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GEOSTATISTICAL MODELLING OF BELOW- AND ABOVE-GROUND CARBON STOCKS OF TEAK STANDS AT DIFFERENT AGES

Pfutz IFP[1,] *, Pelissari AL[1], Rodrigues CK[1], Caldeira SF[2] & Corte APD[1]

[1]*Department of Forest Sciences, Federal University of Parana (UFPR), Av. Prof. Lothário Meissner, 632, Botanical Garden, Curitiba, PR, Brazil, 80210-170*
[2] *Department of Forest Engineering, Federal University of Mato Grosso (UFMT), Av. Fernando Correa da Costa, Coxipó, Cuiabá, MT, Brazil, 78068-000*

**iasminportela@gmail.com*

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Well managed teak stands can contribute towards mitigation of climate change by storing carbon in their solid wood products. However, spatial estimates of teak's potential carbon stocks is lacking in the support of precision forest management. The aim of this study was to estimate the carbon in above- and below-ground biomass of teak stands and predict their spatial variabilities. Tree data were measured biennially in 46 permanent plots of 213 ha, between 2nd and 12th year, in which thinning was performed at 5th, 8th and 11th year. Carbon stocks were estimated using equations, and geostatistical modelling was carried out by semivariance analyses and ordinary kriging method. Above-ground carbon mean values ranged between 2.95 and 59.10 t ha^{-1}, with reduction to 57.61 t ha^{-1} after third thinning. Minimum and maximum below-ground carbon mean values were 0.67 and 8.06 t ha^{-1} respectively, decreasing to 7.51 t ha^{-1} after last thinning. Carbon stocks increased over the years and showed spatial dependence, however, they were influenced by the thinning. Teak stands presented potential carbon stores since the carbon remained in their solid wood products, compared to other species used for energy, pulp and paper. This evidence showed the importance of teak in mitigating climate change.

Keywords: Biomass, climate change, geostatistics, kriging, *Tectona grandis*

INTRODUCTION

Greenhouse effect is a natural process that increases the earth's temperature due to heat retention by atmospheric gases, such as methane, carbon dioxide and nitrous oxide (Burgos et al. 2015). However, this natural process has been intensified by anthropogenic activities that cause climate impacts in terrestrial ecoregions of the world (Yu et al. 2019). To mitigate this problem, Paris agreement recommended procedures to remove carbon dioxide, including forest carbon sinks, bioenergy with carbon capture and storage (BECCS) and other technical solutions that include the management of forest stands (UNFCCC 2015, Chen & Xin 2017).

Sustainably managed forest stands play an important role in the global carbon market due to their potential to store carbon dioxide (CO_2) in their biomass through the growth of trees and their components (Malmsheimer et al. 2008). Carbon is also stored in harvested wood products or when using wood as an alternative for fossil fuel. Forest biomass, as an energy source, was considered "neutral carbon", since CO_2 is captured by trees planted on the same site where trees were previously harvested. However, the sustainability between CO_2 emission and sequestration is questioned by life cycle analyses (Cherubini et al. 2011). Therefore, forests management to produce solid wood products are ideal stands for carbon storage, in which the carbon remains in the wood during the products' use time (Lundmark et al. 2014).

Previous studies estimated the carbon stock in forest stands for carbon market projects (Almeida et al. 2010 and Roquette et al. 2012). However, the authors ignored temporal and spatial aspects of carbon estimates, and silvicuture practices that are recommended for sustainable forest management (Hoover & Stout 2007, Wilkinson 2016, Soriano-Luna et al. 2018). Thus, forest stands can be a land-use strategy to mitigate climate change, besides supplying raw material to forest-based industries.

Teak (*Tectona grandis*) is a hardwood tree species appreciated for valuable commercial purposes in shipbuilding, furniture and carpentry (Miranda et al. 2011, Wanneng et al. 2014). The planted teak forests are estimated to be 4.4 million hectares, with 83% in Asia, 11% in Africa, and 6% in tropical America (Kollert & Kleine 2017). Brazil has 94 thousand hectares of commercial teak stands for solid wood market (IBÁ 2019), in which a defined period of drought and an adequate soil nutritional balance provide higher growth rates, in the absence of infestations and diseases, in North and Midwest regions (Passos et al. 2006, Ugalde Arias 2013).

