Comparative review of models for sustainable yield in indigenous forests

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Published by
Department of Conservation
Head Office, PO Box 10-420
Wellington, New Zealand

This report was commissioned by West Coast Conservancy.

ISSN 1171-9834

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Reference to material in this report should be cited thus:

Manley, B., 2000.
Comparative review of models for sustainable yield in indigenous forests. *Conservation Advisory Science Notes No. 288,* Department of Conservation, Wellington.

Keywords: mathematical models, sustainable yield, indigenous forests, New Zealand.

Summary

A review of the forest models developed and applied by Timberlands West Coast Ltd (TWCL) and Landcare Research Ltd (LRL) has been carried out. The models were reviewed on the basis of default settings for red beech in the Maruia Working Circle.

After identifying the similarities and differences between the two models, a sensitivity analysis was carried out to quantify the impact of any differences on model outputs, in particular stand structure and harvest yield. A sequence of model variants was developed and run, starting with the TWCL default model and ending with the LRL default model. Each variant in the sequence differed in only one factor, thereby allowing quantification of the relative sensitivity of model outputs to that factor.

The review focuses on the impact of differences between the models in terms of mathematical formulation, input data and assumptions. However, it excludes any analysis of the appropriateness and relative merit of the different mathematical formulations, input data and underlying assumptions. Although these are important considerations they are beyond the scope of this review.

Both models can be categorised as Stand Class Models and use the Stand Table Projection Method to project the growth of a stand by simulating the growth of classes of trees. This is a commonly used approach for modelling, particularly for uneven-aged forests.

The differences in mathematical formulation between the LRL model and the TWC model are:

1. Mortality is included in the transition coefficients in the LRL model whereas it is treated as an absolute reduction in the TWCL model.

2. The transition coefficients have a different structure because of different assumptions about the distribution of trees within a size class and the residence time of trees in each class.

Incorporating mortality within the transition coefficients rather than as an absolute reduction has a minimal impact on model outputs. The use of LRL transition coefficients, without any other model changes, has a major impact on model outputs. However, once mortality is adjusted to reflect the different coefficients, model outputs for the LRL approach are similar to model outputs for the TWCL approach. Another difference between the models is that the LRL model allows for compensatory growth (Version 1.1) and mortality (Version 2). The model includes functions which allow tree growth rates and mortality to vary in response to changes in stand basal area. Invoking these functions can have a major impact on model outputs.

Both models have the same initial tree size distribution. There are minor differences between the tree growth rates and the recruitment rates specified in the two models. These differences have a negligible impact on model outputs.

The models (in terms of default settings) differ in the relationship between harvest and mortality. A fundamental assumption of the TWCL model "is that mortality is subsumed into harvest through the careful selection for harvest of trees already prone to direct mortality or mortality by association with dying or falling trees". In contrast, an underlying assumption of the LRL model is that "logging imposes mortality that is largely additional to natural mortality in any one year". These differences have a major impact on model output.

1. Terms of reference

Conduct a review of the forest models developed and applied by Timberlands West Coast Ltd (TWCL) and Landcare Research Ltd (LRL) addressing the following issues:

1. Describe the forest modelling approach used in the TWCL and LRL models.

2. Identify similarities and differences between the mathematical formulations of the TWCL and LRL models. Quantify the impact that any differences have on model outputs (e.g. stand structure, sustainable yield) when the same data are input to both models.

3. Identify similarities and differences between the default input data (initial tree size distribution, tree growth rates, recruitment rate) of the TWCL and LRL models. Quantify the impact that any differences have on model outputs.

4. Identify similarities and differences between the mortality and harvest assumptions of the TWCL and LRL models. Quantify the impact that any differences have on model outputs.

2. The models

The models used for this review are:

Timberlands West Coast Limited (TWCL) model as provided by Ian James on 27 October 1999. This is an Excel spreadsheet model for red beech taken from the original model for the Maruia Working Circle.

Landcare Research Limited (LRL) model is Version 1.1 (June 1999) downloaded from the web. This is an executable version written in Pascal. The model is described in Efford (1999).

A developmental copy of Version 2 was subsequently released to me by Murray Efford on 3 November 1999. This version was used in the later part of this review to evaluate the impact of the compensatory mortality factor.

Both versions of the LRL model are set up for red beech with default data provided for the Maruia Working Circle.

3. Approach

As noted by Vanclay (1995), "common usage of the term `growth model' encompasses the mathematical equations, the numerical values embedded in those equations, the logic necessary to link these equations in a meaningful way, and the computer code required to implement the model on a computer". In reviewing a growth model it is necessary to consider the different components.

The approach taken here is to compare the TWCL and LRL models in terms of:

- mathematical structure,
- input data,
- underlying assumptions.

Both models are very flexible in allowing the user to vary input data and model assumptions (initial stand table, growth rates, recruitment rates, natural mortality, harvest). For the purposes of this review the two models are compared based on the default inputs provided with the models with the following qualifications:

- Ian James advised that the TWCL "model also contains improvement fellings; i.e. stems less than 30 cm dbh. These have since been dropped." Consequently this review considers only the selection harvest of trees greater than 30 cm in diameter. Silvicultural improvement felling of poles and small trees 10 to 30 cm in diameter is excluded from the analysis.

- The two versions of the LRL model have the same default settings with the exception that the harvest fraction for the gross increment (GI) rule is set to 1.0 in Version 1.1 but changed to 0.5 in Version 2. For this review the Version 2 setting has been adopted as the default.

After identifying the similarities and differences between the two models a sensitivity analysis was carried out to quantify the impact of any differences on model outputs, in particular stand structure and harvest yield. A sequence of model variants was developed and run, starting with the TWCL default model and ending with the LRL default model. Each variant in the sequence differed in only one factor, thereby allowing quantification of the relative sensitivity of model outputs to that factor.

Variants were compared using model outputs:

(a) Stand structure over 250 years:
- Number of trees greater than 70 cm (stems/ha)
- Total basal area (m^2/ha)

(b) Annual harvest yield
- Basal area harvested (m^2/ha)
- Trees harvested (stems/ha)
- Volume harvested (m^3/ha)

The TWCL model runs for 50 years. This was extrapolated to run for 250 years to enable outputs for all model variants to be compared over this longer period. In doing so it is appropriate to note a warning provided with the TWCL model:"The time period for projections is 35 years - the length of our resource consents. We believe projections beyond that period for such a simple yield model are invalid since there is no provision for compensatory responses".

4. Mathematical structure

Both models can be categorised as Stand Class Models in which the growth of a stand is projected by simulating the growth of classes of trees. In this case the classes are 11 diameter classes each of which (apart from the largest class which is open-ended) is 10 cm wide.

Both models use the Stand Table Projection Method which "is a traditional diameter class method that estimates the future stand table of a subject stand on the basis of a present one, using actual diameter growth and other information which is collected from the subject stand for each diameter class" (Davis & Johnson 1987). Vanclay (1995) notes that "stand table projection may be the most popular way to forecast yields from tropical forests". These forests are typically uneven-aged with many species.

Both models can be represented as transition matrices. "Transition matrices formalise stand table projection, by assuming that a tree in one of a finite number of size classes has a known probability of moving to another class, dependent only upon its current size. During any period, a tree must either remain in its class, grow into another class, or die" (Vanclay 1995).

The TWC model has the basic structure:

$$N_{t+1,i} = a_i N_{t,i} + b_{i-1} N_{t,i-1} - D_i - H_i$$

where $N_{t+1,i}$ = number of trees in diameter class i in year t+1

a_i = proportion of trees in diameter class i which stay in that diameter class the following year.

b_{i-1} = proportion of trees in diameter class i-1 which move into the next diameter class in the following year.

