

EXPLORING THE SUSTAINABILITY OF CURRENT MANAGEMENT PRESCRIPTIONS FOR *PINUS CARIBAEA* PLANTATIONS IN CUBA: A MODELLING APPROACH

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BLANCO JA & GONZÁLEZ E. 2010. Exploring the sustainability of current management prescriptions for *Pinus caribaea* plantations in Cuba: a modelling approach. The ecosystem model FORECAST was used to evaluate the sustainability of current management practices in *Pinus caribaea* plantations in Pinar del Río (western Cuba). Model predictions were within the range of observed field measurements of height, diameter, stem density and volume. The model performed reasonably well in capturing general growth trends (r values for dominant height, diameter and merchantable volume were 0.91, 0.77 and 0.81 respectively). In the second part of our work, model output of merchantable volume, stem biomass, soil organic matter and available N in soil were analysed in 18 different combinations of rotation length (25 vs. 50 years), thinning intensity (0, 15 and 30% stems) and fertilisation (0, 50 and 100 kg ha⁻¹ N) in order to study the effects of different management regimes on site fertility. Our results indicated that some of the current prescriptions could produce a considerable loss of nitrogen, and in some cases, a decrease in productivity after the third 25-year rotation. However, other prescriptions can keep productivity and soil organic matter at acceptable levels. The results of our analysis illustrated the portability and utility of FORECAST as a scenario-analysis and decision-support tool in managing pine plantations in the Caribbean region and, potentially, elsewhere.

Keywords: Sustainable forest management, model testing, model evaluation, thinning, fertilisation, Caribbean pine, chronosequence, FORECAST, hybrid model

BLANCO JA & GONZÁLEZ E. 2010. Meninjau kemampuan panduan pengurusan semasa untuk ladang *Pinus caribaea* di Cuba : satu pendekatan pemodelan. Model ekosistem FORECAST diguna untuk menilai kemampuan amalan pengurusan semasa di ladang *Pinus caribaea* di Pinar del Río (barat Cuba). Ramalan model termasuk dalam julat cerapan ukuran lapangan bagi ketinggian, diameter, ketumpatan batang dan isi padu. Prestasi model agak baik dalam menawan data umum tumbesaran (nilai r bagi ketinggian dominan, diameter dan isi padu boleh niaga masing-masing ialah 0.91, 0.77 dan 0.81). Dalam bahagian kedua kajian ini, output model bagi isi padu boleh niaga, biojisim batang, bahan organik tanah dan N tersedia dalam tanah dianalisis dalam 18 kombinasi berbeza bagi tempoh pusingan (25 dan 50 tahun), keamatan penjarangan (0, 15% dan 30% batang) serta pembajaan (0, 50 kg ha⁻¹ N dan 100 kg ha⁻¹ N). Tujuannya untuk mengkaji kesan amalan pengurusan yang berbeza terhadap kesuburan tapak. Keputusan menunjukkan bahawa sesetengah panduan semasa mungkin mengakibatkan kehilangan nitrogen yang agak besar dan dalam beberapa kes turut mengakibatkan pengurangan hasil selepas pusingan 25 tahun. Bagaimanapun, panduan lain dapat mengekalkan hasil serta bahan organik tanah pada tahap yang memuaskan. Keputusan analisis menunjukkan kemudahan dan utiliti FORECAST sebagai alat analisis senario dan sokongan dalam membuat keputusan apabila menguruskan ladang pain di daerah Caribbean dan mungkin juga di tempat lain.

INTRODUCTION

In Cuba, species from the genus *Pinus* have an important role in the Forest Promotion Plan for the period 1997–2015 (MINAG 1996). Conifers account for 46% of species used in reforestation in Cuba (Marrero et al. 1998). The economic and social importance of pine forests in Cuba, particularly in Pinar del Río province, is high.

Forests provide timber for multiple uses for local communities and they are usually established in soils too poor to sustain intensive agriculture. *Pinus caribaea* var. *caribaea* is an endemic species from Pinar del Río and Isla de la Juventud (western Cuba), but plantations of this species are now common in central America and also

in areas of central Africa and South-East Asia (Rance *et al.* 1982, Kadeba 1989, Montero-Mata *et al.* 2000). Besides its fast growth, it is valued for its high quality timber and ecological plasticity. However, management plans for *P. caribaea* have traditionally been designed by trial-and-error techniques, which can be very slow in terms of finding the optimal management practices for timber production. Forest management plans in the recent past were mostly designed using simple stand inventory data. Foresters could rely on relatively simple empirical growth and yield curves and tables to guide management practices. Unfortunately, this simple approach does not allow analyses of long-term ecological consequences and sustainability of alternative management plans. The ongoing transition to ecosystem-based forest management, however, requires managers to project probable outcomes of alternative management options within the context of managing the forest for multiple values. This has increased the level of complexity in forest management as it requires the development of decision-support tools that allow for greater flexibility in representing management and environmental conditions, with a scientifically sound representation of ecosystem processes (Kimmins 2004).

To achieve sustainability, a forest practice must succeed in three goals: (1) to be economically and socially profitable when perpetuating forest existence, (2) to maintain biodiversity in the managed area and (3) to maintain nutrient contents in soils and biomass (Sverdrup & Svensson 2002). Forest management practices may affect the long-term sustainability of ecosystem structure and function. Thus, harvesting methods may reduce soil fertility as a function of type of harvesting (e.g. whole-tree harvesting vs. stem harvesting), thinning intensity, rotation time length, fertilisation practices and site quality (Blanco *et al.* 2005). All these factors must be assessed in order to achieve sustainable forest management. In this context of growing concern for forest management sustainability, the use of ecological models as decision-support tools is becoming increasingly important. These models, however, have to be simple enough to be of practical use and at the same time complex enough to capture the basic ecological interactions between forest ecosystem components (Kimmins *et al.* 2008). In addition, these tools have to be flexible to be adapted to local conditions of species and management

combinations. Modelling has been suggested as a good technique to analyse sustainability of forest productivity.

Most of the models used in forest management and research can be classified either as statistical or process-based models (Kimmins 2004). Statistical models project future forest variables for a given set of forest conditions based on a database of previous field observations from sources such as permanent plots or forest inventories. These models are common in forest management because of their simplicity and ease of use and for being based on real field data, but their use is limited to conditions similar to where the original data were collected (Kimmins *et al.* 2008). On the other hand, process-based models project future conditions using empirical relationships between ecosystem variables and tree growth. These models are a good summary of the current knowledge on tree physiology and they can be used to project tree growth under changing conditions. However, they usually rely on complex equations and parameters that are difficult to measure in standard forest management. As a consequence they are usually used only in forest research (Blanco *et al.* 2007).