Well managed teak stands can contribute towards mitigation of climate change by storing carbon in their solid wood products (Gopalakrishnan et al. 2011). Although there are several studies on carbon storage in different forests, spatial estimates of teak's potential carbon stocks is lacking in the support of forest management. Information about spatial patterns of carbon stock in teak forest is useful to guide precision silviculture practices (Chanan & Iriany 2014).

Geostatistics methods have been successfully used to investigate the spatial variability of forest variables, providing more reliable results to support management decisions (Mishra et al. 2012, Chanan & Iriany, 2014). In this context, geostatistics is an important tool for predicting and mapping spatial distributions of biomass and carbon stocks in non-sampled sites (Sales et al. 2007, Fu et al. 2015, Benítez et al. 2016, Kim et al. 2016, Zhao et al. 2016, Morais et al. 2017, Lin et al. 2018a).

The proposed hypothesis is that knowledge of teak's carbon spatial stocks can guide precision forestry practices for carbon projects. Thus, the aim of this study was to estimate the carbon stock in above- and below-ground biomass of teak stands and predict their spatial variabilities at different ages.

MATERIALS AND METHODS

The study was carried out in a pure teak stand of 213 hectares in 3 m × 3 m spacing, located in Mato Grosso State, Brazil, between 16° 13′ S and 56° 22′ W (Figure 1). According to Köppen's classification, the region's climate is Aw: tropical savanna with dry-winter characteristics, 25 °C average annual temperature and 1,300 mm year^{-1} average rainfall (Alvares et al. 2013). The topography is gently sloping and the soil is classified as Haplic Planosol with sandy-clay-loam texture (Pelissari et al. 2017).

Three selective thinning were applied in the teak stands, removing 40% of the initial density at 5th year, and 33% at 8th and 11th years. In addition, pruning was applied at 2nd year, with branches pruning up to 33% of total height, 3rd year, up to 50% of total height, 4th year up to 67%, and maintenance pruning with branches removal up to 7 m height at the following years.

The database was composed by 46 georeferenced permanent plots with 450 m^2, in which the diameter at breast height (DBH, 1.3 height) of all trees were measured. These measurements were carried out biennially, between 2nd and 12th year. Below- and above-ground carbon stock estimates per tree were performed using equations (1) and (2) developed by Kraenzel et al. (2003), with coefficient of determination (R^2) equal to 0.978 and standard error of estimates (SEE) of 0.056. Equation predictions were compared with carbon values obtained from Brazilian teak stands, aiming to corroborate the estimates' accuracy, due to lack of fitted teak carbon models in Brazil.

$$\log(c_a) = 2.574 \log(d) - 1.345 \quad (1)$$

$$\log(c_b) = 2.387 \log(d) - 1.968 \quad (2)$$

where log is base 10 logarithm, c_a is above-ground carbon (kg per tree), c_b is below-ground carbon (kg per tree), and d is diameter at 1.3 m height (cm).

Descriptive statistical analysis and Kolmogorov-Smirnov's normality test were applied ($\alpha = 0.05$) to describe carbon stocks data characteristics with R software (R Core Team 2018). Geostatistical modelling was performed with semivariance analysis, in which spherical, exponential, Gaussian, pentaspherical, cubic and circular models were fitted with gstat package (Pebesma 2004). The best fit was chosen based on the highest coefficient of determination (R^2) and smallest sum of squared residuals (SSR). In addition, semivariograms were fitted in 0°, 45°, 90° and 135° directions to ensure isotropy. Leave-one-out cross-validation was applied to assess spatial uncertainty through systematic statistical tendency (BIAS) and root mean square error (RMSE).

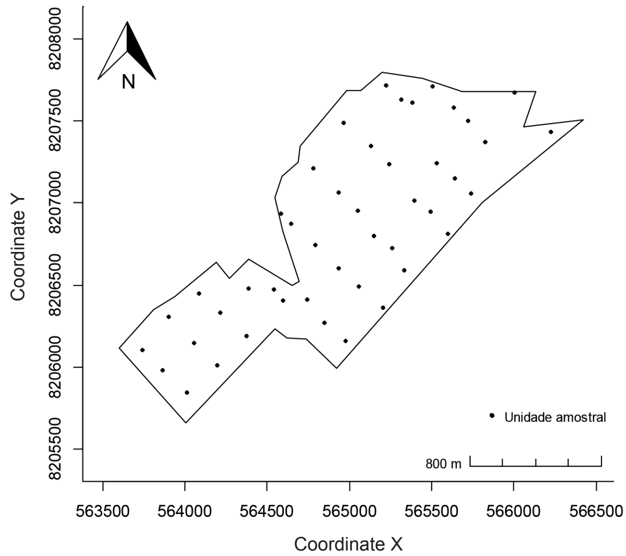

Figure 1 Geographic coordinates of teak stands and spatial distribution of sample units.