D_i = number of trees that die each year in diameter class i

H_i = number of trees that are harvested each year in diameter class i

For the first diameter class the ingrowth term is replaced by the level of recruitment. There is no outgrowth from the largest diameter class.

The model assumes that trees in each diameter class are uniformly distributed through the class and each tree grows at the average growth rate for the class. For each class the "movement ratio" b_i is determined by dividing the average growth rate by the class width:

$$b_i \quad G_i /100$$

$$a_i \quad = 1 - b_i = 1 - G_i /100$$

where G_i growth rate for diameter class i (mm/year)

The basic structure of the LRL model is

$$N_{t+1,i} = a_i N_{t,i} + b_{i-1} N_{t,i-1} - H_i$$

where $b_i = \sigma_i ((\sigma_i^{Ti} - \sigma_i^{Ti-1})/(\sigma_i^{Ti} - 1))$

$a_i \quad = \sigma_i b_i$

$\sigma_i \quad = (1 - M_i)$ is the survival rate for diameter class

M_i = mortality rate for diameter class i

T_i = 100/Gi

The differences in mathematical formulation between the LRL model and the TWC model are:

1. Mortality is included in the a_i **and** b_i coefficients in the LRL model whereas it is treated as an absolute reduction in the TWCL model.

2. The transition coefficients have a different structure because of different assumptions about the distribution of trees within a size class and the residence time of trees in each class.

Other differences relate to:

Compensatory growth -The LRL model includes a function which allows tree growth rates to vary in response to stand basal area:

$$G = G_0 (BA_0/BA)^k$$

where G = adjusted growth rate

G_0 = initial growth rate

BA = current stand basal area

BA_0 = initial stand basal area

k = exponent controlling the strength of compensation (user can vary from 0 to 1).

Any positive value of k will generate faster growth if stand basal area is reduced beneath the initial level, say by harvesting, and slower growth if basal area increases above the initial level.

Compensatory mortality - Version 2 of the LRL model also includes a function which allows mortality rates to vary in response to stand basal area:

$$M = M_0 (BA_0/BA)^k$$

where G = adjusted growth rate

G_0 = initial growth rate

k = exponent controlling the direction and strength of compensation (user can vary from -0.5 to +0.5).

If k is set to a positive value, mortality will increase if basal area is reduced beneath the initial level and reduce if basal area is increased above the initial level. In this case harvesting would lead to an increase in mortality. The converse is true if k is set to a negative value.

Harvesting regime. In the TWCL model the user specifies an absolute harvest level. The LRL model also allows for user to specify a GI harvest rule or a proportional harvest rule.

5. Input data

5.1 INITIAL STAND TABLE

Both models have the same initial stand table for red beech in Maruia (Table 1).

5.2 INITIAL GROWTH RATE

Both models have the same growth rate for diameter classes less than 90 cm. The default LRL growth rates are lower for the 90-100 cm and the >100 cm diameter classes (Table 2).

5.3 RECRUITMENT RATE

The default recruitment rate in the TWCL model is 55.6 stems/ha/year whereas the default recruitment rate in the LRL model is 57 stems/ha/year.

6. Underlying assumptions

The most fundamental difference between the two models (in terms of default settings) is in the relationship between harvest and mortality.

A fundamental assumption of the TWCL model "is that mortality is subsumed into harvest through the careful selection for harvest of trees already prone to direct mortality or mortality by association with dying or falling trees" (TWC 1999).

In contrast, an underlying assumption of the LRL model is that "logging imposes mortality that is largely additional to natural mortality in any one year" (Efford 1999).

7. Sequence of model variants

The following sequence of models was evaluated:

1. TWCL default model

2. TWCL model - constant forest structure

3. TWCL model - with LRL growth rates

4. TWCL model - with LRL recruitment

5. TWCL model - multiplicative mortality

6. TWCL harvesting/mortality assumptions with LRL transition coefficients

7 TWCL harvesting assumptions with LRL transition coefficients and mortality

8. LRL model with no harvest

9. LRL model with harvesting

10. LRL model with compensatory growth

11 LRL model with GI harvest rule

12. LRL default model

Variants 1 to 9 were developed by modifying the TWCL spreadsheet model. Variants 5 to 9 were also run in the LRL model system to ensure that the same outputs were predicted for the same model variant. Variants 10 to 12 were evaluated using the LRL model system.

Model 1 - TWCL default model

The basis of this model is that "The number of trees that can be removed from a forest while maintaining the near natural forest structure over the long-term is called the sustained yield which is equivalent to the gross increment. The permissible harvest for these prescriptions is defined in terms of the gross increment of trees (>30 D.B.H.), and is set at a maximum of 50% of the gross increment across specified diameter classes of each beech species" (TWC Maruia 1998).

The default mortality and harvest assumptions for the TWCL model are given in Table 3.

The TWCL model was run with the full set of TWCL defaults. While noting that the model is set up to run for only 50 years and that "TWCL also raised concerns related to the extreme length of time over which extrapolations were modelled"(TWCL 1999), results have been extrapolated to provide comparability with later models.

Figs. 1.1, 1.2, and 1.3 show the values for residual stems > 70 cm, stand basal area, and harvest basal area over time for Model 1. Harvest statistics are summarised in Table 4.

Model 2 - TWCL model with constant forest structure

As illustrated by Figs 1.1 and 1.2, the TWCL default model does not maintain the initial forest structure. Both the stand basal area and the residual stems greater than 70 em increase over time. The model trajectory justifies the concerns expressed by TWCL about extrapolations over long periods using the model.

It is possible to calculate the combined level of mortality and harvest for each diameter class such that the initial stand structure is maintained. This can be done in a similar way to that described by Efford (1999).

For the TWCL model, the annual level of mortality and harvest which maintains the initial stand structure is given in Table 5. The total row is calculated first and then split between harvest and mortality according to the same rules as used in the TWCL default model (Model 1):

- Harvest rate (selection harvest only) is set to 0% for tree diameter classes less than 30 cm.
- Harvest rate is set to 50% of the total level for tree diameter classes between 30 and 100 cm.
- Harvest rate is set to 30% of the mortality rate for the >100 cm diameter class.

Figs 2.1, 2.2, and 2.3 show the values for residual stems > 70 cm, stand basal area, and harvest basal area over time for Model 2. Harvest statistics are summarised in Table 6.

The harvest statistics for Model 2 are virtually identical to Model 1 but the initial stand structure is maintained, with the residual stems greater than 70 cm constant at 28 and the stand basal area constant at 36.8 M^2/ha (Figs 2.1 and 2.2). The conversion of the TWCL default model to a "steady state" model provides a consistent basis to evaluate the impact of growth rate and recruitment assumptions.

Model 3 - TWCL model with LRL growth rates

Model 3 is based on Model 2 but has LRL growth rates for the 90-100 cm (1.75 rather than 2.04 mm/year) and the >100 cm (1.47 rather than 2.04 mm/year) diameter classes.

There are slight changes to the steady state mortality and harvest levels for these two largest diameter classes (Table 7).

Harvest statistics for Model 3 are given in Table 8. These are virtually the same as those for Model 2. The steady state level of mortality and harvest is found, using TWCL assumptions, by solving for each diameter class:

Mortality level + Harvest level = Ingrowth - Outgrowth

The reduction in growth rate for the 90-100 cm diameter class results in less outgrowth from this class and gives higher mortality and harvest levels. There is less ingrowth into the >100 cm diameter class, giving lower mortality and harvest levels for this class. These two effects exactly offset each other at the total level but because a greater percentage of the total is harvested in the 90-100 cm class (50% compared with 23%) the harvest statistics increase.