As an alternative, hybrid models have been designed to modify statistical data with simplified representations of ecosystem processes. This way, the credibility and ease of use of statistical models are preserved but the physiological knowledge of process-based models is included (Kimmins *et al.* 1999). This fact makes hybrid ecosystem models most adequate to research long-term sustainability of forest management under changing conditions (Kimmins *et al.* 2008).

In this research, we focus on the potential role of the ecosystem-level forest management model FORECAST as a tool to analyse the ecological sustainability of forest management. Although FORECAST has achieved widespread application and has been successfully evaluated in temperate conditions (Blanco *et al.* 2007, Seely *et al.* 2008), its predictions have not been tested against an independent data set in tropical conditions. To our knowledge, Haynes' (2006) pioneer work is the only study carried out in this area using ecosystem-level forest management models. To fill this gap, this paper reports on a series of comparisons between FORECAST predictions and a field data set from *P. caribaea* plantations in Pinar del Río. After evaluating the performance of FORECAST we illustrate its usefulness as a

decision-support tool for managers in Cuba, and its possibilities in tropical forestry by analysing impacts of different combinations of thinning intensity, fertilisation regimes and rotation length on different ecological variables.

MATERIALS AND METHODS

The FORECAST model

FORECAST is a deterministic, management-oriented, stand-level forest growth and ecosystem dynamics simulator. A detailed description of the FORECAST model is provided in Kimmins *et al.* (1999) but a summary is provided here. The model was designed to accommodate a wide variety of harvesting and silvicultural systems in order to compare and contrast their effects on forest productivity, stand dynamics and a series of biophysical indicators of non-timber values. Projection of stand growth and ecosystem dynamics is based upon a representation of the rates of key ecological processes regulating the availability of, and competition for, light and nutrient resources. The rates of these processes are calculated from a combination of historical bioassay data (biomass accumulation in component pools, stand density, etc.) and measures of certain ecosystem variables (decomposition rates, photosynthetic saturation curves, among others) by relating 'biologically active' biomass components (foliage and small roots) with calculations of nutrient uptake, the capture of light energy, and net primary production. Using this 'internal calibration' or hybrid approach, the model generates a suite of growth properties for each tree and plant species to be represented. These growth properties are subsequently used to model growth as a function of resource availability and competition. They include (but are not limited to) (1) photosynthetic efficiency per unit foliage biomass based on relationships between foliage biomass, simulated self-shading and net primary productivity after accounting for litterfall and mortality, (2) nutrient uptake requirements based on rates of biomass accumulation and literature- or field-based measures of nutrient concentrations in different biomass components at site of different qualities, and (3) light-related measures of tree and branch mortality derived from stand density input data in combination with simulated light profiles. Light levels at which foliage and tree mortality occur are estimated for each species.

FORECAST performs many calculations at the stand level but it includes a submodel that disaggregates stand-level productivity into the growth of individual stems with user-inputted information on stem size distributions at different stand ages. Top height and diameter at breast height (dbh) are calculated for each stem and used in a taper function to calculate total and individual gross and merchantable volumes. FORECAST has four application stages, namely, (1) data assembly and input verification, (2) establishing the ecosystem condition for the beginning of a simulation run (by simulating the known or assumed history of the site), (3) defining a management and/or natural disturbance regime, and (4) simulating this regime while analysing model output. The first two stages represent model calibration.

Data from three chronosequences (each one developed on homogeneous conditions, representing three different nutritional qualities) were used to calibrate the accumulation of biomass (above- and belowground components) in trees and minor vegetation at different stand ages. Tree biomass and stand self-thinning rate data are often generated from height, dbh and stand density output of traditional growth and yield models in conjunction with species-specific component biomass allometric equations. To calibrate the nutritional aspects of the model, data describing the concentration of nutrients in the various biomass components are required. FORECAST also requires data on the degree of shading produced by different quantities of foliage and the photosynthetic response of foliage to different light levels. A comparable but simpler set of data for minor vegetation must be provided if the user wishes to represent this ecosystem component.

Lastly, data describing rates of decomposition of various litter types and soil organic matter are required for the model to simulate nutrient cycling. The second aspect of calibration requires running the model in 'set-up' mode to establish initial site conditions. The detailed representation of many different litter types and soil organic matter conditions makes it impractical to measure initial litter and soil conditions directly in the field; consequently, the model is used to generate starting conditions (for a broader discussion on this topic see Seely *et al.* 2002, Welham *et al.* 2007). Starting conditions were created following the same procedure for both the evaluation of FORECAST and the thinning and fertilisation

projections, by simulating five times a 200-year cycle of forest growth with a stand-replacing hurricane at year 100 and a wildfire at year 200.

Calibration data

Data for model calibration of growth and yield and nutrient concentrations in several tree tissues were provided by several works conducted in the region of Alturas de Pizarras, Pinar del Río (González 1999, Herrero 2001, Márquez-Montesino *et al.* 2001, García 2003, García-Quintana *et al.* 2007). Aboveground biomass and litterfall production rates were estimated with data provided by Kadeba (1989), Vidal *et al.* (2004) and Khadka (2005). Soil processes were calibrated with data from Smith *et al.* (1998) and Herrero (2001) and litterfall, with data from González (2008a).

Study sites

Data from 17 *P. caribaea* plantations established at sites of different qualities in Pinar del Río province (western Cuba) were used to create the data set for comparison with FORECAST output. These plantations were pure stands of *P. caribaea* with little understorey. Dominant vegetation in the natural forest in the same area is composed by *P. caribaea*, *Pinus tropicalis*, *Quercus oleoides* ssp. *sagraeana*, *Byrsonima spicata*, *Curatella americana* and *Sorghastrum stipoides*. Although all data came from homogeneous plantations of *P. caribaea* in the same region, stands differed among them in the number of tree strata (1 or 2), the importance of the understorey (most of the stands have very little, but some can have a well developed grass layer) and soils (usually acid, sandy, nutrient-poor soils but with variations in the cation exchange capacity) (Del Risco 1991). Mean annual precipitation values range from 1350 to 1700 mm, with mean annual temperatures ranging from 24 to 27 °C (Herrero *et al.* 1985). Soils in the region are classified as eroded lixiviated yellow ferralitic cuarcitic soils (Obregón & Morleno 1991), with schist and slates as bedrocks (Anonymous 1980).

