	0.076633	0.71
4	14	0.002832	0.047117	0.45

$\beta_2 = 0.013712$ (S.E. = 0.001296). Positive coefficient values are in agreement with expected curve shape.

Size-class basal area increment distribution function is thus

$$\Delta g_{it} = \frac{\Delta G_t}{N_t} + \beta_t s_{it} \quad (4)$$

where ΔG_t is estimated by model (1) and β_t by Eq. (3).

Parameters γ , θ , and β characterising prototype structure are ordinary least square (OLS) regression estimates from model (1) and Eq. (3). Estimates are obtained from the same data base, hence, a slight improvement was gained applying the seemingly

Fig. 3. Trend of β values as a function of stand age and site index.

unrelated regression (SUR) method (Pindyck and Rubinfeld, 1981). Differences between OLS and SUR estimates are within confidence interval limits, nonetheless new standard errors are smaller. Results are synthesised in Table 5.

Based on the analysis of deviations between predicted and observed increment values, the following conclusions can be drawn. Estimates from model (4) are quite accurate: bias is extremely small (0.0000233 m² per ha per year) and has small standard deviation (0.0008 m² per ha per year). The average value of absolute deviations is equal to 0.00065 m² per

Table 4

Correlation matrix between β and major stand variables^a

	β	A	G	N	SI	QD	$\bar{g}$	$\bar{h}$
β	1.000							
A	-0.864	1.000						
G	-0.756	0.870	1.000					
N	0.194	-0.238	0.164	1.000				
SI	0.177	0.000	0.437	0.677	1.000			
QD	-0.818	0.900	0.989	0.092	0.387	1.000		
$\bar{g}$	-0.773	0.888	0.998	0.117	0.411	0.993	1.000	
$\bar{h}$	-0.818	0.917	0.988	0.060	0.364	0.998	0.992	1.000

^a A : stand age; G : stand basal area; N : tree number per ha; SI: site index; QD: quadratic mean diameter; $\bar{g}$: individual mean basal area; $\bar{h}$: mean height corresponding to QD.

Table 5

Non-linear SUR estimation of the coefficients γ , θ , β_1 , β_2 from Eqs. (1) and (3)^a

Coefficient	Estimate	Approximate S.E.	Approximate $P > T $
γ	0.599607	0.09947	0.0001
θ	0.471503	0.01941	0.0001
β_1	0.030288	0.01307	0.0361
β_2	0.013289	0.00127	0.0001

^a In Eq. (1): RMSE = 0.24955 m² per ha per year; adjusted R^2 = 0.7030 and in Eq. (2): RMSE = 0.03414 m²; adjusted R^2 = 0.8810.

ha per year. The plot of deviations against predictions (Fig. 4) displays a uniform distribution, allowing for reasonable behaviour of the model within the observed experimental space.

6. Single tree level

Further developing the growth modelling study down to the single tree level, different individual competition indices have been taken into consideration as potential growth predictors. If, as evaluated through the analysis of residuals, model (4) unbiasedly estimates basal area growth of each size classes by incorporating the influence of stand and size class level variables, and if inter-tree competition affects growth, then it should be possible to detect this effect within available growth residuals, i.e. growth residual for tree j at time $t = f$ (competition index value for tree j at time t).

All the eight neighbours surrounding each subject tree were included as competitors. The considered indices belong to the class of indices based on ratios between tree dimensions and inter-tree distance.

$$CI_{1j} = \sum_{i=1}^{M_j} \left(g_i \frac{1}{l_{ij}} \right), \quad CI_{2j} = \sum_{i=1}^{M_j} \left(\frac{g_i}{g_j} \frac{1}{l_{ij}} \right),$$

$$CI_{3j} = \sum_{i=1}^{M_j} \left(\frac{g_i}{g_j} \right), \quad CI_{4j} = \sum_{i=1}^{M_j} \left(\frac{g_i}{g_j} \frac{1}{l_{ij}^2} \right)$$

where g_i : basal area of i th competitor tree; g_j : basal area of subject tree j ; l_{ij} : distance between i th competitor and subject tree j ; M_j : total number of competitors affecting subject tree j .