The results for residual stems > 30 cm and stand basal area for Model 3 are identical to those presented in Figs 2.1 and 2.2 for Model 2.

Model 4 - TWCL model with LRL recruitment

Model 4 builds off Model 3 (i.e. it includes the LRL growth rates) but has recruitment at the LRL default level of 57 stems/ha/year rather than the TWCL default level of 55.6.

There are slight changes to the steady state mortality level for the 0-10 cm diameter class (Table 9).

The harvest statistics for Model 4 are identical to those for Model 3. The initial stand structure is maintained.

Model 5 - TWCL model with multiplicative mortality

In Models 1 to 4 mortality has been treated as an absolute reduction; i.e. in calculating the number of trees in a diameter class in any year, mortality has been directly subtracted.

An alternative approach is to include mortality in the transition coefficient for each diameter class. This is the approach that Efford (1999) assumes to be incorporated in the TWCL model:

$$b_i = \sigma_i \; (G_i/100)$$

$$a_i = \sigma_i - b_i$$

where $\sigma_i = (1 - M_i)$ is the survival rate for diameter class

M_i = mortality rate for diameter class i

This is the formulation implemented in version 2 of the LRL model under the option "use TWC formula for growth".

The combined mortality and harvest rate that maintains the initial stand structure is given in Table 10. This rate is split into separate mortality and harvest rates using the default TWCL assumptions. Because a constant stand structure is maintained, the levels (expressed in stems/ha/year) of both mortality and harvest will also be constant. These are also presented in Table 10 to allow comparison with previous models.

The harvest statistics for Model 5 are shown in Table 11. These are very similar to those obtained in previous models. The initial stand structure is maintained.

Model 6 - TWCL harvesting/mortality assumptions with LRL transition coefficients

Efford (1999) suggested that the TWCL model "contains a bias because the equations for transition coefficients in the projection matrix assume an inappropriate geometric model for stage duration". He proceeded to develop a model with transition coefficients which, under the condition that the within-class size distribution is stationary, "treat the duration of each stage as a fixed value equal to the time a tree takes to grow from the lower boundary to the upper boundary of the size class".

Model 6 is identical to Model 5 except that it includes the LRL transition coefficients. Both models have the same TWCL mortality and harvest rate assumptions; i.e. the calculation of the LRL transition coefficients for Model 6 is based on the combined mortality and harvesting rate used in Model 5.

The $\mathbf{b_i}$ transition coefficients for Model 6 are compared with those from Model 5 in Table 12. The coefficients for Model 6 are consistently lower, indicating slower movement of trees through diameter classes.

Both the values for residual stems > 70 cm and the stand basal area decline over time (Figs. 6.1 and 6.2).

Fig. 6.3 shows the Harvest Basal Area while Table 13 presents harvesting statistics for year i and year 250. Both mortality and harvest are applied as rates with a fixed percentage of trees in each diameter class dying or being removed every year. Because the residual stand is declining over time, the levels of both mortality and harvest also decline over time.

Model 7 - TWCL harvesting assumptions with LRL transition coefficients and natural mortality

Clearly the combined level of harvesting and mortality specified in Model 6 is too great to maintain the initial stand structure, given the reduced rates of outgrowth from diameter classes arising from the LRL transition coefficients.

According to Efford (1999) "there is no set of mortality rates that can maintain a stable tree population" when combined with the recruitment and growth rates assumed for Maruia red beech. However, in the LRL model default rates of natural mortality have been calculated to keep the tree population approximately constant in the long term.

Model 7 contains these default rates but retains theTWCL harvesting assumption that 50% of this natural mortality is subsumed into harvest; i.e. the combined mortality and harvest rate line is the default LRL natural mortality rate (Table 14).

Changing the mortality rate also changes the transition coefficients. The transition coefficients for Model 7 are presented in Table 12 along with those for Models 5 and 6. The coefficients for Model 7 are generally lower than those for Model 5 indicating slower movement of trees through diameter classes.

Figs 7.1, 7.2, and 7.3 show the values for residual stems > 70 cm, stand basal area, and harvest basal area over time for Model 7. Figs 7.1 and 7.2 indicate that forest structure is maintained within 92% of original levels.

The harvest basal area decreases from an initial level of 0.152 M^2/ha to a steady level around 0.14 M^2/ha after about 75 years (Fig. 7.3). Harvest statistics are summarised in Table 15.

Model 8 - LRL model with no harvest

Model 8 is identical to Model 7 except that it contains, for the first time in the model sequence, the underlying LRL assumption that mortality and harvesting are additive.

The LRL natural mortality rates are assumed to apply to mortality only. It is assumed that there is no harvesting of the forest. The natural mortality rate used in Model 8 is identical to the combined mortality and harvest rate used in Model 7. Consequently the outputs from Model 8 are identical to those from Model 7 apart from there being no harvest volume.

Model 9 - LRL model with harvesting

Model 9 uses LRL default settings for both natural mortality and harvest (Table 16). Note that mortality is specified as a rate while harvest is specified as a level. For this model the "Absolute" harvest rule is used with an interval year of 1 year. No compensatory growth or mortality is included.

Figs 9.1, 9.2, and 9.3 show the values for residual stems > 70 cm, stand basal area, and harvest basal area over time for Model 9. Figs 9.1 and 9.2 indicate that forest structure cannot be maintained under the assumptions made in this model.

Harvest statistics are summarised in Table 17. As illustrated in Fig. 9.3 a constant level of harvest cannot be maintained. The 90-100 cm diameter class is exhausted after about 160 years. Thereafter the harvest level is reduced.

Model 10 - LRL model with growth compensation

Model 10 is identical to Model 9 except that the growth compensation factor k is set to 0.25.

Figs 10.1, 10.2, and 10.3 show the values for residual stems > 70 cm, stand basal area, and harvest basal area over time for Model 10. Figs 10.1 and 10.2 indicate that forest structure cannot be maintained under the assumptions made in this model but that both residual stems over 70 cm (10.0 compared to 4.5) and stand basal area (27.8 compared to 19.8), at year 250, are higher than in Model 9.

Harvest statistics are summarised in Table 18.

Model 11 - LRL model with GI Rule for harvesting

In Model 11 the harvest rule is switched from the absolute harvest rule (Model 10) to the gross increment (GI) Rule which "is intended to mimic the `gross increment' calculation of TWC". Annual harvest levels can vary depending on the prevailing size structure.

Figs. 10.1, 10.2 and 10.3 allow a direct comparison of Model 11 results with those of Model 10. The GI rule gives a lower stand basal area, a generally higher residual stems > 70, and a higher harvest basal area. The basal area harvested increases in steps from 0.14 to 0.18 m^2/ha.

Model 12 - LRL model

Model 12 is the LRL model with the full set of defaults. It differs from Model 11 in that the harvest interval year is changed from 1 to 15 years.

Figs 10.1, 10.2 and 10.3 allow a direct comparison of Model 12 results with those of Model 11. The harvest basal area predicted by the model has been divided by 15 and spread, for presentation purposes, over the actual year of harvest and the subsequent 14 years. This has been done to allow a visual comparison to be made.

8. Conclusions

Table 19 summarises the key outputs from each of the 12 models. Comparison of the outputs from successive models indicates the factors to which they are most sensitive. Main features are:

- Model 1 has much higher residual stems >70 and stand basal area (at year 250) than Model 2, reflecting the danger inherent in model extrapolation, particularly extrapolation of a model with no compensatory mechanisms.

