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# Long-term term effect of bedding and vegetation control on dominant height of slash pine plantations in the southeastern United States

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ABSTRACT

The long-term effect of bedding and vegetation control on dominant height in slash pine (*Pinus elliottii* Engelm) was evaluated using data from a site preparation study established in 1979 by the Plantation Management Research Cooperative (PMRC) at the University of Georgia in the southeastern United States. The experimental design corresponded to a 2 × 2 factorial with replications over 16 different locations, distributed over the natural range of slash pine. Our results show sustained gains in dominant height, reaching a peak increment around age 11, with values of 1.0, 2.2, and 2.9 m of average gain for the bedding, vegetation control, and combined (Bed + Veg.) treatments, respectively. At age 31, an approximate rotation age, these gains were no longer present for the bedding treatment, whose dominant height trajectory converged to the values of the untreated control and decreased to 1.9 m for both treatments involving competing vegetation control. These results are similar to previously reported results in the literature for these two treatments in slash pine. We proposed a modified Chapman-Richards type model to describe these trends. In this modeling approach, the base equation was modified using a set of dummy variables in the form of power functions to reflect the treatment effect. Both treated and untreated plots were simultaneously fitted in this model, and contrarily to the most common approach of adding an independent factor to a base model to account for the treatment response, our model does not assume the control plot to be error free. The flexibility of the proposed model allows practitioners to include observed gains in dominant height from these treatments. A slash pine site index model using the algebraic difference approach (ADA) was also derived.

## 1. Introduction

Slash pine (*Pinus elliottii* Engelm.) is the second most important commercial species in the southern United States (Barnett and Sheffield, 2004). On its natural habitat, characterized by poorly drained flatwoods and seasonally flooded areas, it outperforms other common commercial pine species, producing high quality timber that encompasses a large portion of the regional timber market (Barnett and Sheffield, 2004). Traditionally in this region of the United States, intensive silvicultural management has been prescribed for commercial forest plantations with the aim of increasing resources available to the crop trees and reducing competition as well as to increase end product value (Fang and Bailey, 2001; Martin et al., 1999). Common silvicultural treatments include bedding, herbaceous and/or woody vegetation control at establishment, fertilization with nitrogen and phosphorus, and thinning (Fox et al., 2007; Jokela et al., 2010). These treatments are long justified by different studies showing significant responses in height, basal area, and volume when they are applied at a juvenile stage (Colbert et al., 1990; Jokela et al., 2000; Zhao et al., 2008), with gains visible at mature ages (Fang and Bailey, 2001; Jokela et al., 2010; Zhao et al., 2009). With the increasing interest to maximize carbon capture, investigating whether these gains are maintained or reduced, close to or beyond traditional harvest ages for the species (25 – 30 years), becomes a question of interest, and one that only few studies can answer.

Snowdon and Waring (1984, 1981), studied the nature of silvicultural responses at early stages in other pine species (radiata pine). Their

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work provided the foundations to characterize growth rates of forest plantations after silvicultural treatments were applied, classifying them into two broad categories that link response to short- or long-term resource availability. Type I responses are the product of those treatments which temporarily increase the growth rate of the stand but do not have a sustained effect on site properties (e.g., nitrogen fertilization, weed control), while type II responses are the result of treatments such as phosphorus fertilization, or continuous nitrogen fertilization, which can generate a sustained change in site productivity (Snowdon, 2002). Other classifications in the forestry literature refer to the type I response as type B, and to the response type II as type A, and a third classification called type C is usually used to described treatments such as bedding, which generate an early gain that dissipates with time (Hughes et al., 1979; Morris, 1988).

Analysis of variance (ANOVA) and modeling, are two common approaches employed when analyzing and defining the observed response type, with modeling being a more comprehensive method that has become an essential tool to also determine the economic feasibility of silvicultural treatments (Snowdon, 2002). To include the effect of silvicultural treatments as part of growth and yield systems, practitioners have tried different strategies. These strategies can usually be grouped in one of the following streams: 1. Look-up tables (e.g., Montes, 2001; Logan and Shiver, 2006). 2. The age-shift method (e.g., South et al., 2006; Carlson et al., 2008). 3. Separate equations for untreated and treated plots (e.g., Pienaar and Rheney, 1995). 4. A single equation that incorporates a multiplier function describing the treatment effect (e.g., Hynynen, 1995). 5. Modifications of the model parameters to account for treatment effect (e.g., Mason and Milne, 1999).

Among these strategies, the one proposed by Pienaar and Rheney (1995) has been frequently used due to its ease of implementation (e.g., Mason and Milne, 1999; Quicke, Glover and Glover, 1999; Amateis et al., 2000). With this method, a response to a given treatment is first characterized as the cumulative difference between a control and a treated subject and later added to a baseline model that calculates gains at a stand or plot level. Nevertheless, this approach ignores the inherent variability in state variables (basal area, dominant height and stand density) between different plots of a given stand, assigning the same response based on the treatment applied, without any consideration of how this response would vary depending on specific site attributes (Fang and Bailey, 2001). Including treatments response in this way, implies that the variability in the control plots used to build the response function is passed to the response factor. The same issue can be present if a treatment modifier is added as a multiplicative factor to a base model and treated and untreated plots are fitted independently as in Gyawali and Burkhart (2015). Nevertheless, if both the base and treated plots are modeled simultaneously, as in Hynynen et al. (1998), or a relative response is used as in Scolforo et al. (2020), this problem can be overcome.

Although the other mentioned approaches have proven to be effective to model treatment response, they usually rely on assumptions about the response type and the interaction between treatments. This is the case of the age-shift approach, where it is assumed that the shape of the growth curve does not change with the inclusion of silvicultural treatments (South et al., 2006), being useful only when Type B responses are assumed. Look up tables as in Logan & Shiver (2006) have been used as a way to modify the response according to the base site index (i.e., dominant height at base age for the control treatment), although a linear relationship between site index (SI) and the expected gain was assumed by these authors. On the other hand, few assumptions regarding the treatment effect are necessary when treatment responses are modeled by including variation factors directly on the parameters of the original model (e.g., Mason and Milne, 1999; Salas, Stage and Robinson, 2008; Gyawali and Burkhart, 2015). When following this approach, both treated and untreated plots are modeled simultaneously, avoiding the assumption of an error free control plot. Therefore, a response type does not need to be assumed given that the estimated changes in the parameters account for the response trend.

One important aspect that must be considered when deriving site index equations from dominant height models that include responses to site preparation silvicultural treatments, is that the expected response (or gain) is influenced by the base SI. This relationship has been confirmed across several commercial species and silvicultural treatments (Fang and Bailey, 2001; Logan and Shiver, 2006; Zhao et al., 2016). Therefore, to accurately generate SI curves, the gain in dominant height as a function of base SI should be included so that accurate predictions are made for a given site.

Logan & Shiver (2006) acknowledged this relationship and proposed a response function to adjusts dominant height curves by using values of expected gain for different site indexes and silvicultural treatments. Nevertheless, these authors assumed an arbitrary linear relationship between base SI and gain for all the treatments. For the SI equations developed in the present research, the relationship between base SI and gain in dominant height was hypothesized to be inverse (decrease in gain with increasing SI), but non-linear.