Below- and above-ground carbon stock interpolations were carried out by ordinary point kriging from 2^{nd} to 12^{th} year old teak stands with gstat package, considering the fitted semivariogram parameters of nugget effect (C_0), sill (C_0 + C), and range *(a)*. In this kriging method, distances between sampled point and point to be estimated were considered to determine weights for estimating carbon stock at an unsampled point (3).

$$\hat{Z}(X_0) = \sum_{i=1}^{n} \lambda_i Z(X_i) \qquad (3)$$

where $\hat{Z}(X_0)$ is estimated point, λ_i is weight, $Z(X_i)$ and is sampled point.

RESULTS AND DISCUSSION

Carbon stocks in below- and above-ground biomass showed increase over the years (Table 1). However, stabilisation tendency was observed in above-ground carbon mean values, as well as a decrease of below-ground carbon stock, due to the thinning applied at 8^{th} and 11^{th} years. Thus, it was assume that thinning causes forest structural changes and a small decrease in carbon stock potential per area of post-thinning (Hoover & Stout 2007, Wilkinson et al. 2016, Widiyatno et al. 2017, Lin et al. 2018b).

When the above-ground carbon stock was determined in a Brazilian teak stand at different ages, Almeida et al. (2010) obtained mean values of 5.62 t of C per ha^{-1} at 2.5 years and 14.15 t of C per ha^{-1} at 3.5 years, which is similar to those estimated in the present study. However, below-ground stock results were higher, with 6.7 t of C per ha^{-1} at 2.5 years and 4.9 t of C per ha^{-1} at 3.5 years, due to the differences in the soil chemical elements available for teak roots' development (Behling et al. 2018).

In other teak stand in central-west region of Brazil, Roquette et al. (2012) estimated the wood carbon stock by a biomass/carbon conversion factor equal to 0.5 and obtained 79.8 t ha^{-1} at 9 years and 96.2 t ha^{-1} at 12 years. These carbon estimates are higher than the present study, due to the differences in estimation methodology and forest management, such as the lack of thinning that resulted in different carbon stock dynamics over the years.

Coefficients of variation of carbon stocks were homogeneous after the 4^{th} year, with a small post-thinning change (Table 1) that modified the stand variability by changing data distribution (Andrade et al. 2007, Pelissari et al. 2013). Carbon stocks at 2^{nd} and 10^{th} years showed non-normal distribution by Kolmogorov-Smirnov's test, at 5% significance level (Table 1). Thus, log-transformation was applied to the data, since positive skewed distributions are not recommended for geostatistics (Wu et al. 2006, Huo et al. 2012).

Above- and below-ground carbon stocks showed spatial dependence in all assessed years, with increasing semivariance and subsequent

Table 1 Descriptive statistical analysis of above- and below-ground carbon stocks of teak stands between 2nd to 12th years

Year	Minimum ($t\ ha^{-1}$)	Mean ($t\ ha^{-1}$)	Maximum ($t\ ha^{-1}$)	Coefficient of variation (%)	Kolmogorov-Smirnov
Above-ground carbon stock					
2nd	1.26	3.95	7.41	39.5	0.086*
4th	18.15	31.27	41.87	20.1	0.174ns
6th	19.08	39.96	54.29	20.9	0.162ns
8th	30.68	59.03	81.16	19.3	0.137ns
10th	27.28	59.10	79.64	19.5	0.134ns
12th	20.43	57.61	78.73	20.6	0.134ns
Below-ground carbon stock					
2nd	0.23	0.67	1.22	37.2	0.082*
4th	2.77	4.62	6.09	18.9	0.174ns
6th	2.74	5.62	7.60	20.0	0.153ns
8th	4.27	8.06	11.03	18.6	0.137ns
10th	3.73	7.87	10.54	18.8	0.111*
12th	2.69	7.51	10.22	19.9	0.144ns

ns is normal distribution and * is non-normal distribution by Kolmogorov-Smirnov's test ($\alpha = 0.05$)

stabilisation (Figure 2). These semivariogram characteristics made it possible to apply geostatistical modelling (Table 2). Carbon stocks presented best fit with spherical model, except for 2nd and 4th years with exponential and Gaussian models, respectively (Table 2).