Model evaluation

A linear regression of predicted vs. observed values was fitted to calculate the square of Pearson's correlation coefficient (r^2). In addition,

two different indexes were calculated. The first was Theil's inequality coefficient U (Theil 1966):

$$U = \sqrt{\frac{\sum_{i=1}^n D_i}{\sum_{i=1}^n \text{observed}_i^2}}$$

where

- D_i = observed value_{*i*} – predicted value_{*i*} (for a given variable, the difference between the measured and simulated value *i*)
- n* = number of data pairs

U can assume values of 0 and greater. If U = 0 then the model produces perfect predictions. If U = 1 it indicates maximum disagreement between the model predictions and observations. This means that the model is not better than using the average of observed data and assuming no changes in the future. If U > 1, then the predictive power of the model is worse than assuming no changes from the average of observed values. The second index was modelling efficiency (ME), defined by Vanclay and Skovsgaard (1997) as:

$$ME = 1 - \frac{\sum D_i^2}{\sum (\text{Observed}_i - \text{predicted})^2}$$

This statistic provides a simple index of performance on a relative scale, where ME = 1 indicates a perfect fit, ME = 0 reveals that the model is not better than a simple average, while negative values indicate poor model performance.

In a second set of analysis, the accuracy of model predictions was determined using the technique described by Freese (1960) and modified by Reynolds (1984). The critical error e^* can be interpreted as the smallest error level, in absolute terms, which will lead to the acceptance of the null hypothesis (i.e. that the model is within *e* units of the true value) at the given level. Then, if a user specifies a value of *e* (difference between real and modelled data) higher than e^* then the conclusion will be that the model is adequate. Therefore, these critical errors relate model accuracy to user's requirements. With this test the model is judged to be accurate unless there is strong evidence to the contrary. The critical error test was done at 5 and 20% error

levels ($\alpha = 0.05$ and $\alpha = 0.20$), corresponding to an exigent and a less demanding model user respectively.

In addition to goodness-of-fit indexes, we also carried out equivalence tests. Traditionally, t -tests and χ^2 tests have been widely used to validate model predictions. However, these tests have significant shortcomings. For example, in the case where there is a failure to reject the null hypothesis of agreement between the model and field observations, they provide little information as to whether the failure to reject was merely the result of a test with low power or was actually due to poor model performance (Robinson & Froese 2004). At the other extreme, tests with large sample sizes may have the capability to detect deviations that are not significant biologically (Smith & Rose 1995). These problems can be avoided using a null hypothesis of dissimilarity between the observed and predicted data (Robinson & Froese 2004, Robinson *et al.* 2005). Hence, we evaluated the null hypothesis of dissimilarity between observed and predicted values using an equivalence test. This test requires the user to select a criterion to define the acceptable level of model accuracy (Robinson & Froese 2004). Two criteria (ε) were expressed relative to the sample standard deviation (25 and 50%) to represent a 'strict' and 'liberal' criteria respectively, according to guidelines in Wellek (2003). We compared the t -value (t_d) calculated as follows:

$$t_d = \frac{\text{Average}_{\text{observed} - \text{predicted}}}{\text{Standard error}_{\text{observed} - \text{predicted}}}$$

with the cut-off C , which is the α -quantile of the non-central F distribution with degrees of freedom $v_1 = 1$ and $v_2 = n - 1$, and non-centrality parameter $\psi^2 = n \times \varepsilon^2$. If the absolute t -value is lower than the cut-off, the null hypothesis of dissimilarity is rejected (Robinson & Froese 2004). In essence, the test is simply to check whether the critical values ($\alpha = 0.05$) of a two-tailed F distribution (the C parameter) are contained within the rejection region defined by the selected criteria ($-\varepsilon$, $+\varepsilon$). The power of this test (β) was calculated using the following expression (Wellek 2003):

$$\beta_{\alpha; n-1}(\varepsilon) = 2F_t(C_{\varepsilon; n-1}(\varepsilon)) - 1$$

where F_t is the cumulative distribution function for the non-central t distribution.

Thinning and fertilisation simulations

In order to illustrate the feasibility of FORECAST as a management tool, we analysed the projected tree size (dbh, top height) and volume for current fertilisation and thinning practices in Pinar del Río for a site quality representative of most of the managed stands in the area (site quality index, i.e. a measure of the quality of the site and measured as tree height at a given age is 24 m at year 25). Stands of lower quality exist in the area but are not under formal management, and sites of higher quality are under more intensive management not suitable for most of the regular stands in the area. Therefore, the first round of simulations involves simulating the official existing guidelines for management of *P. caribaea* in this area (Herrero *et al.* 1985, González 1986, Herrero 2001, González 2008a). We simulated a plantation with initial density of 1333 trees ha⁻¹ and a rotation of 25 years. Fertilisation with 100 kg ha⁻¹ of N was simulated at years 3 and 9. Thinning from below was conducted twice: one at year 7, removing 15% of trees, the other at year 11 removing 30% of trees. To illustrate the utility of FORECAST as a decision-support tool to analyse alternative scenarios, we carried out a second round of simulation: a factorial experiment, simulating 50 years of management under 18 different plans by combining two rotation lengths (25 and 50 years), three thinning regimes (no thinning, light thinning removing 15% or moderate thinning removing 30% of trees at year 12) and three fertilisation regimes (no fertilisation, 50 or 100 kg ha⁻¹ of N at year 12). Finally, in order to explore the feasibility of FORECAST as a long-term planning tool, we simulated 200 years of future management under two different kinds of scenarios. The first one was low-impact forestry, with a rotation length of 50 years, no thinning, no fertilisation and stem-only harvesting, designed to maximise volume production when keeping human intervention to the minimum. The second type of management was an intensive plan of 25-year rotations, thinning at years 7 and 12 and fertilisation at years 3 and 9 (as explained before) and whole-tree harvesting (stems, bark, branches and foliage removed from the site), designed to provide a quick production of biomass.

RESULTS

Model evaluation

The model acceptably reproduced main growth trends in both height and diameter, although predictions of volume were slightly less accurate. Although field data had a high dispersion, FORECAST predictions were close to the average value of field observations and always inside the observed data range (Figure 1). Indexes displayed in Table 1 indicated a similar acceptable performance. The square of Pearson's correlation coefficient (r^2) was high for all variables, especially for dominant height, with the model being able to reproduce 83% of observed variance. Modelling efficiency values showed that FORECAST was an efficient model for predicting height and diameter, although its efficiency was lower for merchantable volume. This reduced efficiency was probably caused by the overestimation of volume after 20 years of simulation (Figure 1). Theil's inequality coefficient indicated that predictions by FORECAST were always better than a non-change hypothesis, with very low values for dominant height and diameter. The values of Freese's critical error e^* were similar to the natural variability of observed data for the studied variables, indicating that the model could meet the requirements even of the most exigent user (as defined above). Results from the equivalency test showed that with the strict choice threshold ($\epsilon = 25\%$), the null hypothesis of dissimilarity between observed and predicted data was accepted for dominant height and merchantable volume but rejected for diameter. However, when using the liberal choice, dissimilarity was rejected for all variables except gross volume. Power for the strict choice was above 0.60 for all variables but increased to above 0.95 for the liberal choice.

