IMPROVING MANAGEMENT OF PLANTATION PRODUCTIVITY WITH A NUTRIENT BALANCE MODEL

Simeon J. Smaill

Scion, P.O. Box 29237, Fendalton, Christchurch, New Zealand
simeon.smaill@scionresearch.com

Introduction

The economic sustainability of plantation forestry has been an important topic for several decades (Jorgensen et al., 1975; Erickson et al., 1999). To enable forest managers to optimise the productivity and profitability of plantation forests various models have been developed to allow the productivity of a given site to be predicted under a selection of different management regimes (Battaglia et al., 2004). The ecological sustainability of plantation forestry has also become a significant concern (Rametsteiner and Simula, 2003; Cubbage et al., 2007) and studies have identified the effects of variations in the extent of harvesting operations and the management of harvest residues on nutrient availability both in the short and long term (e.g. Shammas et al., 2003; Ganjegunte et al., 2004; Smaill et al., 2008). Consequently, various models have been constructed to address this concern and predict how plantation management influences nutrient cycling and availability in managed forests (e.g. Liu et al., 1991; Blanco et al. 2005; Akselsson et al., 2007)

The model described here (called NuBalM from Nutrient Balance Model) was developed to integrate the functions of both a productivity and a nutrient availability model, providing managers with the information needed to better predict nutrient availability and the potential benefits of fertiliser application in their plantations. NuBalM is a substantial extension to an unnamed model described by Payn and Clinton (2005), incorporating feedback between productivity and nutrient balance to alter predictions of biomass allocation at a stand level while simultaneously projecting the impacts of alterations to biomass and plantation management on nutrient pools in subsequent years.

Here the processes used by NuBalM to calculate nutrient pools and biomass production and allocation over the life of a modelled radiata pine rotation will be outlined and the performance of NuBalM under different management regimes will be reported. The ongoing improvements and extensions being made to NuBalM will also be briefly described.

Model Processes

The operations and dependencies of NuBalM when configured for nitrogen are illustrated in Fig. 1. The baseline predictions of productivity made by NuBalM are generated by a productivity model called the 300 Index (Kimberley et al., 2005). The 300 Index produces a yield table of predicted volume increments per hectare in live stem wood volume and stem wood mortality on an annual basis throughout the life of the modelled rotation. NuBalM uses this yield table to generate productivity projections for a mass balance nutrient allocation model with an annual step.