- The outputs from Models 2 to 5 are virtually identical and not sensitive to the different model inputs on growth rate and recruitment rate or the treatment of mortality as a multiplicative rate rather than a subtractive level.

- Changing model coefficients from the TWCL approach (Model 5) to the LRL approach (Model 6) has a major impact on the stand composition after 250 years. However, after the level of mortality is adjusted to relate to the LRL coefficients (Model 7) residual stems >70 and stand basal area after 250 years are within 92% and 96% of the initial levels. Harvest basal area is within 90% of the Model 5 level.

- Adopting the LRL approach that mortality and harvest are additive gives an identical stand composition after 250 years (to Model 7) provided that there is no harvesting (Model 8) but gives a severe reduction in both residual stems >70 and stand basal area if there is harvesting (Model 9).

- Allowing for compensatory growth (Model 10) has a moderate effect on stand composition after 250 years.

- Use of the GI harvest rule rather than the absolute harvest rule gives increasing harvest levels over time but a reduced stand basal area after 250 years.

- Modelling harvesting on a 15 year cycle rather than a 1 year cycle has little effect.

Differences between models will to some extent reflect the order in which changes were made to them. Changing the model sequence could alter the differences between models but is unlikely to change the order of magnitude of the impacts observed in Table 19.

9. Compensatory growth and mortality

Model 10 indicated the potential impact that compensatory growth mechanisms can have. A sensitivity analysis was subsequently carried out, using Model 10 as a base, to more fully evaluate the impact of the compensatory growth and mortality factors in the LRL model.

9.1 COMPENSATORY GROWTH

The compensatory growth factor was set successively to 0, 0.25, 0.5, 0.75 and 1. Figs. 10.4 and 10.5 show the values for residual stems > 70 cm and stand basal area for each model variation. Note that the run with k=0 is Model 9 and the run with k=0.25 is Model 10.

9.2 COMPENSATORY MORTALITY

With the compensatory growth factor set to 0.25, the compensatory mortality factor was set successively to -0.25, 0 and 0.25. Figs 10.6 and 10.7 show the values for residual stems > 70 cm and stand basal area for each model variation. Note that the run with k=0 is Model 10.

These results confirm the significant impact that assumptions about compensatory growth and mortality can have on model outputs.

10. References

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11. Acknowledgements

The author wishes to acknowledge the willingness of both LRL and TWCL to provide models and their openness in answering queries.

Table 1: Initial stand table used as a default in both the TWCL and LRL models.

Diameter class (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	>100
Initial stocking (stems/ha)	742	61	29	25	21	22	15	11	7	4	6

Table 2: Default growth rates (mm/year) in the TWCL and LRL models.

Diameter class (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	>100
TWCL model	2.56	2.55	2.85	3.11	3.19	2.88	2.62	2.32	2.04	2.04	2.04
LRL model	2.56	2.55	2.85	3.11	3.19	2.88	2.62	2.32	2.04	1.75	1.47

Table 3: TWCL default mortality and harvest levels

Diameter class (cm	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	>100
Mortality level (stems/ha/ ear)	37.760	16.270	.695	.020	.057	.040	.090	.080	.055	.030	.066
Harvest level (stems/ha/year)	0.000	0.000	.000	.020	.057	.040	.090	.080	.055	.030	.020
Total	37.760	16.270	.695	.040	. 114	.080	. 180	. 160	.110	.0600	.086

Table 4: Annual harvest statistics for Model 1.

Stems harvested stems/ha/ ear)	Basal area harvested m2/ha/year	Volume harvested (m3/ha/year
0.392	0.155	1.522

Table 5: Mortality and harvest levels which maintain the initial stand structure in the TWCL model.

Diameter class (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	>100
Mortality level (stems/ha/ ear)	36.570	17.440	.7290	.0245	.0538	.0182	.1203	.0689	.0562	.0306	.0628
Harvest level (stems/ha/year)	0.000	0.000	.0000	.0245	.0538	.0182	.1203	.0689	.0562	.0306	.0188
Total	36.570	17.440	.7290	.0490	.1076	.0363	.2406	.1378	.1124	0612	.0816

Table 6: Annual harvest statistics for Model 2.

Stems harvested (stems/ha/year)	Basal area harvested (m2/ha/ ear)	Volume harvested (m3/ha/ ear)
0.391	0.155	1.523

Table 7: Mortality and harvest levels which maintain the initial stand structure in the TWCL model with LRL growth rates.

Diameter class (cm)		90-100	>100
Mortality level (stems/ha/year)		.0364	.0538
Harvest level (stems/ha/year)		.0364	.0162
Total		.0728	.0700

Table 8: Annual harvest statistics for Model 3.

Stems harvested (stems/ha/ ear)	Basal area harvested (m2/ha/year)	Volume harvested (m3/ha/ ear)
0.394	0.157	1.536

Table 9: Mortality and harvest levels which maintain the initial stand structure in the TWCL model with LRL recruitment rate.

Diameter class (cm)		0-10
Mortality level stems/ha/ ear)		38.005
Harvest level (stems/ha/year)		0.000
Total		38.005

Table 10: Mortality and harvest rates which maintain the initial stand structure in the TWCL model with multiplicative mortality.

Diameter class cm	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	>100
Mortality rate	.0526	.2766	.0106	.0008	.0026	.0008	.0082	.0061	.0080	.0090	.0088
Harvest rate	.0000	.0000	.0000	.0008	.0026	.0008	.0082	.0061	.0080	.0090	.0027
Combined mortality + harvest rate	.0526	.2766	.0106	.0017	.0052	.0015	.0164	.0122	.0159	.0179	.0115
Mortality level (stems/ha/year)	39.003	16.871	.3075	.0208	.0549	.0169	.1230	.0672	.0558	.0359	.0529
Harvest level (stems/ha/year	0.000	0.000	.0000	.0208	.0549	.0169	.1230	.0672	.0558	.0359	.0159
Total	39.003	16.871	.3075	.0415	.1098	.0338	.2461	.1345	.1116	.0718	.0687

Table 11: Annual harvest statistics for Model 5.

Stems harvested (stems/ha/ ear)	Basal area harvested (m2/ha/ ear)	Volume harvested (m3/ha/year)
0.390	0.156	1.525

Table 12 - bi transition coefficients for Models 5, 6 and 7

Diameter class (cm	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	>100
bi Model											
5	.024	.018	.028	.031	.032	.029	.026	.023	.020	.017	.015
6	.007	.000	.023	.030	.029	.028	.019	.018	.013	.010	.010
7	.004	.019	.024	.026	.027	.024	.022	.018	.016	.013	010

Table 13: Annual harvest statistics of first and last years for Model 6

	Stems harvested stems/ha/year	Basal area harvested (m2/ha/ ear)	Volume harvested m3/ha/ ear
Year 1	0.390	0.156	1.525
Year 250	0.058	0.032	0.316

Table 14: Mortality and harvest rate assumptions used in Model 7.

Diameter class cm	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	>100
Mortality rate	.0750	.0140	.0099	.0048	.0048	.0048	.0049	.0050	.0051	.0054	.0090
Harvest rate	.0000	.0000	.0000	.0048	.0048	.0048	.0049	.0050	.0051	.0054	.0027
Combined mortality + harvest rate	.0750	.0140	.0099	.0097	.0097	.0097	.0098	.0100	.0103	.0109	.0117

Table 15: Annual harvest statistics of first and last years for Model 7

	Stems harvested (stems/ha/ ear)	Basal area harvested (m2/ha/ ear)	Volume harvested (m3/ha/ ear)
Year 1	0.532	0.152	1.465
Year 250	0.520	0.141	1.360

Table 16: LRL default values for mortality and harvest.