We hypothesize that by modifying the parameters of a dominant height model according to the treatment applied, a flexible model will be generated such that the long-term response to treatments is accurately captured. Thus, the objectives of this research were to (i) characterize the long-term effects of bedding and vegetation control on the dominant height of slash pine plantations, and (ii) construct a dominant height and site index model that could account for treatment effects and their interaction.

## 2. Methods

### 2.1. Data

For this research we used a long-term slash pine study established in 1979 by the Plantation Management Research Cooperative (PMRC) at the University of Georgia in the southeastern United States. The study's main objective was to evaluate differences in growth response to site preparation silvicultural treatments. Treatments for this study included burning, chopping, bedding, competing vegetation control, and fertilization. Mid-rotation treatments, including thinnings, were not carried out on the study plots. The study layout comprised 20 installations across Georgia, Florida, and South Carolina, stratified equally over Spodosols and non-Spodosols. From those installations, only 14 of them with measurements up to year 31 remain active. In addition to these installations, 2 more installations that are no longer active but were

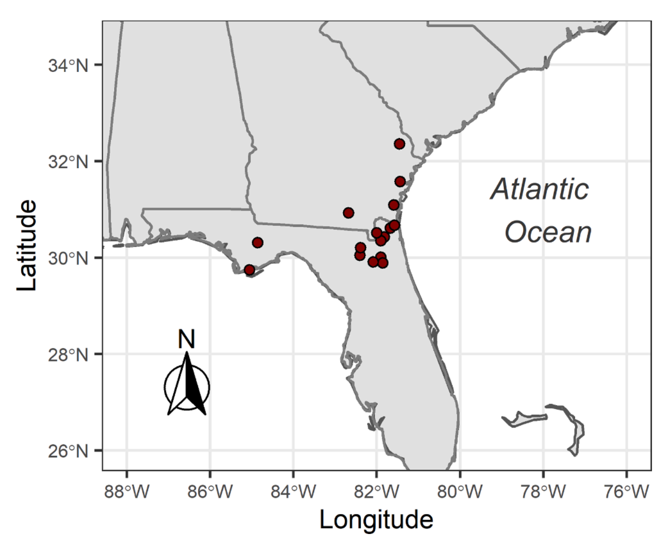


**Fig. 1.** Location of the long-term slash pine study (each dot corresponds to one of the 16 installations used in this research).

measured up to year 26, were included for this research. Fig. 1 shows the distribution of the 16 installations used in this research.

From the mentioned study, a subset of the original treatments was taken to form a 2 × 2 factorial design with bedding and complete vegetation control as main treatments for a complete randomized factorial design. The vegetation control treatment refers to herbicide application targeting all competing vegetation until crown closure (Zhao et al., 2007). Chopping and burning were considered to be the operational site preparation treatments at the time of the trial installation, and plots receiving them were taken as the control plots for this research. Plot size corresponded to 0.2 ha, with a measurement plot of 0.08 ha. At the time of planting, seedlings were double planted to ensure an approximately homogeneous initial planting density. Double planted slots had the smaller seedling removed after one year. Measurements of diameter at breast height (DBH) for all the trees, and total height for a portion of the trees, were taken every 3 years from age 5 to age 31, with the latest measurement taken in 2010. No major mortality events, rather than natural mortality, were observed during the measurement periods. For more details on the study design, see Zhao et al., (2009) and Zhao et al., (2007).

Only a fraction of the tree heights was measured on every plot, therefore a DBH-height model was fitted for each plot at every measured age to estimate the remaining heights and then determine the average dominant height. The height model was:

$$H_{tot_{ijk}} - 1.4 = \beta_{0_{ij}} exp\left(\frac{\beta_{1_{ij}}}{DBH_{ijk}}\right)$$

Where $H_{tot_{ijk}}$ is the total height for the $k^{th}$ tree in the $i^{th}$ plot at age $j$. $\beta_{0_{ij}}$ and $\beta_{1_{ij}}$ are parameters to be estimated for each plot at every age, and $DBH_{ijk}$ is the diameter at 1.4 m for the $k^{th}$ tree in the plot $i$ at age $j$. Once the total height was estimated for all the trees, dominant height was calculated as the per plot average height of the dominant and co-dominant trees (i.e., trees with DBH greater than the quadratic mean diameter). A summary of the dominant height values per treatment is presented in Table 1. Additional stand characteristics are presented in Table 2 for a subset of the measurement periods.

### 2.2. Dominant height model

To model the response to silvicultural treatments, a reparametrized Chapman-Richards (CR) type model was selected, including dummy variables that allow changes over the asymptote and the slope parameters depending on the treatment being applied. This model was compared with a model fitted following the Pienaar and Rheney (1995) modelling approach (PR). These authors developed a height growth and a basal area model including responses to silvicultural treatments by adding an independent treatment factor to base models for each variable. The two models compared are summarized below.

| | | |
|---|---|---|
| $DH_t = a_0 b_1^{z_1} b_2^{z_2} \times (1 - exp(-a_1 b_3^{z_1} b_4^{z_2} t))^{a_2}$ | (CR) | This paper |
| $DH_t = a_0(1 - exp(-a_1 t))^{a_2} + (b_0 Z_1 + b_1 Z_2) t e^{-b_2 YST}$ | (PR) | (Pienaar and Rheney, 1995) |

Where $DH_t$ is dominant height (in meters), at age $t$ (in years), $YST$ is years since the treatments were applied, which is equivalent to $t$ since all the treatments were applied at the establishment phase, $a_0, .., a_2$ and $b_0$, $..b_4$, are parameters to be estimated, $Z_1$ is a dummy variable equal to 1 if bedding was applied and zero otherwise, and $Z_2$ is also a dummy variable that equals 1 if vegetation control was applied, or zero otherwise.

The models were fitted using non-linear least squares using the software R (R Core Team, 2018). The models' performance was evaluated using the adjusted coefficient of determination for non-linear models ($R^2_{adj}$), Root Mean Square Error (RMSE), and Akaike's information criterion (AIC), calculated as follows:

**Table 1**
Dominant height statistics per treatment and age, in meters.

| Age (years) | Treatment | No. of plots | Mean (m) | Standard deviation (m) | Minimum (m) | Maximum (m) |
|---|---|---|---|---|---|---|
| 5 | Control | 20 | 3.2 | 0.7 | 2.1 | 4.7 |
| 8 | | 18 | 6.2 | 1.1 | 3.6 | 8.7 |
| 11 | | 18 | 9.1 | 1.6 | 5.6 | 12.2 |
| 14 | | 18 | 12.2 | 2.0 | 7.9 | 15.7 |
| 17 | | 18 | 14.5 | 2.4 | 9.4 | 18.6 |
| 20 | | 18 | 16.4 | 2.5 | 10.6 | 20.1 |
| 23 | | 17 | 18.3 | 2.9 | 12.6 | 22.5 |
| 26 | | 16 | 19.8 | 3.4 | 13.8 | 24.8 |
| 31 | | 12 | 20.9 | 4.1 | 14.8 | 26.7 |
| 5 | Bedding | 21 | 3.9 | 0.7 | 3.1 | 5.2 |
| 8 | | 19 | 7.1 | 1.0 | 6.0 | 9.2 |
| 11 | | 19 | 10.1 | 1.3 | 8.3 | 13.1 |
| 14 | | 19 | 13.2 | 1.5 | 10.9 | 16.4 |
| 17 | | 19 | 15.5 | 2.0 | 12.6 | 19.5 |
| 20 | | 19 | 17.1 | 2.4 | 13.5 | 21.5 |
| 23 | | 18 | 18.9 | 2.9 | 14.5 | 24.2 |
| 26 | | 17 | 20.2 | 3.3 | 15.0 | 25.4 |
| 31 | | 11 | 20.9 | 4.2 | 15.2 | 27.0 |
| 5 | Vegetation control | 18 | 4.7 | 0.8 | 2.9 | 6.0 |
| 8 | | 17 | 8.3 | 0.9 | 6.5 | 9.5 |
| 11 | | 17 | 11.3 | 1.1 | 9.6 | 13.2 |
| 14 | | 17 | 14.3 | 1.5 | 12.1 | 16.7 |
| 17 | | 17 | 16.5 | 1.8 | 14.2 | 19.9 |
| 20 | | 16 | 18.3 | 2.3 | 15.2 | 22.7 |
| 23 | | 15 | 20.1 | 2.4 | 16.7 | 24.5 |
| 26 | | 14 | 21.5 | 2.8 | 17.8 | 26.3 |
| 31 | | 10 | 22.8 | 3.2 | 19.3 | 28.5 |
| 5 | Bedding + Vegetation control | 20 | 5.3 | 0.6 | 3.9 | 6.3 |
| 8 | | 18 | 8.9 | 0.7 | 7.8 | 10.1 |
| 11 | | 18 | 11.9 | 0.8 | 11.1 | 13.4 |
| 14 | | 18 | 14.9 | 1.1 | 13.2 | 16.8 |
| 17 | | 18 | 17.1 | 1.4 | 14.8 | 20.0 |
| 20 | | 17 | 18.6 | 1.8 | 16.4 | 22.1 |
| 23 | | 15 | 20.4 | 2.2 | 17.2 | 24.4 |
| 26 | | 15 | 21.9 | 2.4 | 18.6 | 26.2 |
| 31 | | 11 | 22.8 | 3.0 | 19.7 | 28.2 |

$$R^2_{adj} = 1 - \frac{(n-1)\sum_{i=1}^{n}(Y_i - \widehat{Y}_i)^2}{(n-p)\sum_{i=1}^{n}(Y_i - \overline{Y})^2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \widehat{Y}_i)^2}{n-p}}$$

$$AIC = n\ln\widehat{\sigma}^2 + 2(p+1)$$

Where $n$ is the total number of observations, $p$ is the number of parameters in each model, $Y_i$ is the observed dominant height, $\widehat{Y}_i$ is the estimated dominant height, and $\widehat{\sigma}^2$ is the estimated mean square error of the model, calculated as follows:

$$\widehat{\sigma}^2 = \frac{\sum_{i=1}^{n}(Y_i - \widehat{Y}_i)^2}{n}$$

A $k$-fold cross-validation with 5 folds was carried out to evaluate the predictive performance of the models. This procedure consisted of removing one fifth of the data points (chosen randomly) and fitting the proposed models with the remaining data. Afterwards, an estimation of the points previously excluded was made with the fitted model and the RMSE was calculated. The procedure was repeated five times using random plots selected without replacement and the RMSEs found for the five iterations were averaged.

### 2.3. Site index model

Site index (SI) equations can be derived from dominant height models following the procedure highlighted by Bailey and Clutter

**Table 2**
Additional stand characteristics, averaged over all the installations (DBH: Diameter at breast height, BA: Basal area, TPH: trees per hectare).

| Treatment | Age (years) | DBH (cm) | BA ($m^2$/ha) | TPH | Treatment | Age (years) | DBH (cm) | BA ($m^2$/ha) | TPH |
|---|---|---|---|---|---|---|---|---|---|
| Control | 5 | 3.5 | 1.4 | 1,184 | Vegetation control | 5 | 7.2 | 5.3 | 1,157 |
| | 11 | 11.0 | 11.2 | 1,109 | | 11 | 14.3 | 18.6 | 1,131 |
| | 17 | 15.1 | 19.3 | 1,046 | | 17 | 17.9 | 26.9 | 1,076 |
| | 23 | 17.3 | 24.4 | 1,017 | | 23 | 20.3 | 31.5 | 992 |
| | 31 | 19.4 | 27.1 | 973 | | 31 | 22.7 | 34.7 | 969 |
| Bedding | 5 | 4.9 | 2.8 | 1,258 | Bedding + Vegetation control | 5 | 8.2 | 6.8 | 1,189 |
| | 11 | 11.9 | 13.8 | 1,192 | | 11 | 14.8 | 20.3 | 1,146 |
| | 17 | 15.6 | 22.6 | 1,141 | | 17 | 18.1 | 28.4 | 1,083 |
| | 23 | 17.5 | 27.4 | 1,095 | | 23 | 20.0 | 32.0 | 1,005 |
| | 31 | 19.5 | 28.6 | 1,042 | | 31 | 22.1 | 37.0 | 1,039 |

**Table 3**
Base models and ADA formulations for the Chapman-Richards (CR) and Pienaar and Rheney (PR) models. Parameters and variables as defined in section 2.2.

| Model | Parameter related to site | Solution for $X$ with initial values ($t_0$, $DH_{t_0}$) | Dynamic Equation |
|---|---|---|---|
| CR | $a_0 = X$ | $X_0 = \frac{DH_{t_0}}{b_1^{z_1} b_2^{z_2} \times (1 - exp(-a_1 b_3^{z_1} b_4^{z_2} t_0))^{a_2}}$ | $DH_t = DH_{t_0} \left[\frac{1 - exp(-a_1 b_3^{z_1} b_4^{z_2} t)}{1 - exp(-a_1 b_3^{z_1} b_4^{z_2} t_0)}\right]^{a_2}$ |
| CR | $a_1 = X$ | $X_0 = -ln\left[1 - \left(\frac{DH_{t_0}}{a_0 b_1^{z_1} b_2^{z_2}}\right)^{1/a_2}\right] \Big/ b_3^{z_1} b_4^{z_2} t_0$ | $DH_t = a_0 b_1^{z_1} b_2^{z_2} \left[1 - \left[1 - \left(\frac{DH_{t_0}}{a_0 b_1^{z_1} b_2^{z_2}}\right)^{1/a_2}\right]^{t/t_0}\right]^{a_2}$ |
| PR | $a_0 = X$ | $X_0 = \frac{DH_{t_0} - (b_0 Z_1 + b_1 Z_2) t_0 e^{-b_2 t_0}}{(1 - exp(-a_1 t_0))^{a_2}}$ | $DH_t = X_0 (1 - exp(-a_1 t))^{a_2} (b_0 Z_1 + b_1 Z_2) t e^{-b_2 YST}$ |
| PR | $a_1 = X$ | $X_0 = -ln\left[1 - \left(\frac{DH_{t_0} - (b_0 Z_1 + b_1 Z_2) t_0 e^{-b_2 t_0}}{a_0}\right)^{1/a_2}\right] \Big/ t_0$ | $DH_t = a_0 (1 - exp(-X_0 t))^{a_2} + (b_0 Z_1 + b_1 Z_2) t e^{-b_2 YST}$ |

(1974), commonly known as the algebraic difference equation approach (ADA). This method replaces one of the parameters in a yield equation by a local parameter, under the assumption that it will be related to the stand SI. Depending on which parameter is selected as local, either anamorphic or polymorphic SI curves can be generated. When more than one parameter is related to SI, a generalized difference equation approach (GADA) proposed by Cieszewski and Bailey (2000) is often followed. These methods have been widely used to derive SI equations for commercial plantations (Diéguez-Aranda et al., 2006, 2005).