Nugget effect (C_0) values were lower than one unit, which represents the variance of random measurement error (Yin et al. 2011). Range (a) indicates the maximum distance at that a sample unit is not affected by the neighbor sample (Cigagna et al. 2015). These values showed high spatial heterogeneity, with a minimum of 206 m and a maximum of 1,303 m for above-ground carbon stock (Table 2). Below-ground carbon presented different range values, lowest of 204 m and highest of 1,101 m (Table 2).

Semivariogram fits were statistically efficient, with coefficient of determination (R^2) superior than 0.91 (Table 2). Minimum value of sum of squared residuals (SSR) for above-ground carbon stock was 3.62×10^{-6} and maximum was to 1.35×10^{-2}. For below-ground carbon, minimum and maximum values were 3.63×10^{-6} and 2.90×10^{-3}, respectively. These results were corroborated by the low values of systematic statistical tendency (BIAS) and root mean square error (RMSE) by leave-one-out cross validation.

Low semivariance dispersions around estimated lines were verified in fitted semivariogram models (Figure 2), resulting in better conditions to predict spatial distribution of carbon stocks (Figure 3). It was observed that the central and southwest regions of thematic maps showed highest carbon values. The largest carbon stock areas have increased and decreased over the years, mainly after thinning application. Thus, as carbon rent increases the value of standing timber, avoiding thinning in less productivity sites is most cost-effective (Pohjola et al. 2018). The result corroborates the hypothesis that knowledge of teak's carbon spatial stocks can guide precision silviculture practices for carbon projects.

Eastern region of thematic maps showed the lowest above- and below-ground carbon stocks (Figure 3). Silvicultural treatments, such as soil fertilisation and acidity correction, may be recommended to meet the technical needs of suitable teak's development (Ugalde-Arias 2013). In addition, this recommendation aims to ensure sustained production and mitigate the negative impacts on soil nutrient reserve (Adekunle et al. 2011, Pelissari et al. 2015, Choudhari 2018).

The carbon spatial distributions were directly influenced by the site spatial heterogeneity,