Diameter class (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	>100
Harvest level (stems/ha/year)	.0000	.0000	.0000	.0208	.0549	.0169	. 1230	.0672	.0558	.0359	.0000
Mortality rate (proportion)	.0750	.0140	.0099	.0097	.0097	.0097	.0098	.0100	. 0103	.0109	.0117

Table 17: Annual harvest statistics for Model 9

	Stems harvested stems/ha/year	Basal area harvested m2/ha/ ear)	Volume harvested (m3/ha/ ear)
Years 1 to 161	0.375	0.142	1.370
Years 162 to 167	0.357	0.130	1.249
Years 168 to 250	0.339	0.117	1.128

Table 18: Annual harvest statistics for Model 10

Stems harvested (stems/ha/year)	Basal area harvested (m2/ha/year)	Volume harvested (m3/ha/year)
0.375	0.142	1.370

Table 19: Comparison of outputs from each model.

Model		Residual Stems > 70 cm at Year 250		Stand Basal Area at Year 250		Harvest Basal Area
		(Stems/ha)	(% of initial value of 28)	(m2/ha)	(% of initial value of 36.8)	
1	TWCL default model	55.0	196	58.2	158	0.155
2	TWCL model - constant forest structure	28.0	100	36.8	100	0.155
3	TWCL model- LRL growth rates	28.0	100	36.8	100	0.157
4	TWCL model - LRL recruitment	28.0	100	36.8	100	0.157
5	TWCL model- multiplicative mortality	28.0	100	36.8	100	0.156
6	TWCL harvesting - LRL transition coefficients	7.3	26	7.8	21	0.156 (yr 1) 0.032 (250)
7	TWCL harvesting - LRL coefficients and mortality	25.7	92	35.4	96	0.152 (yr 1) 0.141 (250)
8	LRL model with no harvesting	25.7	92	35.4	96	0
9	LRL model with harvesting	4.0	14	19.5	53	0.142 (yr 1) 0.117 250)
10	LRL model with compensatory owth	10.0	36	28.0	76	0.142
11	LRL model with GI cutting rule	9.4	34	22.0	60	0.14 (yr 1) 0.18 250
12	LRL model with 15 year cutting cycle	8.4	30	22.0	60	0.143 (yr 1) 0.187 (250)