Simulation of current management plans

Growth and yield predictions for current management prescriptions are illustrated in Figure 2. It shows the positive response in tree growth one year after the first fertilisation. This stage of fast growth was maintained with the second fertilisation. In addition, the first thinning right after the first fertilisation almost did not produce a noticeable reduction in stemwood biomass. However, the more intense second

thinning clearly reduced the total amount of stemwood biomass. Finally, dominant height was not affected by thinning (Figure 2). Nitrogen uptake by trees increased quickly with time as young trees grew bigger, reaching a maximum around 9 years, with small bumps due to thinning (Figure 3). As for nutrient cycling, N mineralised from litterfall was predicted to follow the same declining pattern as litterfall mass, with a substantial release of N at the beginning of the plantation that stabilised after year 10. A big amount of N leaching losses was observed after fertilisation events (the peaks in Figure 3) and a progressive reduction in leaching losses with plantation age was predicted.

Simulation of alternative management plans

Results from the factorial experiment with a number of alternative management plans are presented in Table 2. The most important factor affecting merchantable volume was fertilisation; it was especially important in the 25-year rotations, although this effect was moderate in the long rotation. Rotation length was less important. For biomass, however, rotation length was the most important individual factor. Humus mass (all organic matter in the forest floor and mineral soil that was not litterfall) was generally not seriously affected by any factor, and fertilisation also produced a slight increase in humus mass. Thinning had only marginal effect on the mass of humus (Table 2). As for litterfall mass, fertilisation effects were of opposite signs depending on rotation length, with the biggest decreases in forest floor mass having intense fertilisation in short rotations but small increases in 50-year rotation (Table 2). Effects of rotation length in forest floor mass were small but thinning caused a moderate increase. Finally, available soil N after 50 years of management was the variable with the biggest differences between rotation lengths and between management plans (Table 2). One 50-year rotation had 59.5% less available soil N at year 50 than two consecutive 25-year rotations. However, for the short rotations, the average effect of fertilisation was a reduction of 28.5 and 58.5% for the low and moderate fertilisation respectively. This negative effect was opposed by average increases due to thinning. On the other hand, fertilisation and thinning effects were much smaller in the 50-year rotation plantation,

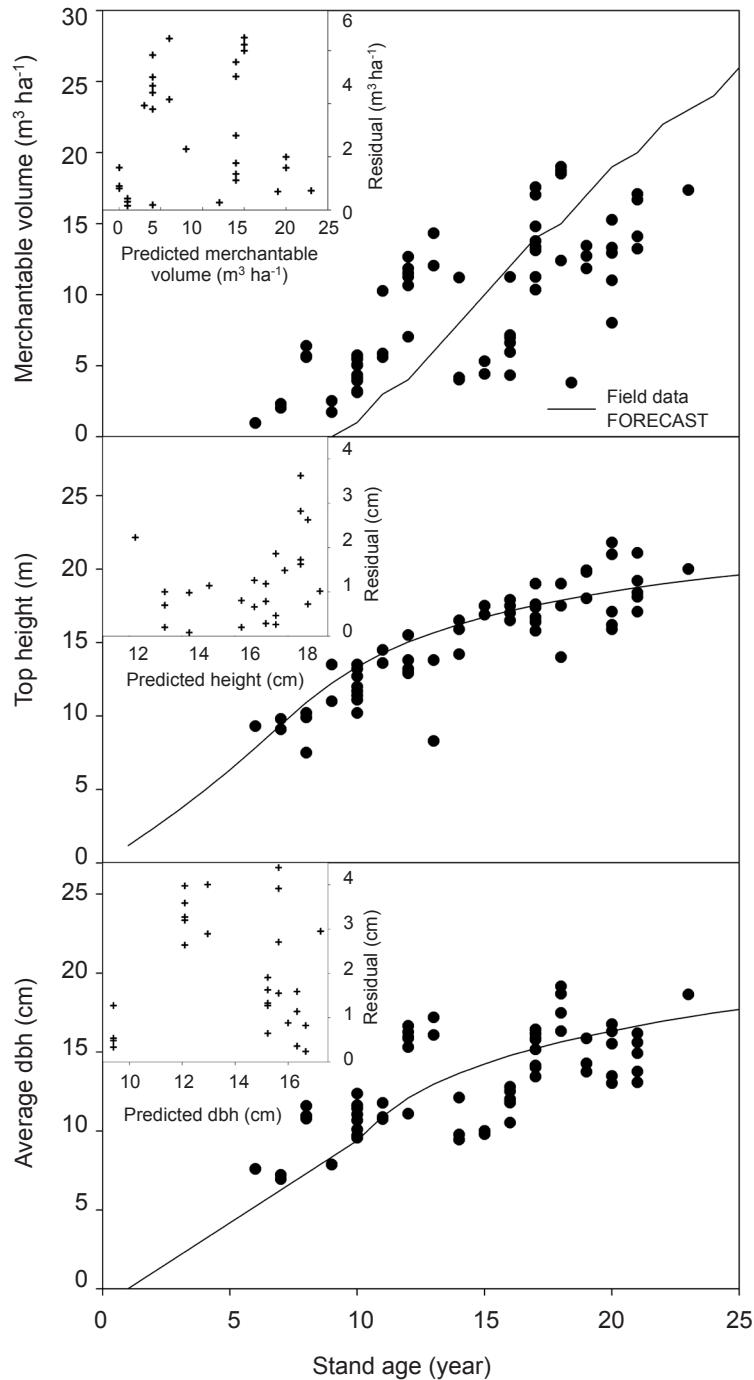


Figure 1 FORECAST predictions (solid line) and field data obtained for *Pinus caribaea* plantations in western Cuba (dots) for merchantable volume (top panel), dominant top height (medium panel) and average dbh (bottom panel). Residuals for the linear regression of observed vs. predicted are in the small panel for each variable.

with reductions due to fertilisation and increases due to light thinning.

