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Tree diameter increments following silvicultural treatments in a dipterocarp forest in Kalimantan, Indonesia: A mixed-effects modelling approach

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ABSTRACT

An individual-tree-based growth-and-yield model (SILFOR) was developed to evaluate the long-term effects of silvicultural treatments beyond logging in a tropical forest is described. Here we focus on the model's approach to prediction of the magnitude and duration of silvicultural treatment effects on growth of the residual trees that will contribute most of the timber available to the next planned harvest in 25–40 years. Data from 30 1-ha permanent sample plots monitored for up to 20 years in dipterocarp forest in Kalimantan, Indonesia were used to develop the model. The treatments were different logging intensities with or without post-logging silvicultural treatments. Each species was assigned to one of five groups based on their ecological traits and the merchantability of their timber. A mixed-effects model was used to account for the spatially and temporally autocorrelated permanent plot data.

The mixed-effects approach improved model performance substantially compared to a fixed-effects approach; specification of the variance function and correlation structure of the error term further improved model fit. Patterns and rates of tree diameter increment varied substantially, as indicated by the large differences among species groups in terms of the level of random-effects, number of parameters assigned as mixed-effects, and the covariates that define the best model. Similarly, silvicultural treatment effects also varied among species groups, as indicated by differences in the treatment dummy variables in the final model. Among-treatment differences diminished over time. We also found that species group representation is effected differentially by the silvicultural treatments. Overall, the study presents a novel and hopefully useful approach to the analysis of growth-and-yield data from tropical forests under intensified management for timber.

1. Introduction

Given that the growth rates of tropical trees in managed natural forests are extremely variable and often slow coupled with the scarcity of long-term data from permanent sample plots (Clark and Clark, 1999; Gourlet-Fleury and Houllier, 2000), stand projection models are usually employed to extend the findings from monitored permanent plots to cutting cycles or full rotations. Many such models are available, but most were developed for and parameterized with data from stands in which the only silvicultural intervention was selective logging [e.g., SYMFOR (Phillips et al., 2003) and DIPSIM (Ong and Kleine, 1996)]. With increasing recognition that to secure timber yields with financially viable cutting cycle durations, additional silvicultural treatments are often required (e.g., enrichment planting or liberation thinning; Adjers et al., 1995; Fredericksen and Putz, 2003; Peña-Claros et al., 2008; Putz and Romero, 2015), new stand projection models are needed.

We developed an individual tree-based model (SILFOR) and used it to project timber yields, changes in tree species composition, and biomass dynamics in a selectively logged and silviculturally treated forest in Indonesia (Ruslandi et al., 2017). In brief, SILFOR is an empirical growth-and-yield model (Peng, 2000) that simulates population dynamics of trees in tropical forests after silvicultural interventions in a way that takes into account individual tree characteristics and competition. SILFOR includes sub-models for annual diameter growth, mortality/survival, and recruitment. Here we describe the tree diameter growth component of that

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model. We focus on modelling the magnitude and duration of silvicultural treatment effects on growth of the residual trees that will contribute most of the timber available to the next planned harvest in 25–40 years (Ruslandi et al., 2012; Shenkin et al., 2015). We evaluate silvicultural treatment effects by assigning a dummy variable to each as part of the model-development process. We model stem diameter increments in response to differences in logging intensity and the planting of seedlings of native commercial tree species either in the understory or along cleared lines through logged forest.

For model development we used data from 30 one-ha permanent sample plots (PSPs) that were re-measured biennially for up to 20 years. Such data are characterized by spatial and temporal autocorrelations due to their hierarchical structure (trees nested within PSP) and repeated measurements of the same trees. As a consequence, the data clearly violate the assumption of independence required for standard frequentist statistics (e.g., analysis of variance; Laird and Ware, 1982; West et al., 1984; Gregoire, 1987). To address the autocorrelation issue we employ a mixed-effects model approach that is relatively new for tropical forestry but has been used for decades in other fields as well as in temperate-zone and boreal forestry (e.g., Adame et al., 2008; Calama and Montero, 2005; Gregoire and Schabenberger, 1996; Kuehne et al., 2016; Lhotka and Loewenstein, 2011; Pinheiro and Bates, 2000; Pokharel and Dech, 2012; Subedi and Sharma, 2011; Uzoh and Oliver, 2008). The objective of this study is develop diameter increment models using mixed-effects approach for dipterocarp forests following silvicultural interventions and compare them to fixed-effect models in terms of model fit and predictive ability. We also integrate the silvicultural treatment effect evaluation into the model-construction process by assigning silvicultural treatments as dummy variables and comparing all models with different combinations of these variables. Given that future timber yields are determined by the growth rates of trees of commercial species as well as by their representation in the stand, we also assessed the effects of silvicultural treatments on the relative abundances of the different species group, with a focus on the dipterocarp species that are the major source of commercial timber. To the best of our knowledge, this study is among the first to use a mixed-effects model to evaluate the effects of silvicultural interventions beyond logging in tropical forests (e.g., de Avila et al., 2017).