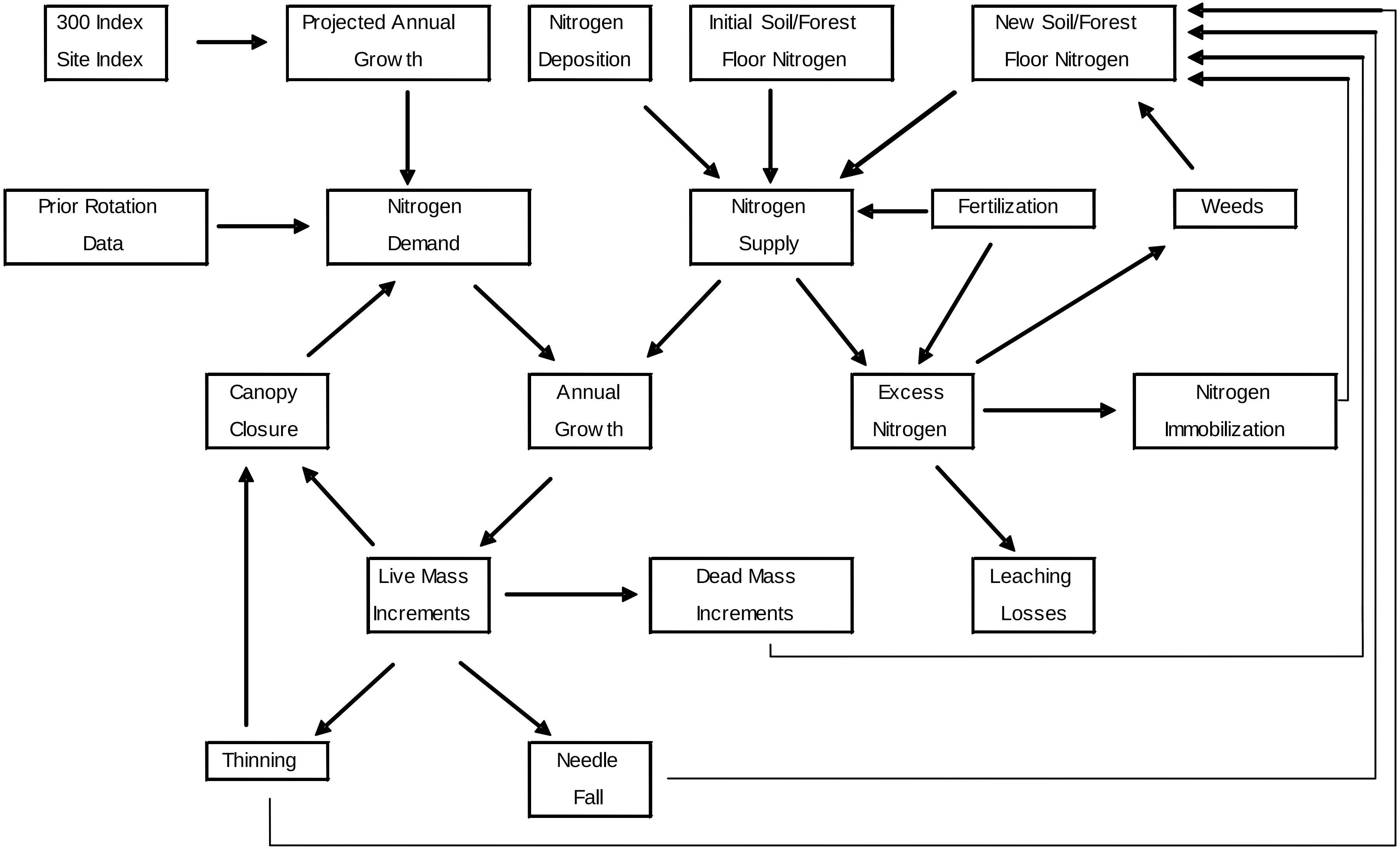

Fig. 1. Framework of interactions between the different components of NuBalM assuming dependency on nitrogen availability (taken from Smaill et al. 2011)

As evident in Fig. 1, the balance of nutrient supply and demand influences the projection of biomass production and allocation in a given year, and the feedback pathways by which biomass production influences nutrient demand and supply in later years. NuBalM, as it is described here, is configured to modify predictions of radiata pine plantation productivity based on estimations of N supply and demand. However, NuBalM also tracks the demand and supply of phosphorous, calcium, potassium, magnesium and boron over the life of the rotation, and can be configured to calculate productivity based on the availability of these elements, or by the relative ratios of two or more of these elements, given suitable data to initiate the model.

The N demand required to meet projected mass production is calculated by estimating the mass of tissue generated (e.g. foliage, branches, roots) based on the ratio of stem wood mass to other tissue types, then determining the mass of N required to support all tissue generation. Tissue mass ratios are age dependent, and functions were calculated from data extracted from several studies of biomass production in radiata pine plantations of various ages across a range of sites (e.g. Madgwick et al., 1977; Madgwick 1994). If N concentrations for the different tissue types are known, they can be entered into the model if the user desires; if not, values derived from *Pinus radiata* tissue sampled from plots established over a wide range of sites are used (e.g. Smith et al. 1994). Nitrogen supply in a given year is calculated from atmospheric deposition, release from mineral soil, the decomposition of plant matter and fertilization events. The pool of N in decomposing plant matter is calculated by various subroutines, accounting for various natural processes and management options. The rate of release of N from the various plant matter tissue types available for decomposition is defined by k values (Olson, 1963) specific to each tissue type. If any k values are known they can be specified, but otherwise the model uses a set of default k values to govern the release of N (e.g. Girisha et al., 2003; Ganjegunte et al., 2004).