SI models seldom include responses to silvicultural treatments. Some authors (e.g., Antón-Fernández et al., 2011; Sharma et al., 2002; Tymińska-Czabańska et al., 2022), have developed SI models that are sensitive to stand density, nevertheless, silvicultural treatments such as bedding or vegetation control are not frequently included in SI models. Both of the models presented could be used to derive a SI model which includes responses to silvicultural treatments by relating parameters $a_0$ or $a_1$ to SI and deriving a dynamic equation. These formulations are presented in Table 3.

The dominant height model that presented the best fit (from section 2.2) was selected to derive the SI model by estimating locally the parameters $a_0$ or $a_1$ using the dummy variable approach. The initial values required for the non-linear least squares' optimization were selected from the global values estimated for the dominant height model in section 2.2. The best SI model was selected using the $R^2_{adj}$ and $RMSE$ metrics.

The SI model required to be modified to properly express gains in SI. We hypothesized that gains in SI are inversely related to the base SI. The modification consisted of adding a gain function that models this relationship. The gain function was constructed by fitting the dominant height model individually for each one of the 16 installations, calculating the SI for the control treatment ($SI_{25}$), and then calculating the gain in SI due to the treatments ($G_{HDOM_i}$). Different models were fitted to these values including a linear, a logarithm and an exponential function (Table 4). The model with higher coefficient of determination ($R^2$) was selected to be combined with the SI model.

The gain function was added to the SI model by replacing the value of $DH_{t_0}$ in the dynamic equations in Table 3 by ($DH_{t_0} + G_{HDOM_i}$). Adding this factor guarantees that dominant height predicted at the base age reflects treatments gains. This gain function is required regardless of the used approach (ADA anamorphic or polymorphic, or even GADA). Without this additional function, all the dominant height curves would yield the same dominant height at the point where $t = 25$ (base age used for slash pine). This would be incorrect since some treatments do show gains in dominant height at age 25 and the fact that the models predict the same dominant height at the base age is an artifice of the model generated by the way the dynamic equations are derived. This was evident in the work of Socha et al., (2021) who developed a dominant height model for Scot pine in Poland using the GADA approach. In their work, parameters were modified to account for regional differences, and the described issue is evident when plotting the dominant height trajectories for the different regions.

## 3. Results

Bedding and vegetation control had a positive effect on dominant height through age 11. The average dominant height for all the treatments, as well as the average gain is shown in Fig. 2. Vegetation control had a stronger effect compared to bedding alone, whereas the combined treatment generated the highest response of all the treatments. At age

**Table 4**
Models tested for base SI vs Gain in SI.

| ID | Formula |
|---|---|
| 1 | $G_{HDOM_i} = \beta_{0i} + \beta_{1i} SI_{25}$ |
| 2 | $G_{HDOM_i} = \beta_{0i} + \beta_{1i} \log(SI_{25})$ |
| 3 | $G_{HDOM_i} = \beta_{0i} exp(\beta_{1i} SI_{25})$ |

Where $G_{HDOM}$ is the gain in expressed SI (m), $a_{0i}$ and $a_{1i}$ are the specific parameters for treatment $i$, and $SI_{25}$ is the base site index, or dominant height at age 25 for the control treatment. The indicator $i$ goes from 1 to 4 and indicating the treatments applied in the following order: control, bedding, vegetation control, and Bed + Veg. treatment.

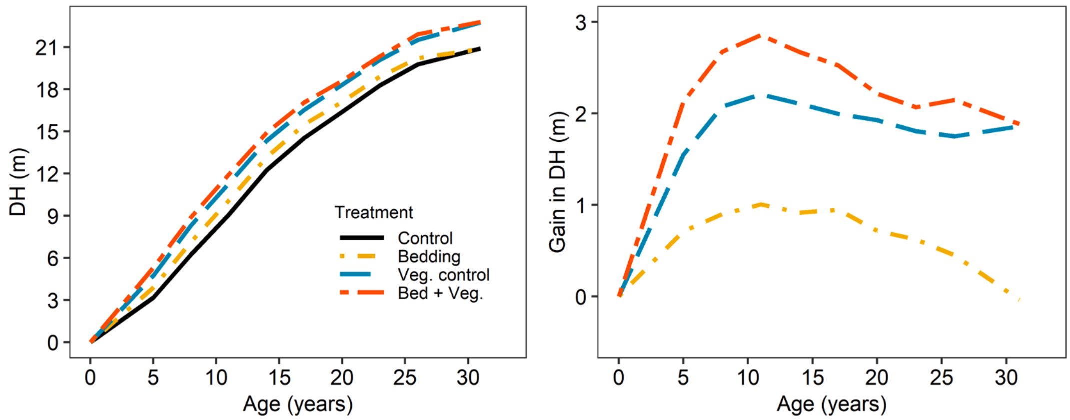


**Fig. 2.** Average dominant height (DH) by treatment (left) and gain with respect to the control treatment (right).

31, the effect of bedding was no longer visible, converging to the control treatment. On the other hand, the vegetation control still had a positive effect on dominant height at this age. At age 31, stands where vegetation control was applied (with or without bedding) had a dominant height 1.9 m higher than those on the control treatment for the average condition.

From the analyzed data, the effect of bedding on dominant height can be categorized as a Type C response (initial increase, then decreasing over time), with an initial increase in dominant height compared to the control treatment, but a decrease to zero at age 31. The vegetation control treatment generated a type B response (initial increase, then sustained gain over time), attaining a maximum at age ~ 11 and remaining relatively stable until age 31. When combined with bedding, a type C response was observed, with values decreasing after reaching the maximum response. The combination of bedding and vegetation control showed no strong interaction. This was expected since the two treatments were targeting different resources on the site. While bedding improves soil physical conditions and increases runoff in poorly drained sites, providing an elevated environment out of saturated conditions for the seedlings (Morris, 1988), the vegetation control treatment reduces the loss of resources to competing vegetation and produces a major allocation of these resources to the crop-trees (Allen et al., 1990). In general, an additive response was observed. Major differences between the vegetation control and the combined treatment were observed at younger ages (less than15 years), where the bedding effect was greater. At age 31, these two treatments generated a very similar response due to the almost null effect of bedding at this late age in the rotation.

**Table 5**
Estimated parameters for the two models evaluated, Chapman-Richards (CR), and Pienaar and Rheney (PR).

| Model | Parameter | Estimated value | Standard error |
|---|---|---|---|
| CR | $a_0$ | 26.94 | 1.27 |
| | $a_1$ | 0.07 | 0.01 |
| | $a_2$ | 1.68 | 0.07 |
| | $b_1$ | 0.94 | 0.03 |
| | $b_2$ | 0.94 | 0.03 |
| | $b_3$ | 1.16 | 0.04 |
| | $b_4$ | 1.31 | 0.05 |
| | $\beta$ | 0.88 | |
| | $a_0$ | 24.62 | 0.85 |
| PR | $a_1$ | 0.08 | 0.01 |
| | $a_2$ | 1.86 | 0.15 |
| | $b_1$ | 0.15 | 0.05 |
| | $b_2$ | 0.42 | 0.09 |
| | $b_3$ | 0.07 | 0.01 |

### 3.1. Dominant height models

The estimated parameters for the CR and the PR model are presented in Table 5. The CR model was modified to include a variance stabilization parameter ($\beta$) to correct for heteroscedasticity. Weighted regression was used for estimating the parameters with weights equivalent to the inverse of the variance ($1/\sigma^{\beta}$). The statistics used to evaluate the models' performance are presented in Table 6. A very similar performance was found between the two models, with the same $R^2_{adj}$, and very similar values of RMSE. Both models also performed similarly when evaluating their performance using cross-validation. The AIC was the only criteria where there was a bigger difference between the models, favoring the PR model, most likely for having two less parameters compared to the CR model.