Fig 1.1 - Model 1 Residual Stems > 70cm

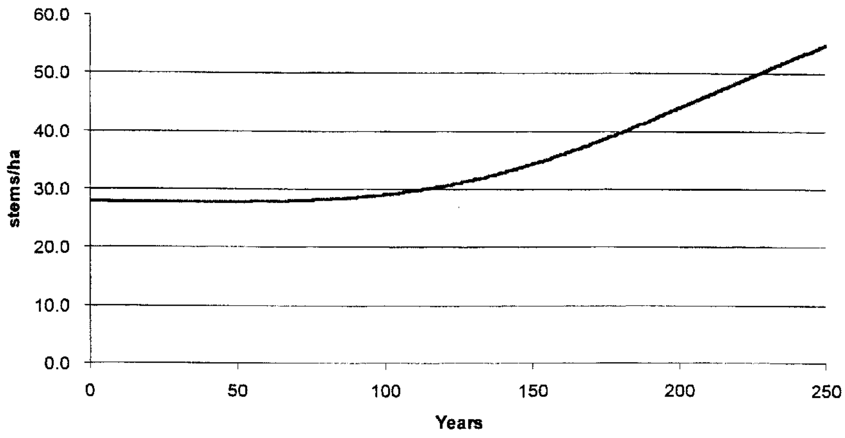

Fig 1.2 - Model 1 Stand Basal Area

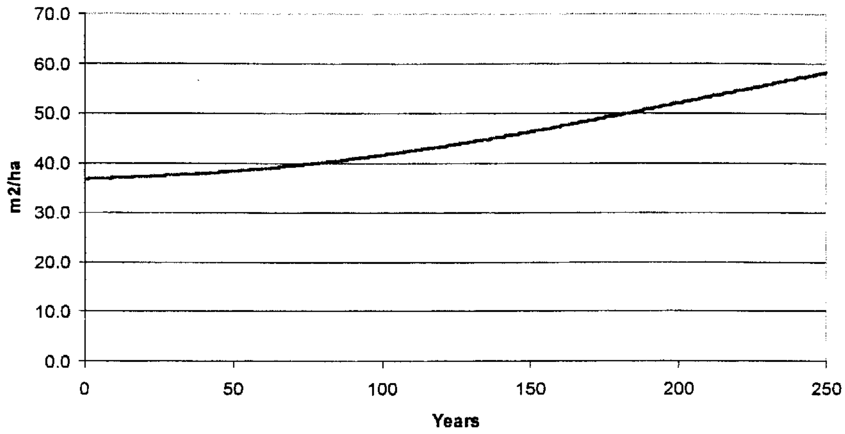

Fig 1.3 - Model 1 Harvest Basal Area

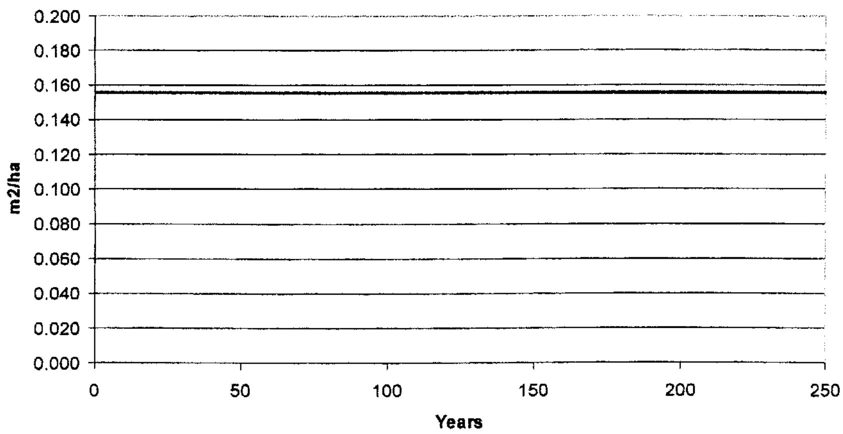

Fig 2.1 - Model 2 Residual Stems > 70 cm

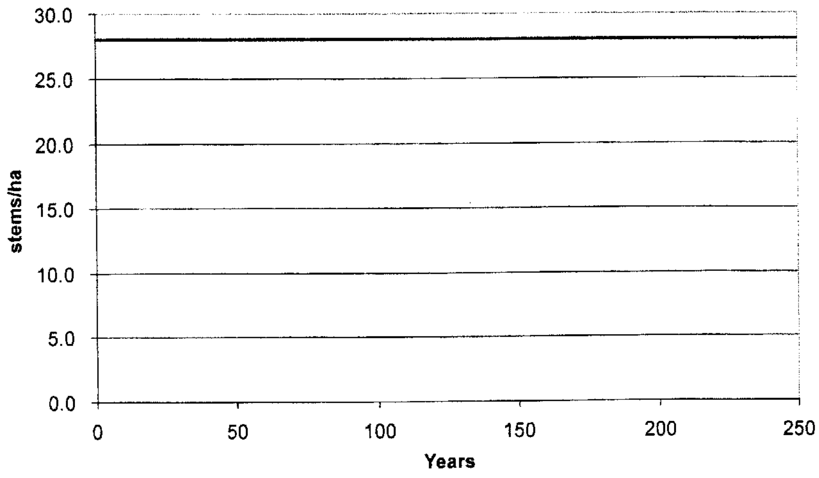

Fig 2.2 - Model 2 Stand Basal Area

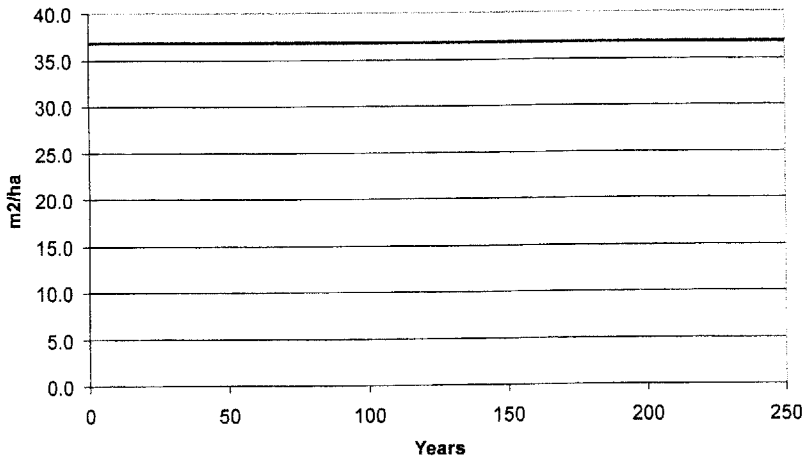

Fig 2.3 - Model 2 Harvest Basal Area

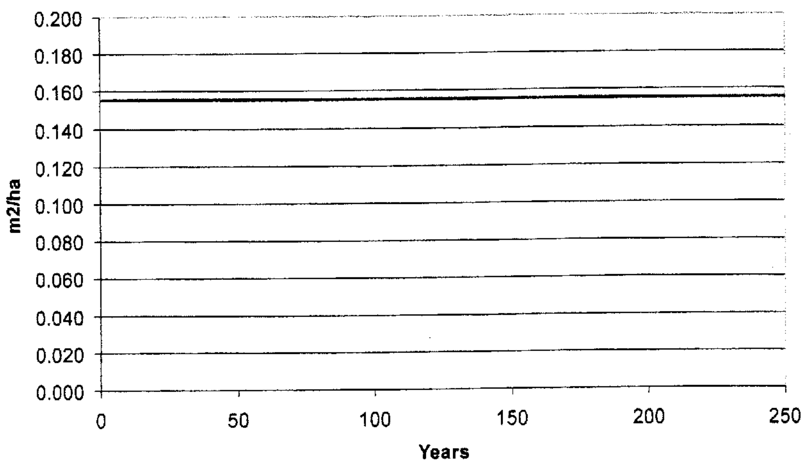

Fig 6.1 - Model 6 Residual Stems > 70 cm

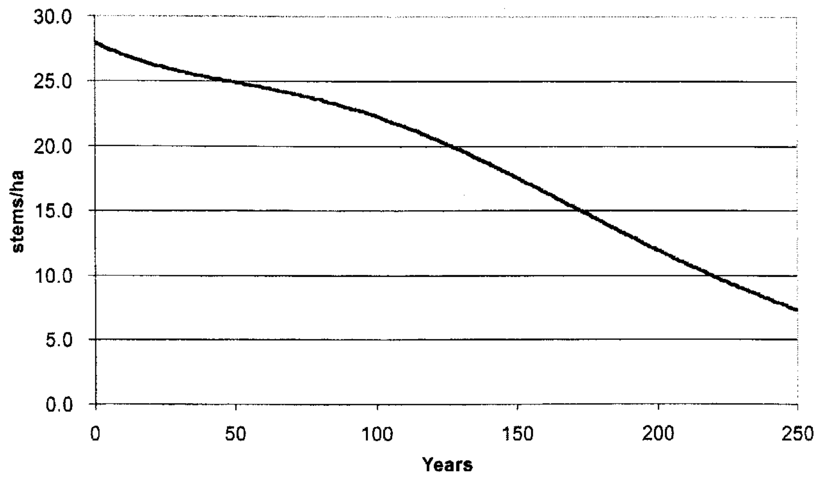

Fig 6.2 - Model 6 Stand Basal Area