Correlation coefficients, evaluated for each sample plot age combination, are presented in Table 6. Differences between considered competition indices are only marginal. Overall, growth residuals (model (4) residuals) do not appear to be clearly associated with inter-tree competition. Only 30 correlation coefficient values out of 64 are significant ($P < 0.05$): nine display positive sign, 21 negative sign. In any case, statistical association between individual growth residuals and competition indices proves to be quite low. This result is in agreement with applied silviculture: no thinning is practised in such plantations, since spacing is so wide that inter-tree competition is expected to be negligible within considered rotation ages. On the other hand, it is frequently the case analysing plantation trees that, given the relatively limited variability of inter-tree distances, even distance-based competition indices appear to be ineffective as growth predictors.

Fig. 4. Single tree residuals from size-class level estimation (model (4)).

Table 6

Correlation coefficients between the examined individual competition indices and estimation residuals from Eq. (4)^a

Plot	Age	CI ₁	CI ₂	CI ₃	CI ₄
1	5	0.2932	−0.1249	−0.1247	−0.1242
1	8	− 0.4173	0.0362	0.0646	0.0092
1	11	− 0.4045	− 0.4097	− 0.3973	− 0.4183
1	14	− 0.3320	0.1401	0.1510	0.1293
2	5	−0.1320	− 0.3758	− 0.3662	− 0.3830
2	8	−0.0400	0.0285	0.0430	0.0147
2	11	− 0.2550	− 0.2843	− 0.2746	− 0.2921
2	14	−0.1520	−0.1079	−0.1124	−0.1033
3	5	−0.1691	0.3032	0.2966	0.3092
3	8	− 0.3517	0.2939	0.2847	0.3024
3	11	0.0434	− 0.4853	− 0.4933	− 0.4763
3	14	0.0222	0.1200	0.1260	0.1138
4	5	− 0.4148	0.1338	0.1418	0.1260
4	8	− 0.7876	0.4233	0.4281	0.4183
4	11	− 0.3115	−0.1238	−0.1234	−0.1240
4	14	−0.0086	0.2014	0.1947	0.2074

^a Values in bold are significant at $P < 0.05$.

7. Conclusions

The study sets up an innovative methodological framework for the development of growth models for widely spaced unthinned tree plantations like hybrid poplar (I-214 clone) plantations in Italy. In this country, for poplar plantations only local yield tables are available, and they are used to cope with management requirements according to static (i.e. practically time-invariant) conventional operational plans. Such tables are shaped to provide only (aggregated) stand-level estimates of wood assortments with rigidly predefined sizes. Based on the proposed model, a stand table projection system can be developed. Coupling the stand table with appropriate height curve and taper equation (e.g. see Marziliano, 1998), production of wood assortments up to any given upper-stem diameter/height can be predicted.

The presented top-down approach starts, where bottom-up models such as ECOPHYS end: with the measurable/harvestable/marketable outcome expressed in terms of tree size/number (ECOPHYS is an ecophysiological growth process model providing mechanistic predictions of poplar biomass by tree component, Rauscher et al., 1990). In the top-down

approach, overall stand volume, basal area, or other characteristics are the primary quantities predicted and these quantities are disaggregated into size-class, and, eventually, into individual-tree information.

The adopted top-down approach has been shaped on the basis of reasoning and biological knowledge. The proposed prototype can predict growth quite accurately, and the prediction is based on readily available forest inventory data. In such a direction, it can be refined, expanded, and calibrated by a vaster set of such data. Indeed, one of the main advantages of top-down models is that they are effectively able to extract knowledge from the wealth of accumulated long-term observations usually carried out in forestry.

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