The key process that underpins the projections of NuBalM is the comparisons of N supply and demand in a given year. If the supply of N is less than demand in a given year, growth is N limited and the model will recalculate the projected mass increments for live and dead tissue for that year to account for this limitation. In this case, all tissue types are allocated a basal mass of N and the remaining N is allocated preferentially to support the production of the remaining projected mass of foliage, roots, branches and then stem wood and bark. The projected growth increment of each tissue type is then recalculated based on N supply from basal and preferential allocation and standing live biomass is calculated by adding the live biomass increment to the standing biomass of the previous year, minus any losses attributed to natural mortality and thinning. If N supply exceeds demand the annual projected mass of each tissue type is unchanged and the excess N is allocated to weed production, immobilisation and leaching. The distribution to these three compartments is governed by a set of functions based on the findings of several field trials and surveys (Dyck et al., 1981, Carlyle et al., 1998; Schipper et al., 2004; Hamilton, 2005; Quinn, 2005).

Validation

The ability of NuBalM to predict stem wood production was assessed by comparing simulated data with 112 observed measurements in 32 individual plots across multiple radiata pine trial sites (Madgwick et al., 1977; Jackson et al., 1983; Webber and Madgwick, 1983; Mead et al., 1984; Madgwick and Oliver, 1985; Beets and Pollock, 1987; West, 1998). The treatments examined at these trial sites included variations in site preparation prior to planting, initial stocking levels, the extent and timing of thinning and the extent and timing of fertilizer application. The age of the plantations in the trial sites ranged from 2 to 29, with a mean age of 12.5. Predictions of the production of different types of above ground biomass and the extent of N pools was assessed by comparing simulated data with observed data collected during sampling of the second rotation of radiata pine at the Tarawera and Kinleith Long Term Site Productivity (LTSP) radiata pine trial series. These trials are described by Dyck et al. (1991) and Smith et al. (1994). Both sites contained replicated 400 m^2 plots from which different quantities of organic matter had been removed during the harvest of the previous rotation, significantly influencing nutrient pools during the life of the studied rotation (Smith et al., 1994; Smaill et al., 2008). The biomass removal treatments applied at both sites were stem-only harvesting (SO), whole tree harvesting (WT) and whole tree harvesting plus forest floor removal (FF).

The observed and predicted values for stem wood production were plotted in Fig. 2. The majority of the data points fell in the vicinity of the 1:1 line, with the exception of data points from a trial reporting the effects of ultra-high applications of N fertilizer (Jackson et al., 1983); in this case the observed stem wood masses were substantially underestimated by NuBalM. Regression analysis determined that observed and modelled values were significantly correlated ($p < 0.001$), but the terms of the regression equation for the twenty plots receiving high application rates of N fertilizer strongly suggested NuBalM performed poorly in these circumstances.