Analysis of long-term sustainability

Figure 4 shows how an intensive short-rotation scheme can be more unsustainable and nutrient-

depleting in the long term than a longer and less intensive series of 50-year rotations. Although for both series of rotations the long-term pattern showed a decrease in productivity, this decrease was more severe in the 25-year rotation. It also showed how both strategies had pros and cons: short rotations provided forest products (and

Table 1 FORECAST performance results of observed vs. predicted values for three variables in *Pinus caribaea* plantations in western Cuba

Index	Dominant height	Diameter	Merchantable volume
Bias	3.55%	0.49%	5.84%
r ²	0.83	0.60	0.66
U	0.11	0.20	0.45
ME	0.99	0.96	0.80
e* $\alpha = 0.05$	2.86 m	4.79 cm	7.52 m ³ ha ⁻¹
e* $\alpha = 0.20$	1.98 m	3.33 cm	5.21 m ³ ha ⁻¹
t _d	3.05	0.19	-1.03
C ($\epsilon = 25\%$)	0.49	0.30	0.52
C ($\epsilon = 50\%$)	8.91	7.05	9.23
Diss ($\epsilon = 25\%$)	Not rejected	Rejected	Not rejected
Diss ($\epsilon = 50\%$)	Rejected	Rejected	Rejected
β ($\epsilon = 25\%$)	0.74	0.63	0.75
β ($\epsilon = 50\%$)	0.97	0.96	0.97

U = Theil's coefficient; ME = modelling efficiency; e* = Freese's (1960) critical error; t_d = equivalence t-value; C = equivalence cut-off; Diss = hypothesis of dissimilarity; β = power of the equivalence test

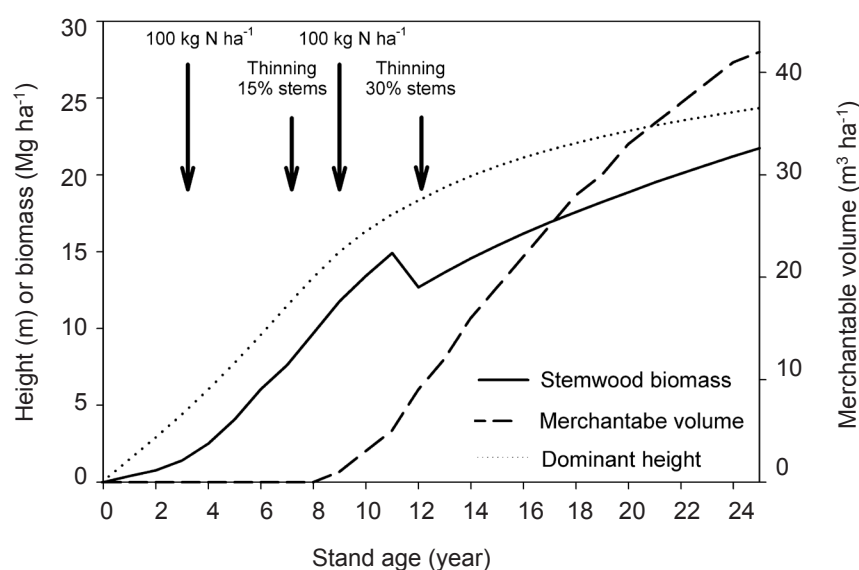


Figure 2 Growth and yield predictions for a simulated *P. caribaea* plantation in western Cuba under current local management prescriptions for a good site (site index 24 m at year 25) and an initial plantation density of 1333 stems per hectare. Arrows indicate the year of application of prescribed fertilisation and thinning.

therefore cash) more frequently than long rotations, creating a more stable cash-flow for forest managers. However, the accumulated production was 255.4 Mg ha⁻¹ of total tree biomass or 259 m³ ha⁻¹, much less than the 362.1 Mg ha⁻¹ of total tree biomass or 417 m³ ha⁻¹ that can be extracted from plantations of

50-year rotations. This decrease in productivity was coupled with a decrease in humus biomass, which was reduced by 75.1% in short rotations and by 46.6% in long rotations. Finally, changes in available N through time are clear in both management plans. For the 25-year rotations, the peaks created by fertilisation are clear, but

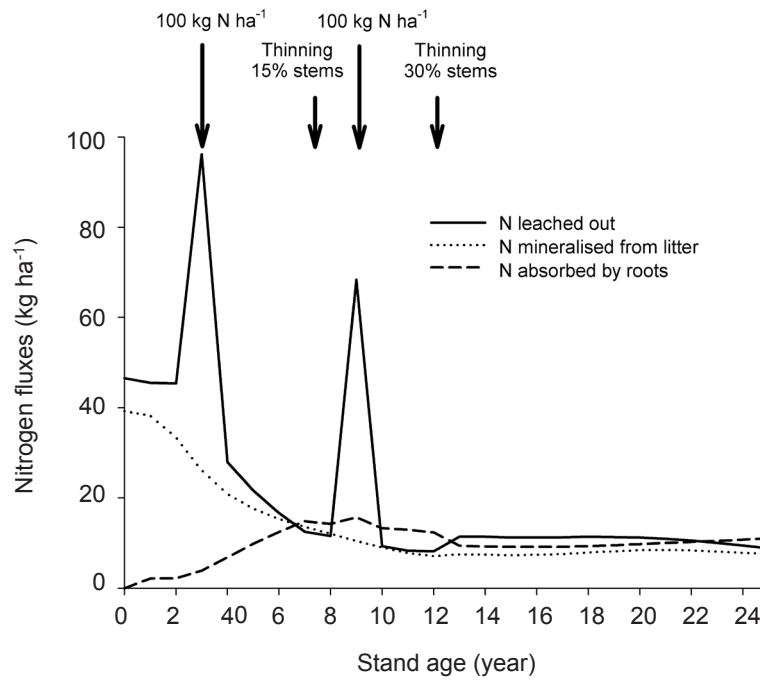


Figure 3 Nitrogen cycle in a simulated *P. caribaea* plantation in western Cuba under current local management prescriptions for a good site (site index 24 m at stand age 25) and an initial plantation density of 1333 stems per hectare. Arrows indicate the year of application of prescribed fertilisation or thinning.