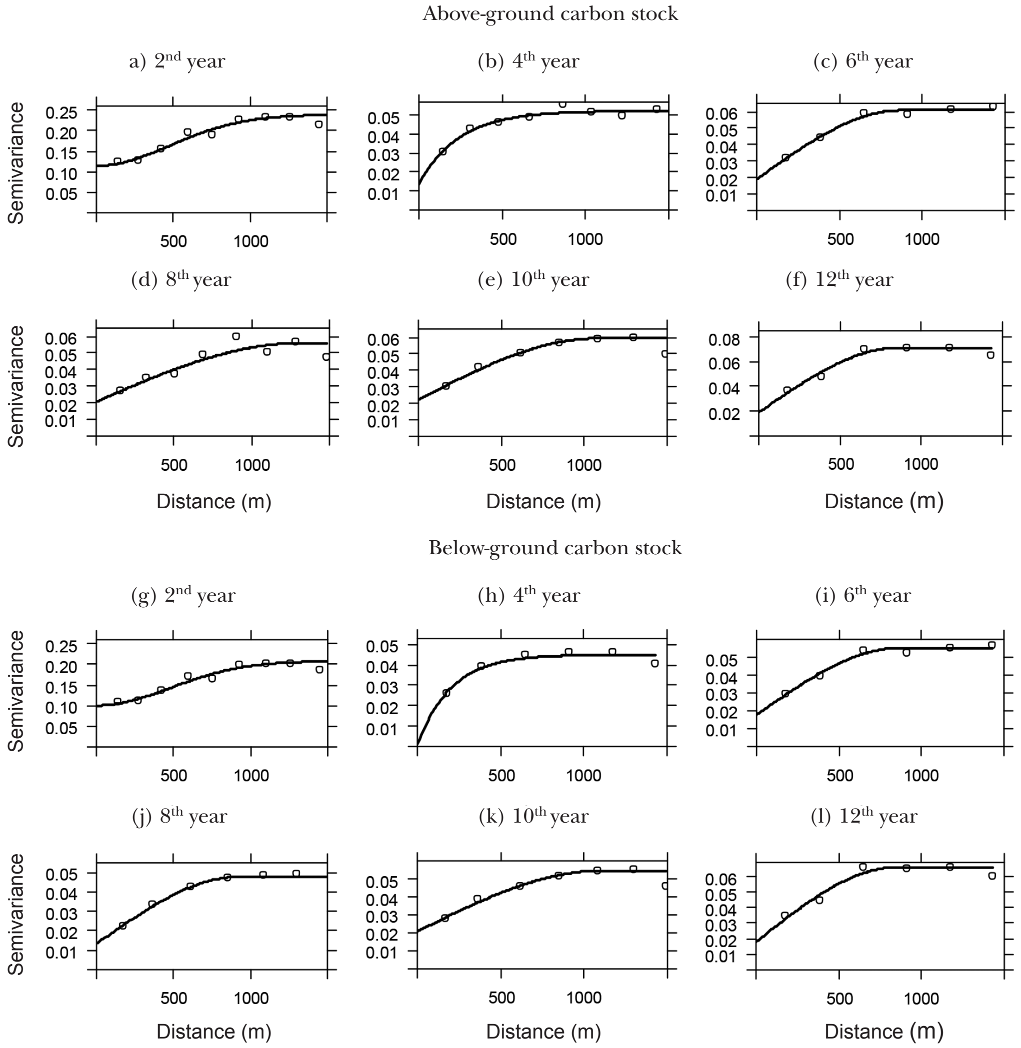

Figure 2 Semivariograms fitted for above- and below-ground carbon stocks in teak stands

Table 2 Parameters of semivariograms fitted for above- and below-ground carbon stocks of teak stands

Year	Model	C_0	$C_0 + C$	a (m)	R^2	SSR	BIAS	RMSE
				Above-ground carbon stock				
2nd	Gaussian	0.1143	0.2396	675	0.964	1.35×10^{-2}	-0.001	0.373
4th	Exponential	0.0138	0.0525	241	0.927	2.91×10^{-5}	-0.002	0.199
6th	Spherical	0.0190	0.0609	870	0.978	1.79×10^{-5}	-0.005	0.213
8th	Spherical	0.0206	0.0560	1,303	0.954	2.91×10^{-5}	-0.003	0.179
10th	Spherical	0.0221	0.0594	1,072	0.995	3.62×10^{-6}	-0.003	0.199
12th	Spherical	0.0190	0.0713	860	0.971	2.96×10^{-5}	-0.006	0.229
				Below-ground carbon stock				
2nd	Gaussian	0.1002	0.2084	675	0.962	4.08×10^{-4}	-0.001	0.349
4th	Exponential	0.0009	0.0452	204	0.947	1.66×10^{-5}	-0.002	0.188
6th	Spherical	0.0178	0.0554	874	0.975	1.64×10^{-5}	-0.005	0.203
8th	Spherical	0.0134	0.0479	929	0.986	8.58×10^{-6}	-0.004	0.169
10th	Spherical	0.0208	0.0546	1,101	0.994	3.63×10^{-6}	-0.003	0.191
12th	Spherical	0.0180	0.0661	854	0.969	2.70×10^{-5}	-0.006	0.223

C_0 is nugget effect, $C_0 + C$ is sill, a is range, R^2 is coefficient of determination, SSR is sum of squared residuals, BIAS is systematic statistical tendency and RMSE is root mean square error