Even though both models had similar precision (Table 6), when evaluating them by comparing the predicted and observed gain, the differences between the models become more apparent (Fig. 3). The CR model more accurately predicts the average gain observed when bedding is applied, whereas the PR model underestimates the gain at early ages (less than 20 years) and overestimates the gain at later ages (>20 years). Nevertheless, when underpredicting, the difference between the average gain and the predicted gain for this model were not >0.3 m, and when overpredicting, the maximum difference observed (at age 31) was less than 0.5 m.

On the other hand, for the vegetation control treatment the opposite result was found, with the PR model outperforming the CR model. The CR model performed well up to year 10 but overestimated the gain between years 10 and 25 and underestimated the gains at later ages (>25 years). For this model, the errors when overpredicting were less than 0.6 m and when underpredicting, reached a maximum at age 31 of 1.3 m.

The ability of a model to accurately predict gains from a given treatment depends on how accurately it predicts dominant height for both the control and the respective treatment. This can be better seen in

**Table 6**
Statistics of the models evaluated, Chapman-Richards (CR), and Pienaar and Rheney (PR). $R^2_{adj}$: adjusted coefficient of determination, RMSE: Root mean square error, AIC: Akaike information criteria.

| Model | $R^2_{adj}$ | RMSE (m) | RMSE crossvalidation (m) | AIC |
|---|---|---|---|---|
| CR | 0.8893 | 2.039 | 2.085 | 875.3 |
| PR | 0.8905 | 2.028 | 2.086 | 867.9 |

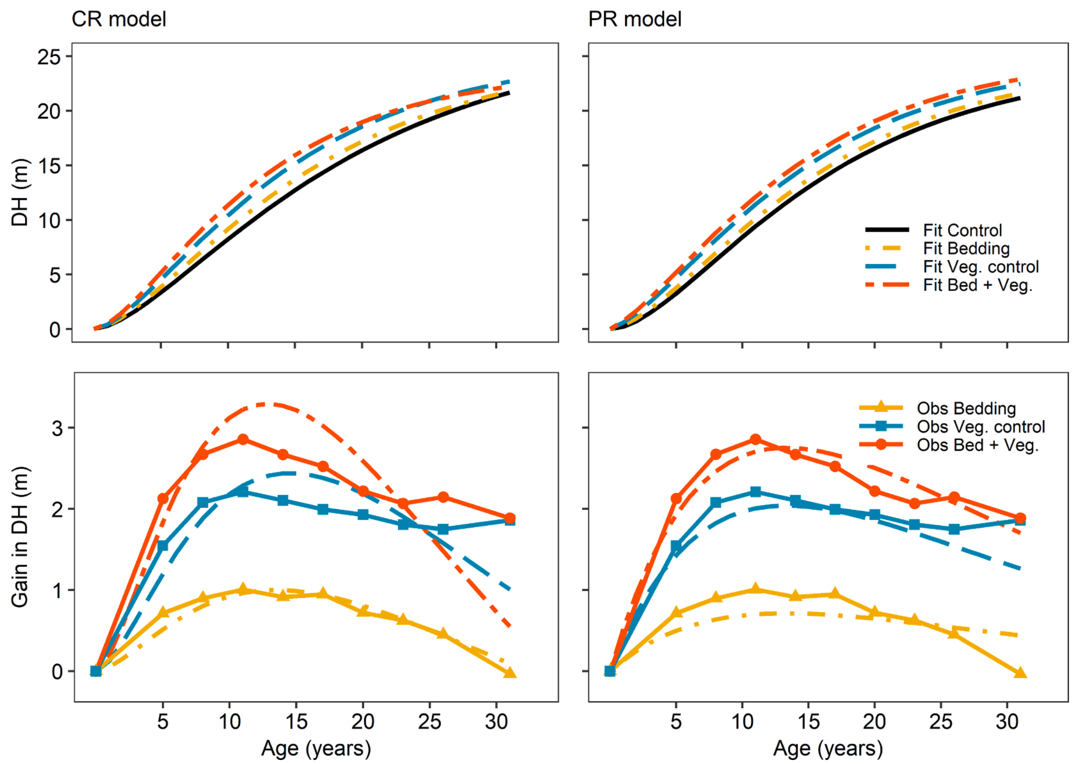


**Fig. 3.** Average predicted dominant height (DH) and gain with the Chapman-Richards (CR) and Pienaar and Rheney (PR) models.

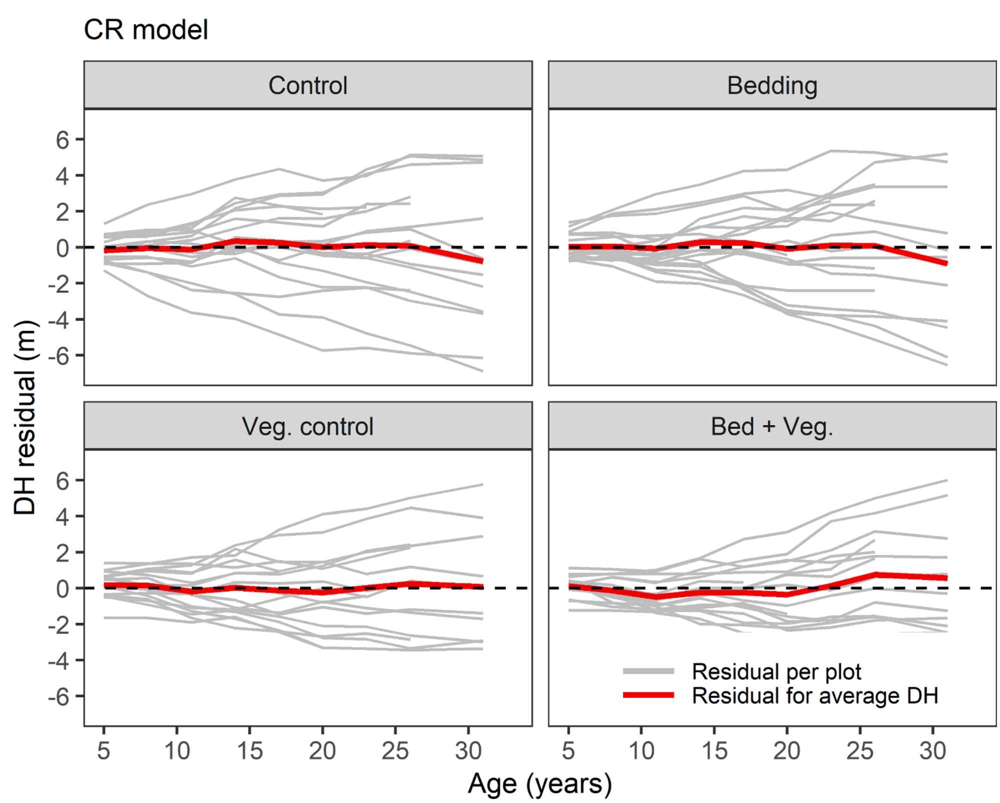


**Fig. 4.** Residuals for the Chamman-Richards (CR) model calculated as 1. The observed value per plot minus the predicted value from the CR model (grey lines), and 2. The average dominant height (of all plots) at every age minus the predicted value from the CR model (red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