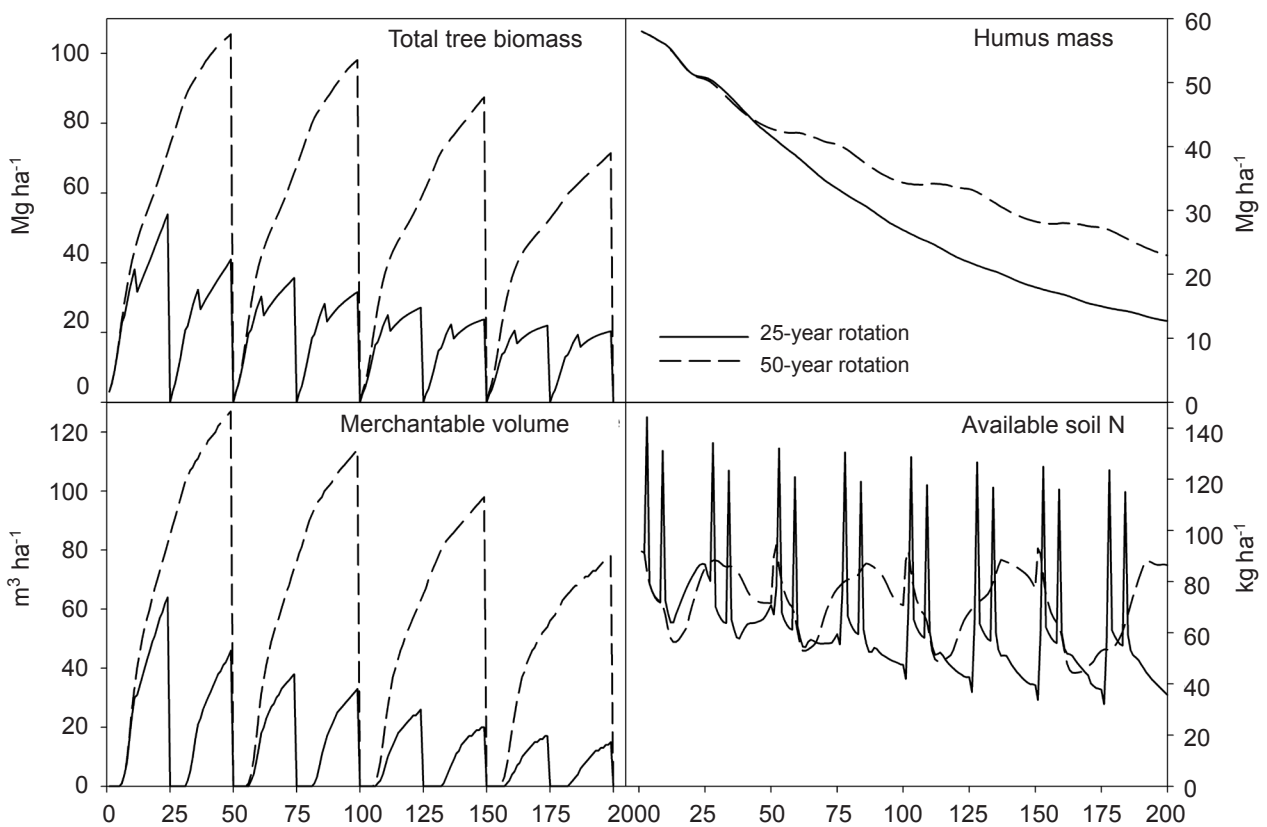


Figure 4 Evolution of stemwood biomass, merchantable volume, humus mass and litter mass in a simulated *P. caribaea* plantation in western Cuba under current local management prescriptions (25-year rotation) and alternative 50-year rotations, for 200-year simulation

Table 2 Values at year 50 (after one 50-year rotation or two consecutive 25-year rotations) for several ecosystem variables

Rotation length (years)	Thinning intensity (% trees removed)	Fertilisation		Merchantable volume		Stemwood biomass		Humus mass		Litterfall mass		Available N in soil		
		kg ha ⁻¹	NP	m ³ ha ⁻¹	Fert %	Thin %	Mg ha ⁻¹	Fert %	Thin %	Mg ha ⁻¹	Fert %	Thin %	kg ha ⁻¹	Fert %
25	0	0	0	120		67.5		41.6		73.7		73.7		
		50	50	145	20.8		75.9	12.4	42.8	2.9	74.3	0.8	74.3	-53.3
	15	0	0	117		61.8	-2.5	41.5	-0.2	77.8		77.8		
		50	50	141	20.5	-2.8	69.5	-8.4	42.8	3.1	76.4	-1.8	76.4	-22.4
	30	0	0	108		54.5	-10.3	41.6	0.0	80.6		80.6		
		50	50	131	21.3	-9.9	61.9	-20.1	42.8	2.9	79.2	-1.7	79.2	-9.7
	50	0	0	0	117		50.6		42.8		71.6		71.6	
			50	50	131	12.0		55.2	9.1	43.4	1.4	74.2	3.6	74.2
		15	0	0	112		47.2	-4.3	43.0	0.5	71.4		71.4	
			50	50	126	12.5	-3.8	52.0	-5.8	43.6	1.4	74.3	4.1	74.3
30		0	0	104		42.9	-11.6	43.1	0.7	71.6		71.6		
		50	50	117	12.5	-11.1	47.5	-14.8	43.9	1.9	73.3	2.4	73.3	-8.9
100		0	0	120	15.4	-10.2	48.2	-14.4	44.4	3.0	73.5	2.7	73.5	-6.7
		50	50	128	14.3	-3.8	52.6	11.4	44.0	2.3	76.4	7.0	76.4	-4.3
100		0	0	104		42.9	-11.6	43.1	0.7	71.6		71.6		
		50	50	117	12.5	-11.1	47.5	-14.8	43.9	1.9	73.3	2.4	73.3	-8.9
100	0	0	120	15.4	-10.2	48.2	-14.4	44.4	3.0	73.5	2.7	73.5	-6.7	
	50	50	128	14.3	-3.8	52.6	11.4	44.0	2.3	76.4	7.0	76.4	-4.3	

Merchantable volume and stemwood biomass are values accumulated after harvesting for one 50-year or two 25-year rotations; Fert % = relative change in the given variable compared with the non-fertilised combination of rotation-length and thinning intensity; Thin % = relative change in the given variable compared with the non-thinned combination of the same rotation-lengths and fertilisation

the productivity showed a decreasing pattern that ended at 35.7 kg ha⁻¹ at year 200, a reduction of 61.1% from the starting point. This reduction is much smaller in the 50-year rotations, with 86.3 kg ha⁻¹ of available soil N or a decrease of 5.9% after 200 years of exploitation.