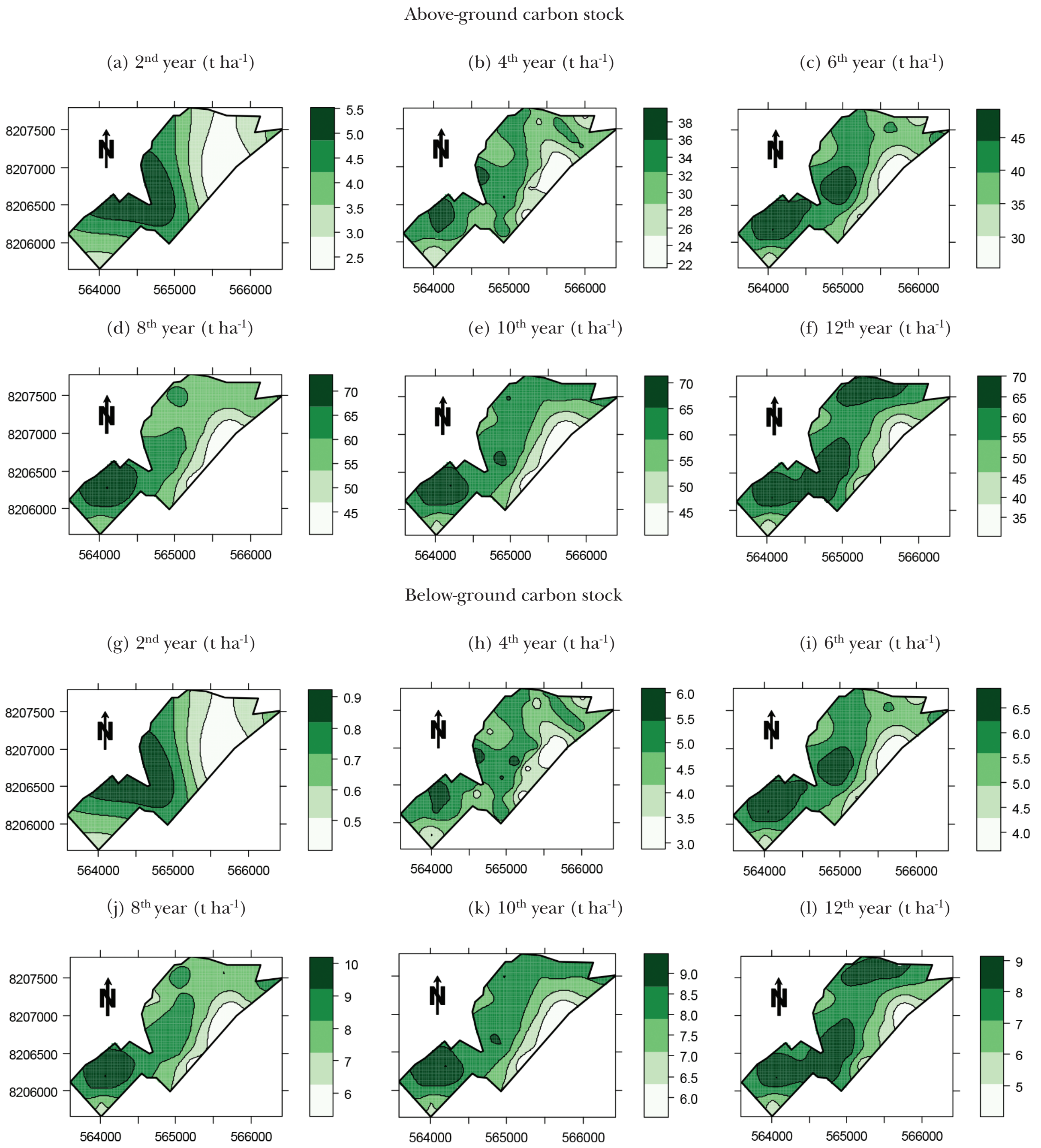

Figure 3 Spatial distribution of above- and below-ground carbon stocks in teak stands

where productive capacity is higher in areas with greater carbon stocks and smaller in sites with lower productivity (Pelissari et al. 2015). Thus, carbon spatial variability is an indicator of local productive capacity and useful for designing silvicultural practices (Soriano-Luna et al. 2018). In contrast, teak potential in carbon projects needs to be emphasised, since its forest stands are managed for solid wood and high value uses, such as furniture and shipbuilding (Tripati et al. 2005, Miranda et al. 2011). In this sense, the carbon stored in the biomass of teak stands remains in their wood products. This teak's characteristic is an advantage compared to other forest species used for energy, whose burning emits CO_2 into the atmosphere, and this shows the importance of teak plantation to mitigate climate change (Gopalakrishnan et al. 2011, Pichhode & Nikhil 2017).

CONCLUSION

Above- and below-ground carbon stocks in teak stands increase over the years, however, they are influenced by thinning operations. In addition, carbon stocks show spatial dependence and make it possible to apply geostatistical modelling.

Carbon spatial patterns are directly influenced by the site heterogeneity, in which silvicultural treatments, such as soil fertilisation and acidity correction, may be recommended to meet the technical needs of suitable teak development.

Teak stands are potential for carbon projects, since the carbon stored in the biomass remains in their solid wood products, compared to other species used for energy, pulp and paper. This evidence shows the importance of teak plantation to mitigate climate change.

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