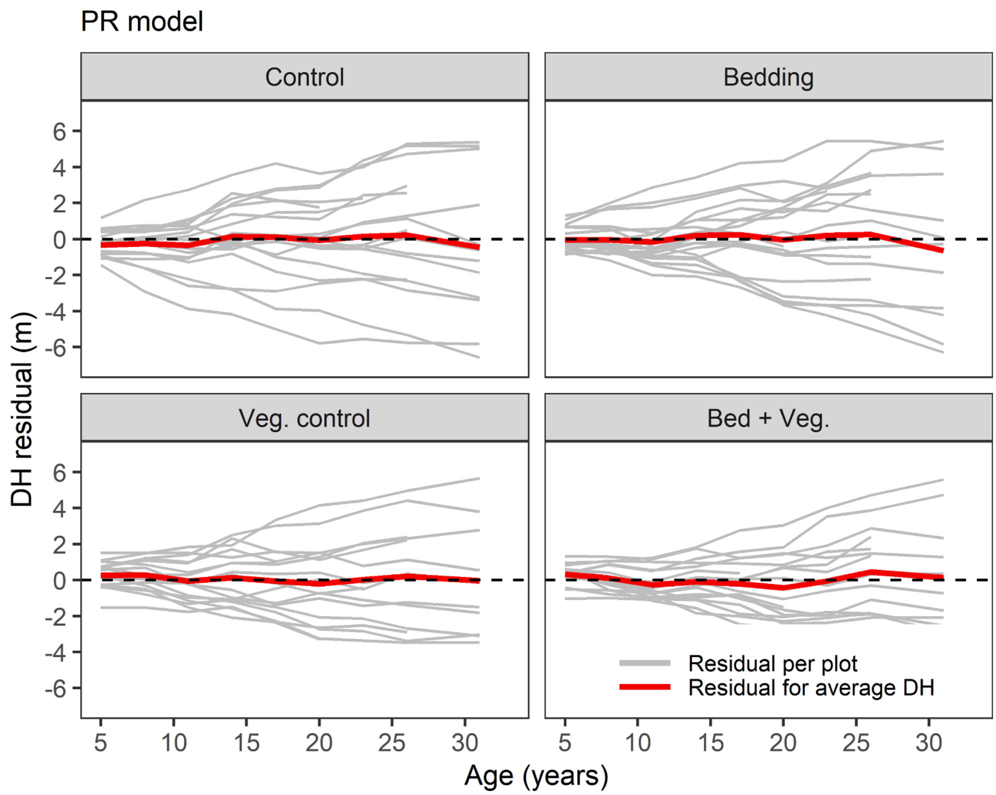


**Fig. 5.** Residuals for the Pienaar and Rheney (PR) model calculated as 1. The observed value per plot minus the predicted value from the PR model (grey lines), and 2. The average dominant height (of all plots) at every age minus the predicted value from the PR model (red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 4 for the CR model and Fig. 5 for the PR model. In fact, both models predict with a low error (less than 0.2 m) the average dominant height (red line) for the control treatment up to age 26 but overestimate this value when approaching to age 31. Both models also accurately predict dominant height for the vegetation control treatment. The biggest differences observed in Fig. 3 are the result of combining the errors for the control and the treatment predictions. These differences are magnified when the control is underestimated but the gain is overestimated. For example, if the dominant height is underestimated for the control, by 0.2 m, and the dominant height for the treatment is overestimated by the same 0.2 m, the gain would be overestimated by 0.4 m, which is what happened with the CR model when evaluating gains for the vegetation control treatment.

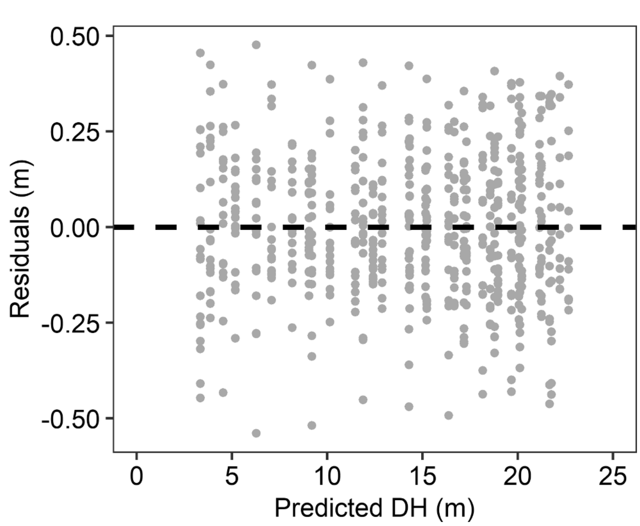


**Fig. 6.** Residuals for the Champan-Richards (CR) model. DH: dominant height.

When comparing both models with the observed average dominant height (red lines in Figs. 4 and 5), the differences between them become less apparent, and both show good predictions especially over the range of 5–25 years. The variation in the observed dominant height for the different plots of the study (grey lines in Fig. 4 and Fig. 5) is hypothesized to be a consequence of the different local conditions. The inclusion of site index into the dominant height model was then tested in an attempt to include this variability into the dominant height model. The CR model form was chosen to test this hypothesis and further construct a dynamic dominant height model that allowed derivation of the site index model. The residual error distribution of this model is presented in Fig. 6 and additional diagnostics plots for the CR model are presented in Fig. 7. The predicted vs observed plot shows how the original data is distributed equally along the 1 to 1 line. Although there is higher dispersion for the higher values of dominant height, there are not obvious patterns of subestimation or overestimation. The normal Q-Q plot shows slight deviation from the normal distribution, especially, in the tails. Nevertheless, since the main purpose of this model was not to do inference, these deviations were not considered a significant pitfall of the model.

### 3.2. Site index model

To generate the SI model, the two dynamic equations presented in Table 3 for the CR model were fitted using local parameters (either $a_0$ or $a_1$) per installation. When $a_0$ was related to site index and fitted locally for each installation, the RMSE was 0.955 m, while when the growth rate ($a_1$) was related to site index, the RMSE was 1.123 m. Thus, the anamorphic dynamic equation using $a_0$ as the parameter related to site was used to generate the SI model by assuming $t_0 = 25$ and $DH_{t_0} = SI_{25}$, as follows:

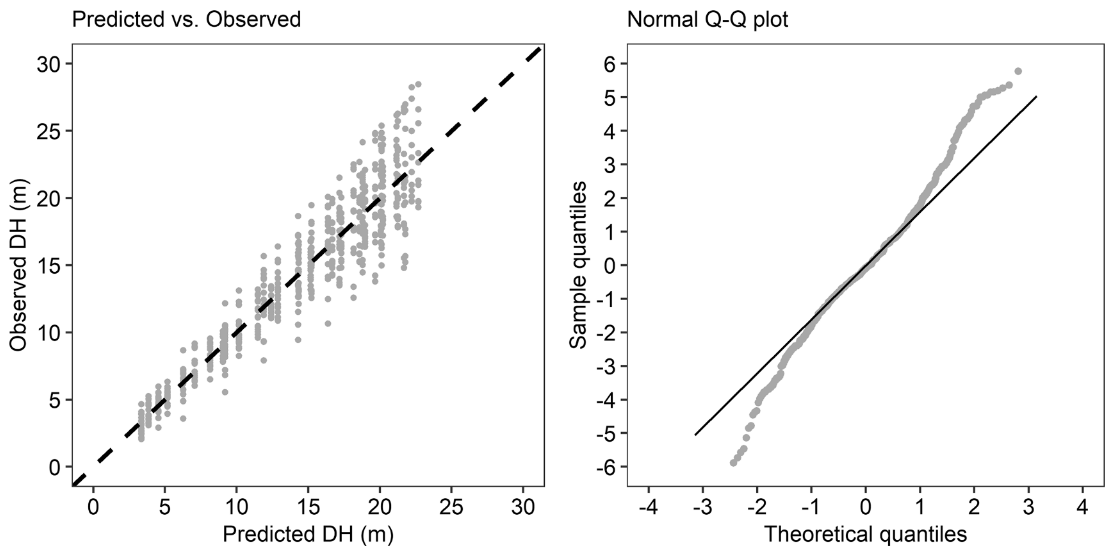


**Fig. 7.** Diagnostic plots for the Chapman-Richards (CR) model. DH: Dominant height.

**Table 7**
Estimated parameters for the dynamic site index model.

| Parameter | Estimated value | Standard error |
|---|---|---|
| $a_1$ | 0.070 | 0.003 |
| $a_2$ | 1.649 | 0.049 |
| $b_1$ | 0.959 | 0.016 |
| $b_2$ | 1.001 | 0.017 |
| $b_3$ | 1.120 | 0.026 |
| $b_4$ | 1.221 | 0.029 |
| $\beta$ | 0.207 | |

$$DH_t = SI_{25}\left[\frac{1-exp(-a_1 b_3^{z_1} b_4^{z_2} t)}{1-exp(-a_1 b_3^{z_1} b_4^{z_2}(25))}\right]^{a_2}$$

The estimated parameters for this model are presented in Table 7. (Only the global parameters are presented).

After exploring different models (Table 4), it was found that for the treatments involving chemical vegetation control, a linear model can be justified to explain the relationship between the base SI and the gain in expressed SI. The logarithm model (model 2 in Table 4) performed similarly to the linear model, but the latter was preferred for being more parsimonious. For the bedding treatment, parameters of the tested models were not significantly different from zero, meaning that there is not a significant change in expressed SI due to this treatment, therefore, no modification was needed for the SI equations including bedding. Consequently, for the treatments with vegetation control, the same model can be used regardless of being combined with bedding or not. The SI model can be then modified as follows:

$$HD_t = [SI_{25} + (\beta_0 + \beta_1\, SI_{25})]\left[\frac{1-exp(-a_1 b_3^{z_1} b_4^{z_2} t)}{1-exp(-a_1 b_3^{z_1} b_4^{z_2}(25))}\right]^{a_2}$$

With $\hat{\beta}_0 = 9.38$ and $\hat{\beta}_1 = -0.39$.

The gain function added to the SI model ensures that dominant height estimated at the base age of 25 years reflects the gain in dominant height due to the treatment applied. Without this modification, all the dominant height curves would converge to the base SI at age 25, without reflecting the actual gain generated by the treatments (even when parameter $b_3$ and $b_4$ modify the function). The gain model was constructed combining the information of the vegetation control and the combined treatment plots; the $R^2$ for this model was 0.50 with a standard error of 4.5 m. Fig. 8 shows the data and fitted line for the gain model.