DISCUSSION

Model performance

FORECAST seemed to perform acceptably well for management standards according to all the indexes of model performance explored in this work. In the present analysis, three different measures of goodness-of-fit were calculated and, in general, all showed acceptable fits between observed and predicted values. Although biases were found for all the three variables, their small values were acceptable for regular management plans, which usually deal with degrees of uncertainty higher than the bias produced by the model. The r^2 coefficient indicated acceptable agreement between observed and predicted values. The associated linear regressions can be considered a 'hypothetical re-calibration' (Mayer & Butler 1993) in which the model minimises these differences between predicted and observed values. However, it has been argued that it is not the most reliable measure of model performance because the r^2 coefficient is not related to the perfect fit line (the line in which observed equals predicted) (Power 1993). As a consequence, this coefficient was more about the capacity of the model to get a calibration data set to reduce differences between observed and predicted values rather than a measure of 'perfection' of predictions by the model.

Similar insights of model performance were given by Theil's U coefficient (Theil 1966). Results for this statistic were always lower than one, indicating that the model always performed better than the hypothesis of no change. In other words, the model was a better predictor than a general mean value. Values of Theil's U and r^2 also indicated that the model simulation results were similar to observed data. The inequality coefficient U also indicated that model outputs were better than projections of averages of present conditions that assumed no changes in future forest growth. The ME statistic also pointed out to FORECAST as an efficient model with values close to one. This index was proposed

as an important overall measure-of-fit by Mayer and Butler (1993) and was also recommended by Power (1993) and Smith *et al.* (1998) because ME is a dimensionless statistic which directly relates model predictions to observed data. In addition, average biases were also small, in spite of the high dispersion of the field data compared with model output.

Although goodness-of-fit analysis gives us useful insights into model performance, we also should ask whether we can distinguish model predictions from reality. Freese's critical errors were set as a limit of acceptable accuracy for model users. Therefore, FORECAST calibrated for this area would serve well exigent users who specify minimum levels of accuracy above the values presented in Table 1. These values (and more so for a relaxed user) were well inside the levels of uncertainty and error range of most height, diameter and volume assessment for regular management plans. Finally, the equivalence tests showed that model predictions were not distinguishable from field measures when moderate accuracy was needed for volume and height. However, for diameter and situations that require more accurate predictions, the model can produce a series of output that are considered as coming from a data population different from observed measurements. This level of accuracy is, however, usually reserved for more sophisticated research on ecological processes (Blanco *et al.* 2007), and it is hardly ever needed for practical management operations (Kimmins *et al.* 2008). We are confident that the accuracy needs of the most regular management plans in this area are met by FORECAST with the calibration data set used. This good statistical behaviour is also supported by the graphical results shown in Figure 1, with model predictions inside the range of observed values of the selected variables and residuals not showing any distinctive pattern. All things considered, our results support the use of this ecosystem-level model in the management of *P. caribaea* in this region as a way to improve predictions and to develop more adequate forest management plans.

One final consideration when testing FORECAST for Caribbean conditions was that to test and apply such models in tropical conditions, the scarcity and difficulty in obtaining long-term data on tree growth and yield are usually a problem. This is especially true for *P. caribaea* in Cuba. Thus, as a way of using all the

scarce information, we decided to include all the available data to create the database in order to not subjectively select some plots above others. This approach is better when testing the feasibility of using a model in a new area because it relates model outputs to the whole set of observed situations in the field, and not just to a limited sample of field conditions. In addition, given that FORECAST is an ecosystem-level model, the simulation of ecosystem processes should also be tested against ecological variables such as litterfall and humus masses and litterfall production rates (Blanco *et al.* 2007). Unfortunately, due to the scarcity of ecological studies related to this species in western Cuba, we were not able to obtain an accurate and extended database of these variables to be tested against FORECAST predictions. To solve this problem we have set a series of experiments and long-term plots that will provide the needed data in the future (González 2008b). In addition, we provided data on some ecological variables provided in studies of *P. caribaea* carried out in other countries (Table 3). Although these data are not directly comparable with the output from FORECAST (different ecosystem conditions, different stand densities, different climate and soils, etc.), they are an example of how FORECAST is at least able to produce predictions of variables other than traditional growth and yield outputs that are in the range of observed field data.

Sustainability of current prescriptions

Given the acceptable performance of the model, we feel confident in our analysis of alternative

management prescriptions. The existing official prescriptions provided by the Cuban forest authorities seem to be improving growth and yield in *P. caribaea* plantations. The positive response to the first fertilisation showed how the model was able to simulate the main ecological processes involved in tree growth. At the time of the first fertilisation (year 3), trees were young and in a stage of free growth and maximum photosynthetic production. However, because trees are still small and there are usually few roots in planted trees near the soil surface (Bowyer 2001), total N uptake is also small and, therefore, most of the N provided by fertilisation is leached away. Similar effects have been reported by Heilman and Norby (1998) in tropical poplar plantations. This fact is an indication that the fertilisation rate for this first application of urea could likely be reduced without affecting tree growth, and thus fertilisation costs and impacts on other parts of the ecosystem could also be reduced (Heilman & Norby 1998). Similar problems of high losses of N after fertilisations early in the rotation have occurred in other areas of the tropics (Bigelow *et al.* 2004, Silver *et al.* 2005). The second fertilisation (at year 9) seemed to be more effective and it was predicted by FORECAST that fertilisation will push tree growth to the stage of starting to produce merchantable volume. However, N losses by leaching were still high because tree uptake was not able to recover the entire N that was being applied. This can be interpreted as that there is no critical need to fertilise these plantations at the current level because the N provided by decomposing litterfall in the first part of the

Table 3 Comparisons of field observations of ecological variables and FORECAST outputs for the same stand ages but in plantations in western Cuba

Variable	Observed value	FORECAST	Stand characteristics for field observation	Source
Small root biomass (Mg ha ⁻¹)	1.00	0.95	11-year-old plantation in Puerto Rico	Cuevas <i>et al.</i> (1991)
	0.81	0.55	4-year-old plantation in Puerto Rico	Lugo (1992)
Biomass production (Mg ha ⁻¹ year ⁻¹)	0.30	0.53	14-year-old plantations in Nigerian savannahs	Kadeba (1989)
	0.56	0.59	18-year-old plantation in Puerto Rico	Lugo (1992)
Litterfall production (Mg ha ⁻¹ year ⁻¹)	4.50	4.02	14-year-old plantations in Nigerian savannahs	Kadeba (1989)
	2.12	1.33	4-year-old plantation in Puerto Rico	Lugo (1992)
N in litter (kg ha ⁻¹)	155	180	19-year-old plantation in Brazil	Poggiani (1985)

rotation and then by humus may be enough to support tree requirements. Composite NPK chemical fertilisers are not usually applied in the area given their high costs and the difficulty in obtaining them in Cuba. It has been pointed out that many tropical forests are not especially deficient in N (Silver *et al.* 2005). However, some soils in the area of Altura de Pizarras are slightly deficient in P (Obregón & Morleno 1991). This P deficiency may cause the increase in tree growth after N fertilisation to be lower than if N is the only limiting factor. This could explain why the simulated increases in biomass and volume were also moderate. In addition, it has also been suggested that N fertilisation can increase N nitrification from litterfall and, therefore, the risk of losses from the system also increases (Silver *et al.* 2005). All things considered, a review of the current fertilisation prescription should be carried out, especially if the future goal is to move towards a low-input forestry in the area. Our results also indicated that there was a trade-off between using intensive fertilisation for short- or long-term objectives. In short rotations, intensive fertilisation can accelerate tree growth, but more frequent biomass removals can cause soil organic matter depletion. Combined with long rotations, intensive fertilisation can be a tool to maintain soil fertility in the long term. If fertilisation is applied, selecting the dry season for it can be a way to reduce leaching losses (Laclau *et al.* 2005).