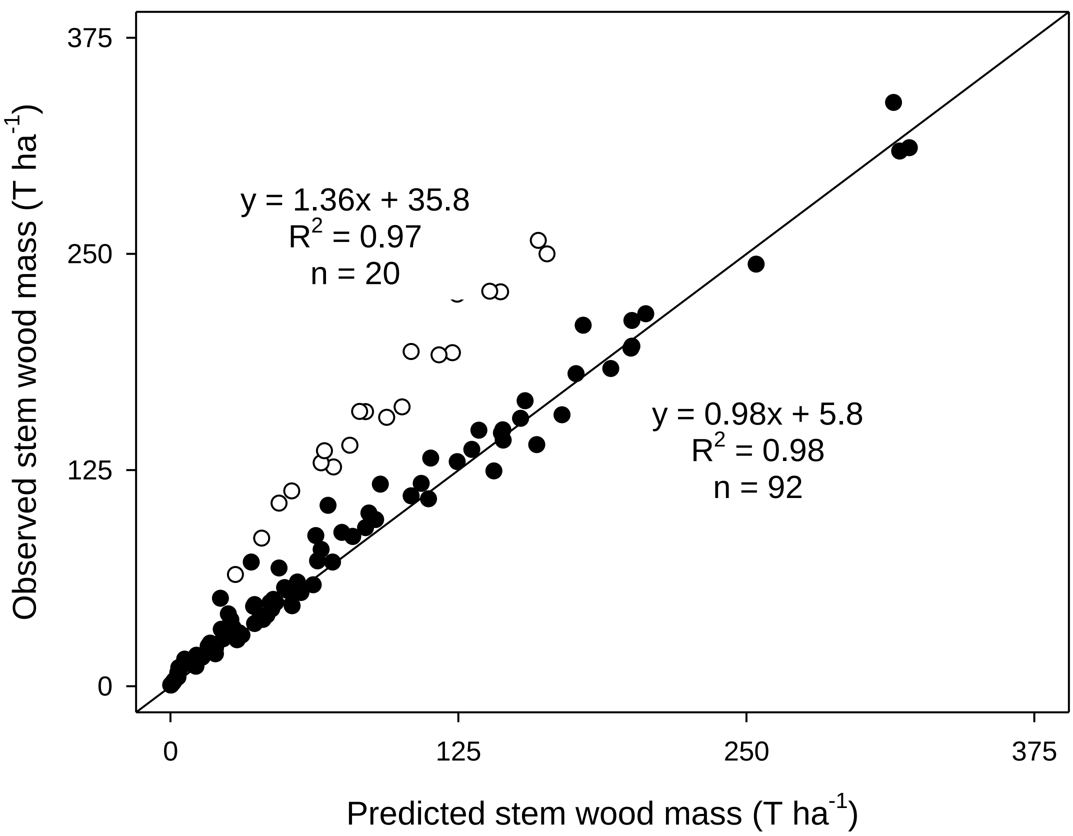

Fig. 2. Relationships between predicted and observed stem wood mass compared to a 1:1 line. Data points representing an ultra-high N fertilization trial are indicated by open circles. Data points from all other examined trials are indicated by solid circles (taken from Smaill et al. 2011).

The observed and predicted values for the masses of the different radiata pine tissue types at Tarawera and Kinleith are given in Tables 1 and 2, respectively. NuBalM did not predict branch mass accurately in the FF or WT treatments plots for the Tarawera site and also consistently underestimated foliar masses at this location but predictions of total above ground mass were relatively accurate. NuBalM substantially underestimated the effects of the FF treatment on stem wood mass and total above ground mass at Kinleith (Table 2), but generally predicted biomass allocation in the WT and SO treatment plots relatively accurately, with the exception of foliar mass.

The Kinleith dataset was also used to examine the ability of NuBalM to predict N pools in the forest floor and soil in the presence and absence of fertiliser application (Tables 3 and 4). In general NuBalM was able to predict the total pool of N with a reasonable degree of accuracy, although the relative error associated with projections of N in the litter plus FH layer was substantial in some cases. However, as the majority of the N was associated with the mineral soil, this had less of a bearing on the projection of the total pool size.

Applications and Future Developments

NuBalM accurately predicted stem wood masses across a range of stocking and thinning trials at different ages, but performed very poorly when used to simulate high levels of fertilization. However, NuBalM did satisfactorily predict the stem wood masses in the unfertilised plots used in the same study (Jackson et al., 1983), suggesting fertilization was the cause for the differences between observed and predicted values rather than any characteristics of the site. Furthermore, fertilizer application was a component of the studies of Mead et al. (1984) and West (1998) (200 and 400 kg N ha^{-1}, respectively, applied once at thinning), and in these instances NuBalM predicted stem wood masses with a satisfactory degree of accuracy. Consequently, it was concluded that NuBalM does not predict stem wood mass accurately when extremely high rates of N are added to the modelled stand, but as such rates are much greater than those used in conventional plantation forestry management, this was not considered to be a substantial limitation. Therefore, we conclude that NuBalM has utility as a tool to aid in the optimisation of fertiliser use in the forestry industry.

Several issues currently limit the applicability of NuBalM to wider use. As the capacity of NuBalM to predict productivity based on the availability and flux of any nutrient other than N has not been verified, NuBalM cannot be used with any confidence to predict growth and nutrient pools for any other nutrient. Furthermore, the ability of NuBalM to be used in conjunction with a growth model predicting the productivity of a species other than radiata pine has not been tested. Lastly, the accuracy of the N translocation, weed production and leaching components of NuBalM are also deliberate simplifications, and cannot be relied upon with any confidence. To address these issues a new study is being established to integrate NuBalM with a Maritime pine productivity model, which will be developed and tested with both N and phosphorous as limiting nutrients. Additional work has recently been completed to improve the ability of the model to predict leaching with and without the addition of fertilisers, and a new project is being developed to assess the effects of weed and understory growth on nutrient availability.