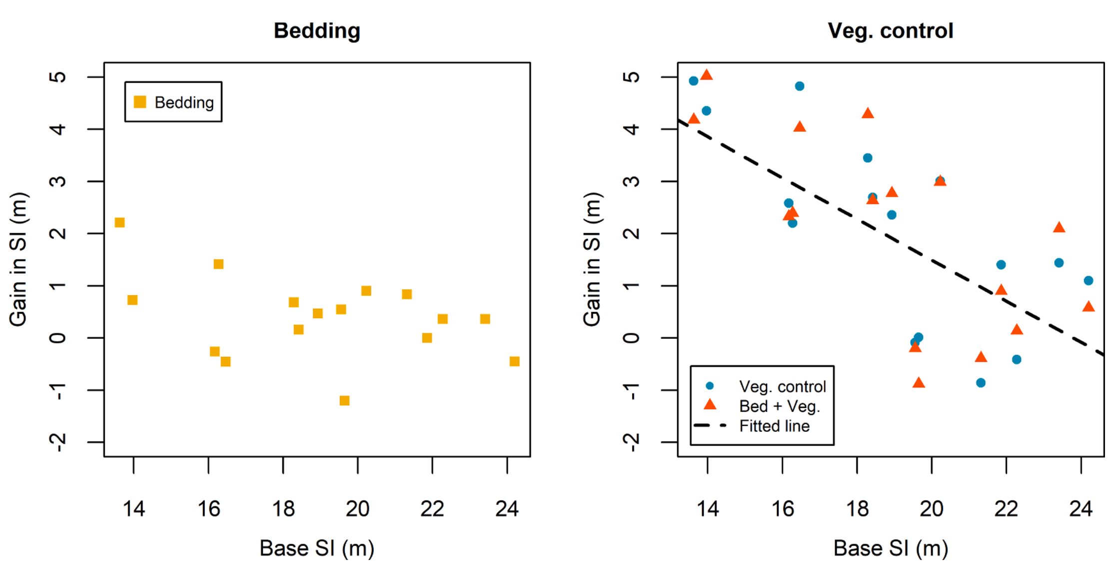


**Fig. 8.** Relationship between base site index (SI) and gain in SI.

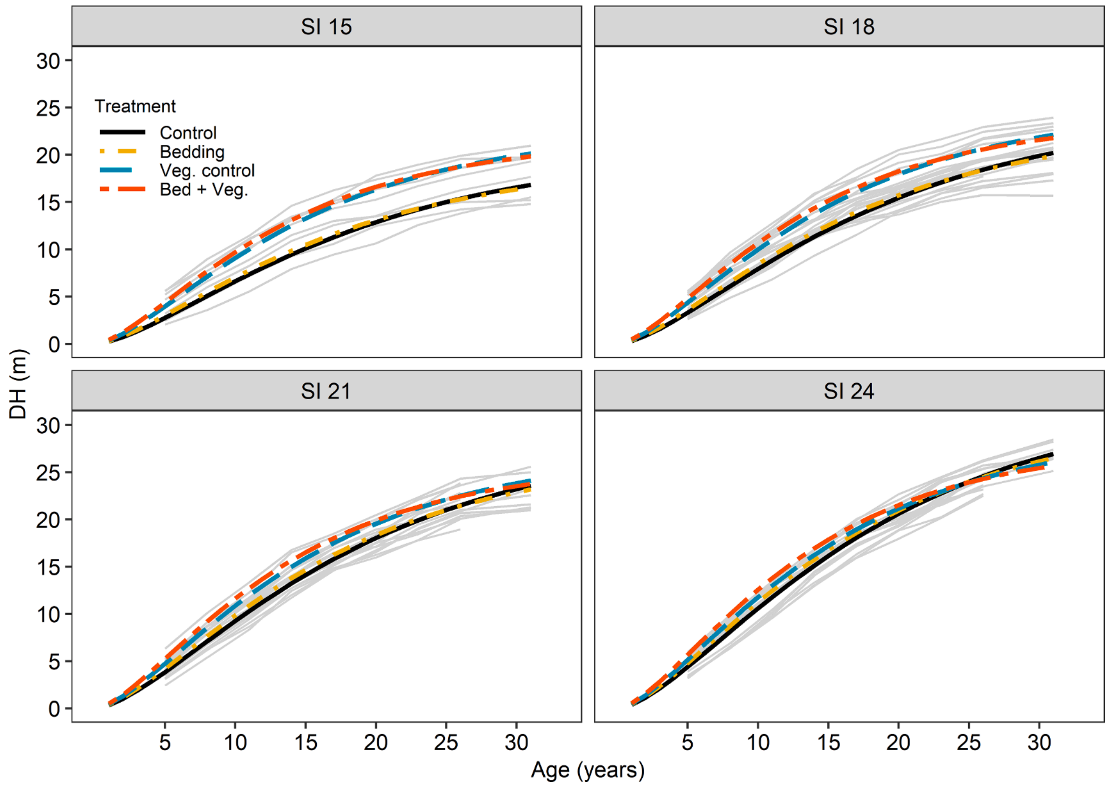


**Fig. 9.** Site Index curves including treatment response. DH: dominant height.

Using the derived site index model, SI curves were generated (Fig. 9). It is evident how greater responses compared to the control treatment are observed for lower quality sites (SI 15 m and 18 m), versus the responses for higher quality sites (SI 21 m and 24 m).

## 4. Discussion

Long-term studies bring opportunities to analyze how silvicultural treatments affect pine plantation growth, how different treatments interact, and what type of response is observed. In this study, a type C response was observed for the bedding treatment, consistent with previously reported studies (Zhao et al., 2009). Bedding has been acknowledged as a tillage treatment that improves rooting, soil moisture and nitrogen availability (Morris, 1988), increasing diameter and heights in pines, especially when these are established in wet, poorly drained sites (Gent et al., 1986; Pritchett, 1979). In this research, installations were distributed over somewhat poorly drained soils (Shiver et al., 1990), which explains the gains observed. These gains were not maintained through age 31, as bedding is expected to improve establishment conditions without adding any extra resources to the site, therefore, a type C response was expected.

The effects of vegetation control on slash pine height growth have been widely documented in the southern US (Zhao et al., 2009, 2007). Gains between 0.7 m and 1.5 m have been reported at young ages (2–7 years) when treatments removed competing vegetation (Creighton et al., 1987; Lauer and Glover, 1998), showing a peak gain at age ~ 11 and a subsequent slow decrease in growth over the control (Zhao et al., 2009). Similar results are reported in this study, with a maximum average gain in dominant height of 2.2 m achieved at age ~ 11 for the vegetation control treatment, and a 2.9 m gain for the combined treatment at the same age. The type B response observed for this treatment has been previously observed for slash pine. Jokela et al. (2000) observed a decline in average height gains between ages 5 and 8 for slash pine due to early growth benefits requiring additional inputs to sustain acceptable growth rates (fertilizer additions or more intensive understory competition control). In this study, dominant height gains were maintained due to the continuous control of competing vegetation until crown closure. Nevertheless, a decline was still observed at later ages, probably due to the lack of available resources on the site and intra-specific competition that limited growth even when no competing vegetation was present.

The CR dominant height model performed similarly to the PR model when comparing $R^2_{adj}$ and RMSE. Mason and Milne (1999), when modeling basal area growth in Pinus radiata in New Zealand, also compared the PR model with a model that included treatment responses using parameter modifiers. In their study, modifying the parameters to represent the effects of site-preparation treatments resulted in reductions (although very small) of the model residual sum of squares. These authors found that adding an adjustment factor (as in the PR model) provided a better fit. In the research presented here, parameter modifiers showed a better fit when modeling the effect of bedding, but not the effect of vegetation control.

With either of the models fitted, a dynamic equation that leads to a SI model can be derived. For both models, an additional factor (or gain function) that accounts for gains in expressed SI due to the treatments, must be included. When this is not done, all the treatments converge to the same SI value at the base age of 25 years. Since treatment gains were shown to be related to site quality, including a gain function that depends on the base SI was found to be necessary when modeling dominant height for the vegetation control treatment. The results showed expressed SI was not changed significantly when only bedding was applied (0.5 m increase), but those treatments including vegetation control had an average increase in expressed SI varying from approximately −1.0 to 5.0 m, with the magnitude decreasing with increasing base SI.

Negative values of changes in SI due to the treatments are generated when higher values of dominant height for the control are observed compared to the treated plots. This might have been the result of differences between the site qualities of a control plot and its counterpart receiving the treatment. Zhao et al., (2016) reported that if the plot receiving the treatment has a somewhat higher or lower site quality than its counterpart plot not receiving the treatment, the calculated response may be greater or less than the true response. The study design of this long-term study controlled for this factor by allowing no more than1.5 m of difference in SI between the control and the treated plots. Nevertheless, this difference can still have a significant influence in the resulting gain in SI values, especially for the low-quality sites, as showed in this research.

Higher gains in low quality sites have been previously reported for slash pine. Oppenheimer et al. (1989) found for this species that responses to complete vegetation control could be affected by site quality, expecting lower gains for high quality sites which can support both understory and overstory vegetation. Logan & Shiver (2006) also confirmed this relationship for slash pine, reporting the variation in maximum gain differentiated by base SI, after applying treatments including bedding, vegetation control during site preparation, fertilization and mid-rotation release. These authors proposed a linear relationship between base SI and maximum expected response. In this research, a linear relationship was confirmed for base SI and expected gain at age 25. This inverse relationship has been confirmed for other pines in the southern United States (Zhao et al., 2016). According to Zhao et al., (2016) the lack of response on high quality sites might be a consequence of the treatment not providing limiting resources, or the trees being limited by other resources different that the ones provided by the treatment, which limit the effect of the treatment applied. These authors also mention plot to plot site variability, pest activity, weather events, and potential uneven treatment applications, as possible factors driving this relationship.

## 5. Conclusions

The control of competing vegetation by means of herbicide applications during site preparation activities for slash pine plantations had a long-lasting effect on dominant height still observed at age 31. The observed site index at age 25 was increased up to 5 m, with higher responses (relative to the control treatment) observed in low quality sites (i.e., base site index of 14 m). Higher quality sites (i.e., SI $>$ 22 m) showed no significant increase in observed site index due to the treatment application. These findings imply that a more efficient application of herbicides can be done by targeting low quality sites which will show higher responses. On the other hand, bedding did not have a long-term effect on dominant height. Nevertheless, this treatment improved growth in dominant height at earlier stages (less than20 years). The proposed SI model can be used to determine likely gains in dominant height due to treatment applications up to a rotation age of approximately 30 years and to evaluate whether this expected gain justifies the application costs.

## CRediT authorship contribution statement

**Laura Ramirez:** Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Visualization. **Cristian R. Montes:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Bronson P. Bullock:** Writing – review & editing, Supervision.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The authors do not have permission to share data.

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