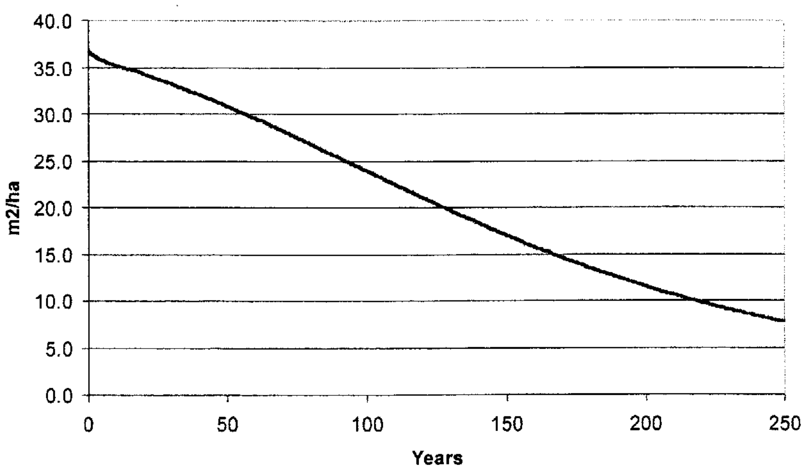

Fig 6.3 - Model 6 Harvest Basal Area

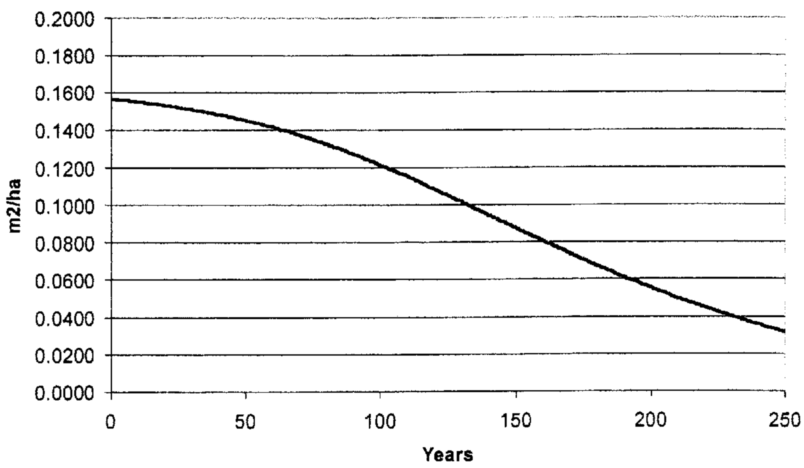

Fig 7.1 - Model 7 Residual Stems > 70 cm

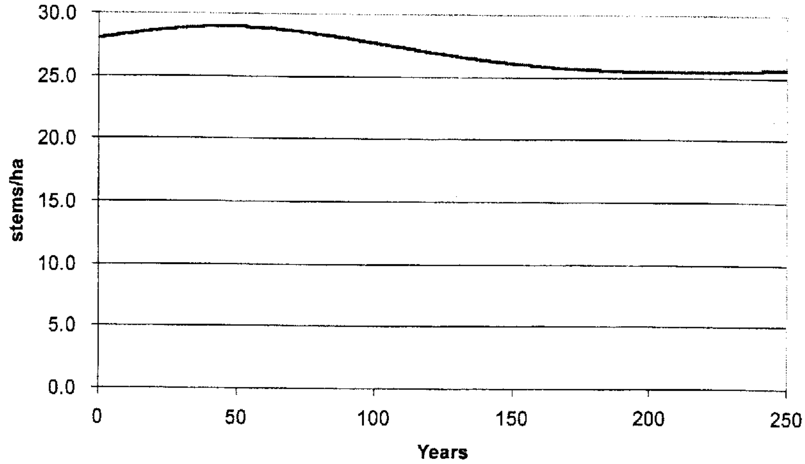

Fig 7.2 - Model 7 Stand Basal Area

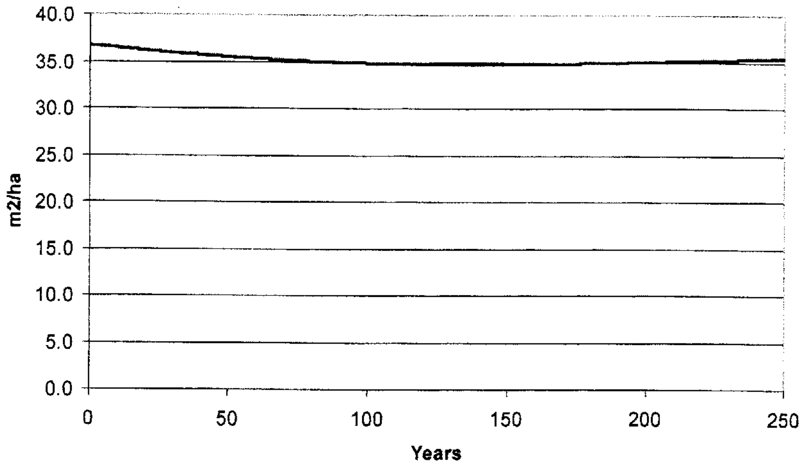

Fig 7.3 - Model 7 Harvest Basal Area

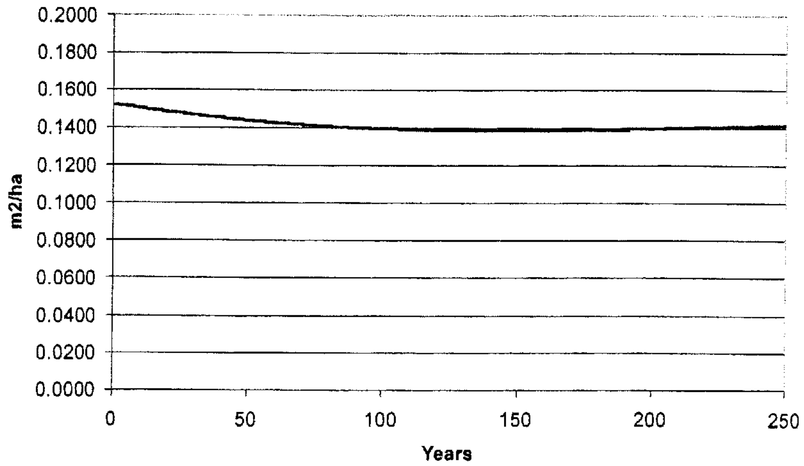

Fig 9.1 - Model 9 Residual Stems > 70 cm

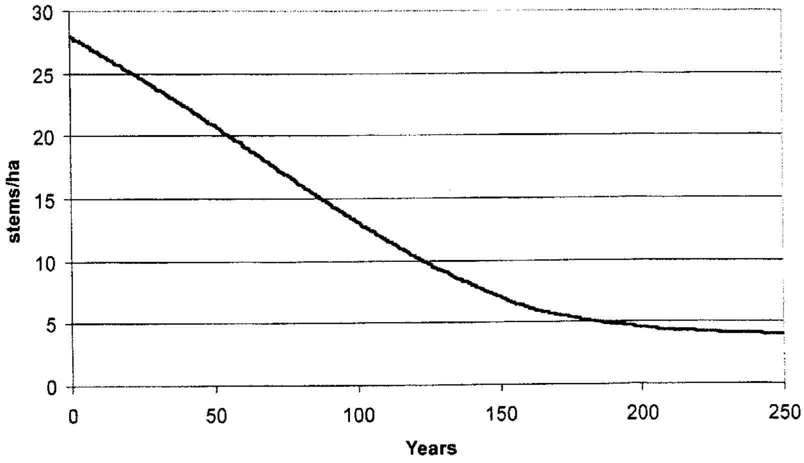

Fig 9.2 - Model 9 Stand Basal Area

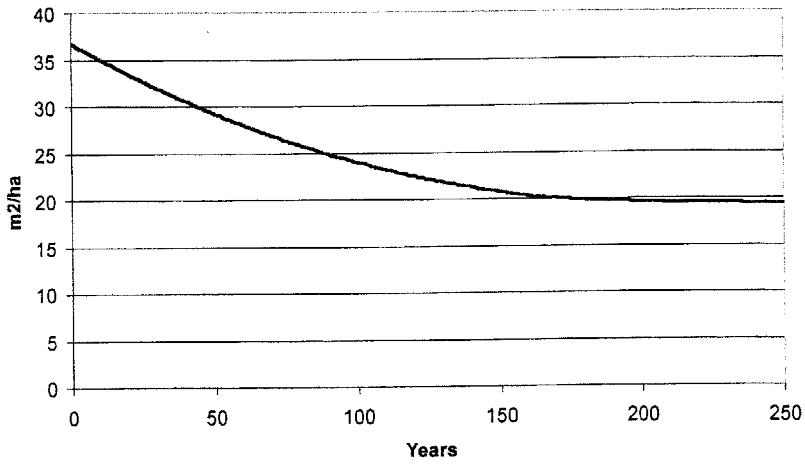

Fig 9.3 - Model 9 Harvest Basal Area

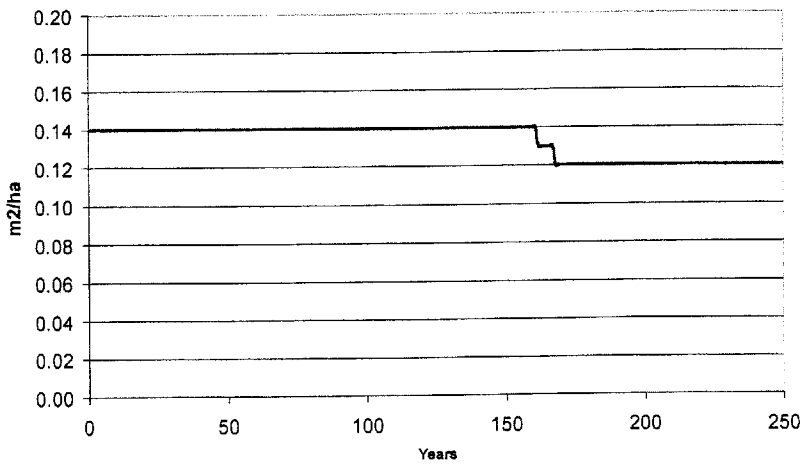

Fig 10.1 - Models 10,11 & 12 Residual Stems > 70 cm