2. Methods

2.1. Study site, silvicultural treatments, and data

The study was conducted in mixed dipterocarp lowland forest in the logging concession of PT Sari Bumi Kusuma (SBK) in Central Kalimantan, Indonesia (0°56′N, 111°68′E; for a detailed site description, see Ruslandi et al., 2017). The forest is characterized by the domination of trees in the Dipterocarpaceae that are also the major commercial species (Sist and Saridan, 1999). These trees are somewhat shade tolerant (Clearwater et al., 1999), so low intensity logging that opens small canopy gaps is a potentially sustainable approach to management of this forest (Sist et al., 1998). Over the past decades and following changes in Ministry of Forestry regulations (MoF, 1989, 2009), SBK has implemented a range of silvicultural treatments and monitored their impacts with the 30 1-ha square permanent sample plots we use in our model. The plots were monitored for 2–20 years after being subjected to one of four silvicultural treatments (Table 1): once-logged with a minimum cutting diameter (MCD) of 60 cm (L60); once logged followed by under-planting with seedlings of commercial timber species (L60UP); twice-logged with MCDs of 60 cm and then 40 cm (L60L40); and, twice-logged followed by strip planting along cleared lines (L60L40SP).

Each 100 × 100 m PSPs was divided into 10 × 10 m subplots in which all trees >10 cm DBH were tagged, identified to species, and monitored for DBH increments; no exact tree positions were recorded in the subplots; recruits were treated likewise when they reached 10 cm DBH. In enrichment-planted PSPs, all planted trees were monitored for survival and growth since they were planted (see Ruslandi et al., 2017 for details about PSP monitoring).

The total data set includes 19,013 trees (15,227 naturally regenerated and 3786 planted) measured 2–13 times for a total of 101,960 observations. To develop a stem diameter increment models for naturally regenerated trees, 65,000 diameter increments were initially obtained (as the difference in diameter from the two consecutive measurements divided by the time between measurements). After deleting obvious measurement errors (i.e., annual increments of <0 or >5 cm for most species or >3 cm for slow-growing species) and additional outliers, which together constituted 0.4% of the observations, and excluding trees that were <10 m from a plot boundary for which competition indices could not be calculated (Gourlet-Fleury and Houllier, 2000), 45,211 diameter increments from 9265 trees remained (Table 2). Trees not included in the growth analyses were used in calculation of competition indexes.

2.2. Species grouping

To render the data on 225 species more manageable for modelling, we grouped them into five species groups (SGs) on the basis of their growth rates, commercial value for timber, and maximum size (Table 2).

2.3. Model development

For each species group, the following modelling steps were followed:

2.3.1. Response variable form selection

Exploratory data analysis revealed that residuals were not normal and showed heteroscedasticity. To achieve normality and reduce heteroscedasticity, the response variable (mean annual

Table 1
Silvicultural treatments monitored in 1-ha PSPs with year of intervention, brief description of the treatments, sample sizes, and years of monitoring of growth, ingrowth, and survival of trees >10 cm DBH (Ruslandi et al., 2017).

Treatment	Treatment date	No. of 1-ha plots	Years of observation	Treatment Description
L60	1994 or 1999	6	14 or 20	Selectively logged once with a minimum cutting diameter (MCD) of 60 cm
L60UP	1994 or 1999	6	14 or 20	UP = under planting at 5 × 5 m; under-brushed annually for the first 5 years
L60L40	2000 or 2007 or 2011	9	2, 8, or 14	Twice-logged with MCDs of 60 cm & then 40 cm with 22-years between harvests (second harvests started in 1999)
L60L40SP	2000 or 2007 or 2011	9	2, 8, or 14	SP = strip planted with spacing between plants & lines of 5 m & 25 m (before 2006) & 2.5 m & 20 m afterwards; seedlings liberated from vines & overhead shade for the first 3 years