On the other hand, it was not clear that the first thinning had an actual impact on growth. Biomass reduction was very small and model outputs clearly show that this light thinning from below only eliminated trees that were very small or sick, or even dead. It has been proven that, in pine forests, light thinning is not able to reduce resource competition (Blanco *et al.* 2006, 2008, 2009). As a consequence, it is expected that thinning at this early stage will not substantially improve conditions for remaining trees. In this case, forest managers may consider whether this early thinning can be eliminated from the management plan and, therefore, saving the associated operational costs and environmental impacts. The model, however, predicted that the second thinning, carried out in a more developed stand (year 11) and removing a higher percentage of trees, had evident effects on growth of remaining trees. This second thinning reduced standing stemwood biomass and final

harvest volume, but it also produced some timber products ready to be used and commercialised, which could be important to maintain a more constant cash flow. In addition, trees removed by the second thinning were competitors of remaining trees for light and crown space, and their removal clearly accelerated the production of merchantable volume. However, merchantable volume increased by almost 20% in the most intensive plans when compared with the longer 50-year rotations. Therefore, an economic analysis should be carried out to study if this production increase compensate for the increased production costs in fertilised, thinned and short-rotation scenarios. Nevertheless, longer rotations provide the ecosystem more time to recover from the human-induced disturbances, and longer rotations are likely more similar to the ecological rotation for natural Caribbean pine forests (Morris *et al.* 1997, Kimmins 2004).

An important aspect to be taken into account when assessing sustainability of forest practices is soil organic matter. The maintenance of a sufficient level of organic matter in the long term is needed to support tree growth because decomposition of humus and litterfall are the main source of nutrients for trees (Kimmins 2004). Forest productivity *per se* is not a good indicator of soil sustainability (Richardson *et al.* 1999) and the evolution of organic matter in the long term has been proposed as an important indicator of forest management sustainability (Morris *et al.* 1997). This is one of the main improvements of FORECAST when compared with traditional growth and yield tables, which lack the capability to predict soil organic matter evolution. Short-term forecasts with empirical models based on past observations that lack explicit representation of ecological process are prone to a high degree of bias and inaccuracy when simulating new environmental conditions different from the dominant conditions in the past (Nambiar 1999). However, the capability of FORECAST to simulate soil organic matter dynamics and nutrient cycling gives managers the tool to study the effects of practices such as fertilisation or site preparation on the growth of trees and understorey (Kimmins *et al.* 1999, Bi *et al.* 2007). In our simulations, it was clear that humus in forest soil decreased along the rotation. If intense management is adopted for a long time, organic matter at these sites may decrease to levels low enough to affect tree

production and site quality (Morris *et al.* 1997, Seely *et al.* 2002). Decrease in soil organic matter also means reductions in nutrient release from decomposing organic matter and the soil capacity to retain nutrients. As a consequence, there are less available nutrients resulting in a decrease in production and thus, in economic sustainability, i.e. production and, therefore, revenues from the forest are also reduced. Nitrogen uptake increased with time, with a small decrease caused by thinning. However, its effect was small given that the trees removed by thinning from below were the suppressed, small trees in the stand, which had low nutrient demand. Therefore, the predicted relative decrease in nutrient uptake was smaller than the relative decrease in tree density. Given that organic matter is the main reservoir of nutrients (especially N) besides providing the soil with many physicochemical properties, maintaining acceptable levels of soil organic matter should be a priority when designing sustainable forest management plans (Morris *et al.* 1997, Kimmins *et al.* 1999, Seely *et al.* 2002).

Our results indicated that keeping intensive and short rotations in plantations could be problematic in the long term. Available N, litter and humus biomass decrease faster with short rotations due to less litterfall and enhanced decomposition and mineralisation (Ewel 2006). This effect could be avoided, however, if changes in management are done when the first reductions arise (Heilman & Norby 1998, Bowyer 2001). Our results for the long rotation scenario showed that low frequency of disturbance could lead to the maintenance of N levels in the soil. It has been reported that adaptive management in tropical plantations can increase productivity in the long term (McNabb & Wadouski 1999) keeping in mind, however, that any new management plan should be adapted to local conditions (Nambiar 1999, Bowyer 2001). We should also point out that although being an ecosystem-level model, FORECAST does not currently include simulation of ecosystem features such as hydrology or microclimate, which can affect nutrient cycles and are themselves affected by changing management. This capability is under development. Therefore, a site-specific assessment of the importance of such ecological factors should be done before applying this model. Finally, it is important to know how the uncertainty related to calibration values is transmitted to output variables. Studies on the

sensitivity of FORECAST (Kimmins *et al.* 1999, Blanco *et al.* 2007, Bi *et al.* 2007) indicate that the model is more sensitive to uncertainty of calibration parameters when applied in more complex stands than the one simulated here (multiple tree and understorey species, complex site-preparation practices). Our future research in *P. caribaea* stands will directly address this issue.

CONCLUSIONS

Our work has shown that FORECAST can be a useful decision-support tool to design sustainable forest management plans in tropical plantations. The model can produce acceptable predictions for the most important growth and yield variables and it is also a good research tool for ecological studies. However, to increase the accuracy of the model, data calibration needs to be done more frequently—meaning more time, money and people are required. This model has also been successfully tested in other ecological zones and the consistency of its projections provides expanded credibility to how forest ecosystems are simulated by FORECAST. It also proves how this model can be applied to other forest regions different from the ones used for its original design, demonstrating the high portability of this model when applied to different ecological regions. Finally, our work also showed that N fertilisation did not have important impacts on these sites in western Cuba and that longer rotations were more suitable to ensure higher levels of soil organic matter and, therefore, long-term forest productivity.

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