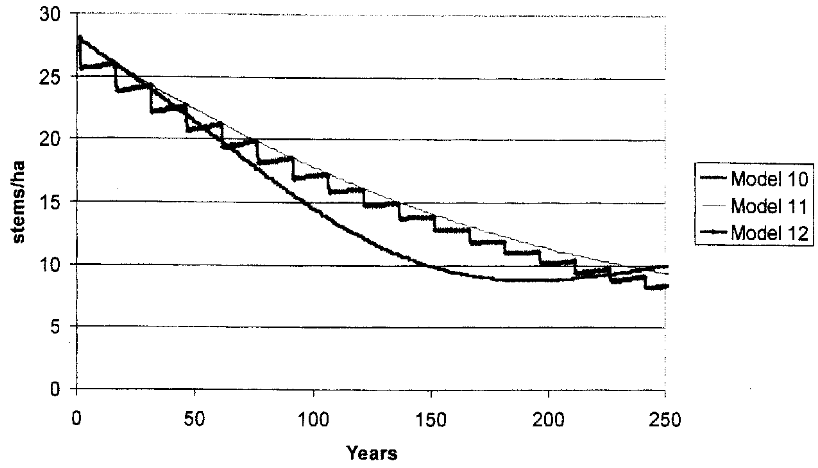

Fig 10.2 - Models 10, 11 & 12 Stand Basal Area

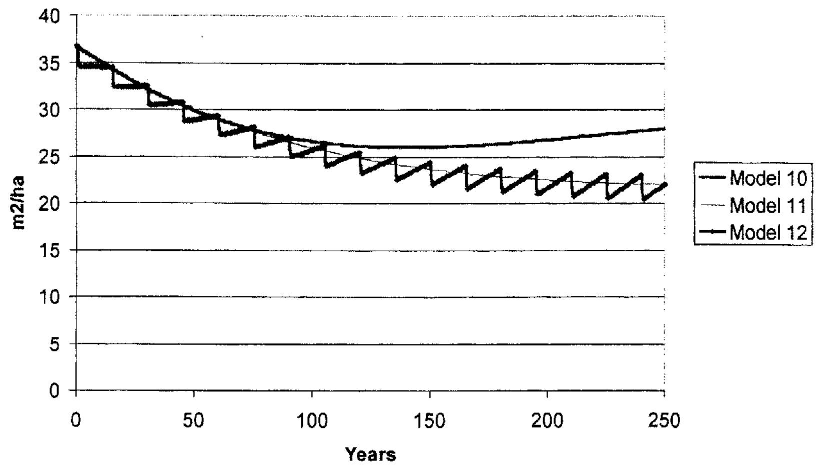

Fig 10.3 - Models 10, 11 & 12 Harvest Basal Area

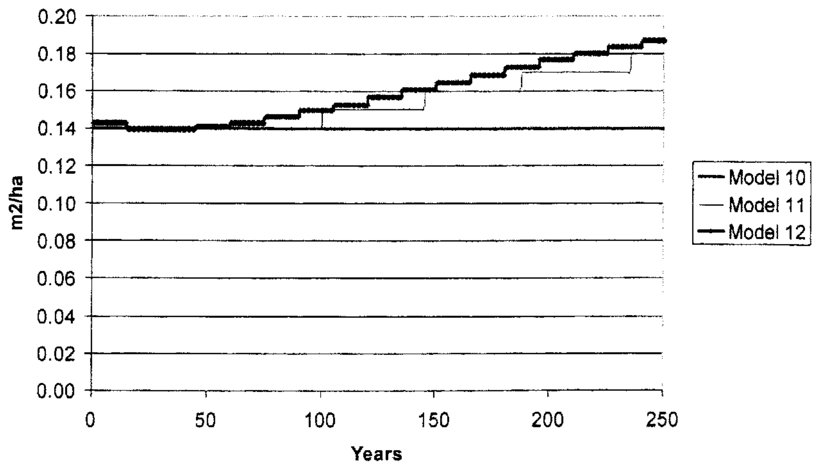

Fig 10.4 - Compensatory growth Impact on Residual Stems > 70 cm

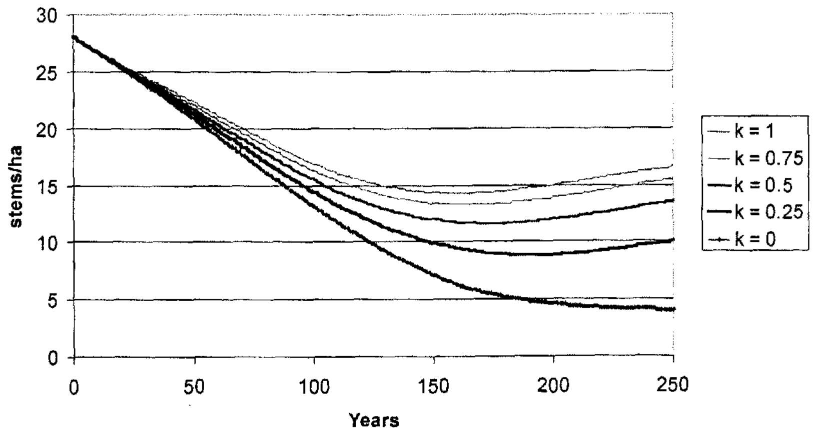

Fig 10.5 - Compensatory growth Impact on Stand Basal Area

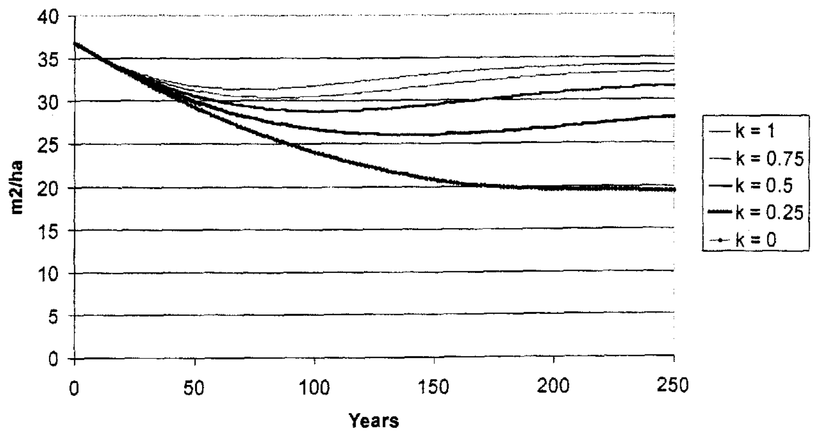

Fig 10.6 - Compensatory mortality Impact on Residual Stems > 70 cm

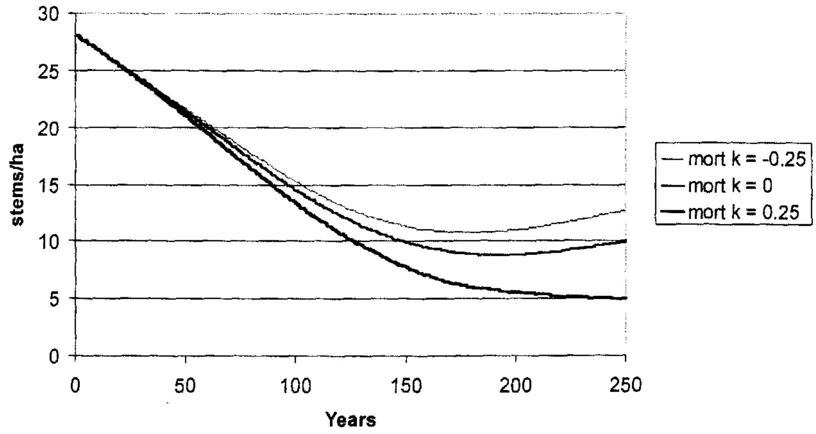

Fig 10.7 - Compensatory mortality Impact on Stand Basal Area