Table 1 Observed and predicted masses of above ground radiata tissue at Tarawera (adapted from Smaill et al. 2011)

Treatment	Stem mass ($T\ ha^{-1}$)	Bark mass ($T\ ha^{-1}$)	Branch mass ($T\ ha^{-1}$)	Foliar mass ($T\ ha^{-1}$)	Above ground mass ($T\ ha^{-1}$)
FF					
Observed[1]	148.5	17.0	22.7	8.3	196.5
Projected	138.1 (-7.0%)	16.3 (-4.1%)	18.6 (-18.1%)	7.7 (-7.2%)	180.7 (-8.0%)
WT					
Observed[1]	136.9	18.2	27.0	8.4	190.5
Projected	145.1 (6.0%)	17.1 (-6.0%)	20.7 (-23.3%)	7.7 (-8.3%)	190.5 (0.0%)
SO					
Observed[1]	162.7	18.0	25.3	10.1	216.1
Projected	169.3 (4.1%)	19.9 (10.6%)	26.7 (5.5%)	7.7 (-23.8%)	223.7 (3.5%)

Table 2 Observed and predicted masses of above ground radiata tissue at Kinleith (adapted from Smaill et al. 2011)

Treatment	Stem mass ($T\ ha^{-1}$)	Bark mass ($T\ ha^{-1}$)	Branch mass ($T\ ha^{-1}$)	Foliar mass ($T\ ha^{-1}$)	Above ground mass ($T\ ha^{-1}$)
FF					
Observed[1]	93.8	12.0	23.9	6.8	136.5
Projected	111.6 (19.0%)	13.1 (9.2%)	25.3 (5.9%)	7.2 (5.9%)	157.3 (15.2%)
WT					
Observed[1]	111.4	12.8	25.6	9.8	159.6
Projected	119.1 (6.9%)	14.0 (9.4%)	25.6 (0.0%)	7.3 (-25.5%)	166.0 (4.0%)
SO					
Observed[1]	113.1	13.9	27.0	9.3	163.3
Projected	116.2 (2.7%)	13.7 (-1.4%)	25.5 (-5.6%)	7.3 (-21.5%)	162.6 (-0.4%)

Abbreviations for Tables 1 and 2 are as follows: FF is whole tree plus forest floor removal; WT is whole tree removal; SO is stem only removal; values in parentheses are percentage difference from the observed value. [1] data from G. R. Oliver, unpublished data; values are means across 4 plots.

Table 3 Observed and predicted N soil pools at Kinleith (adapted from Smaill et al. 2011)

Treatment	L+FH layer N pool ($kg\ ha^{-1}$)	Mineral soil (0-20 cm) N pool ($kg\ ha^{-1}$)	Combined N pools ($kg\ ha^{-1}$)
FF			
Observed[1]	320	2180	2500
Projected	247 (-22.8%)	2343 (7.5%)	2590 (3.6%)
WT			
Observed[1]	290	2830	3120
Projected	331 (14.1%)	2676 (-5.4%)	3008 (-3.6%)
SO			
Observed[1]	350	2830	3180
Projected	425 (21.4%)	2779 (-1.8%)	3204 (0.8%)

Table 4 Observed and predicted N soil pools in fertilised plots at Kinleith (adapted from Smaill et al. 2011)

Treatment	L+FH layer N pool ($kg\ ha^{-1}$)	Mineral soil (0-20 cm) N pool ($kg\ ha^{-1}$)	Combined N pools ($kg\ ha^{-1}$)
FF			
Observed[1]	340	2600	2940
Projected	247 (-27.4%)	2762 (6.2%)	3009 (2.3%)
WT			
Observed[1]	390	2970	3360
Projected	330 (-15.4%)	3106 (4.6%)	3435 (2.2%)
SO			
Observed[1]	480	2910	3390
Projected	425 (-11.5%)	3166 (8.8%)	3591 (5.9%)

Abbreviations for Tables 3 and 4 are as follows: FF is whole tree plus forest floor removal; WT is whole tree removal; SO is stem only removal; values in parentheses are percentage difference from the observed value. [1] data from H. S. Jones, unpublished data; values are means across 4 plots.

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