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RESEARCH PAPER

Modelling the growth response to climate change and management of *Tectona grandis* L. f. using the 3-PGmix model

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Abstract

Key message **Teak (*Tectona grandis* L. f.) is a native tree species of India. It is one of the most desirable timber species because of its strength, fine texture, and durability. Its growth is strongly dependent on the climatic conditions, but empirical data are often unavailable to support management decisions. The physiological principles for predicting growth incorporated in the 3-PGmix model make it a useful tool in modelling the growth responses and management in the changing climate. We assessed that under elevated atmospheric carbon dioxide (CO_2) concentration and no thinning, teak would store more carbon than currently.**

Context Uncertainty and lack of scientific understanding about the growth response to climate change and thinning regimes have created challenges in teak sustainability, both regionally and globally.

Aims This research examines climate change and management implications on teak growth in India using the 3-PGmix model.

Methods The 3-PGmix model was coupled with climate scenarios (Representative Concentration Pathway (RCP) 4.5 and 8.5) to forecast growth response up to the year 2100 with 1981–2010 as the baseline under thinning (G-quality, P-quality) regimes. Thinning under G-quality is performed at earlier stand age than P-quality, and then simulations under 'no thinning' based on stocking/ha at different thinning intensity.

Results Under 'no thinning', predicted net primary productivity (NPP) for RCP4.5 and RCP8.5 became 5.77 t/ha/year and 5.28 t/ha/year in 2100. However, under increasing CO_2, it became 7.39 t/ha/year and 8.22 t/ha/year respectively in 2100. In the future, increasing CO2 would be the dominating factor for an increase in teak growth; however, abnormal precipitation and warmer temperature could produce an unforeseen growth condition. The carbon stock and CO_2 sequestration are predicted to be higher under no thinning, which signifies the CO_2 fertilisation effect in teak.

Conclusion The set of parameters used in 3-PGmix offers an opportunity to predict teak responses to future climatic conditions and management treatments.

Keywords 3-PGmix · Teak · Process-based model · Climate change · NPP · Sensitivity analysis

1 Introduction

Forests produce timber, sequester carbon dioxide (CO_2), maintain biodiversity, protect soil, and conserve water (FAO 2010; Gustafsson et al. 2012; Franklin et al. 2016; Gupta and Sharma 2019). However, they are also strongly impacted by climate change and mismanagement in both direct and indirect ways (Kirilenko and Sedjo 2007; Keenan 2015). Climate change disturbs the plant's physiological processes and causes a change in their net primary productivity (NPP) and carbon (C) sequestration rates at a species level (Scheller and Mladenoff 2005; Morin et al. 2018). Therefore, information on projected changes in species performances in future

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climatic conditions is important to make informed forest management decisions with regard to both public and privately owned forests in India and elsewhere.

Seely et al. (2015) suggested the need for simple forest growth models that forest managers can use. These models must also be effective in determining the long-term impact of climate change on forests. Notably, models based on empirical data cannot be used for site or climatic conditions outside the range of data used to produce them. However, teak plantations might be grown in conditions not included in empirical data sets, such as different climatic conditions or silviculture. Process-based models (PBMs) can therefore be helpful to fill this gap. PBMs serve as the framework of physiological principles and mechanisms (Johnsen et al. 2001; Fontes et al. 2010; Seely et al. 2015; Cristal et al. 2019), and can extrapolate growth across the landscape, by remote sensing and geographic information systems (RS & GIS) (Tickle et al. 2001). Coupling PBMs and global climate models (GCMs) is a pre-eminent approach to determining climate change impacts on forest growth and C dynamics (Almeida et al. 2009; Battaglia et al. 2009; Pinkard et al. 2010; Seely et al. 2015; Elli et al. 2020). The number of research papers on the physiological principles in predicting growth using the 3-PG/3-PGspatial/3-PGmix model has increased since its development (Gupta and Sharma 2019). Forest practitioners in Africa, Australia, and South/North America use 3-PG for short-term operational planning, and long-term strategic planning for many different tree species and forest types (Dye 2005; Paul et al. 2006; Battaglia et al. 2007; Almeida et al. 2010). Therefore, 3-PGmix could be used for modelling the growth of deciduous species (Forrester and Tang 2016), such as teak in the changing climate and management options in varying teak growing sites in India.

Over seventy tropical/sub-tropical countries are planting teak; however, natural teak forests (nearly 29 Mha) exist in South Asian countries, including India, Myanmar, Laos People's Democratic Republic, and Thailand (Kaosa-ard 1981; Kollert and Cherubini 2012). The overall level of teak plantation is between 4.35 and 6.89 Mha worldwide, from which 83% are in Asia, 8% in Africa, and 4% in tropical Americas (Kollert and Kleine 2017). India has 6.3 to 8.9 Mha natural and 1.5 to 2.5 Mha planted teak, and interestingly is the second most planted species (Palanisamy et al. 2009; Gopalakrishnan et al. 2011). Natural teak forests are mostly found in Madhya Pradesh, Maharashtra, Karnataka, Tamil Nadu, Kerala, Uttar Pradesh, Gujarat, Orissa, and Rajasthan (Troup 1921; Tewari et al. 2013; Choudhari and Prasad 2018). However, plantations are also made in non-native sites (Tewari et al. 2014). Therefore, such large areas of natural and planted teak plantations with high growth rates could act as significant C sinks contributing to global climate change mitigation (FAO 2015; Kenzo et al. 2020).

Both India and the world at large are unclear about the long-term impacts of climate change and thinning on teak growth, as very few studies have actually explored this topic. Gopalakrishnan et al. (2011) simulated the long-term impacts of climate change on Indian teak productivity. For future simulations, they coupled the regional climate model HadRM3 and the dynamic vegetation model integrated biosphere simulator (IBIS). Their study estimated that about 30% of India's teak locations are vulnerable to climatic changes. However, both biomass and NPP are expected to increase because of elevated CO_2. Deb et al. (2017) found shrinkage in the teak distribution mainly due to deforestation, and local impacts of climate change. Nölte et al. (2018) stated that extension of rotation periods and thinning intensity reduction could be used as a management measure to increase C storage in teak plantations. Xie et al. (2020a) found that low and moderate thinning in RCP8.5 and RCP4.5 climate scenarios caused an increase of NPP in the deciduous *Larix olgensis* plantations in China.

3-PGmix is a site and species-specific forest growth model; therefore, parameterisation is needed to apply it to other species or different site conditions that were not parameterised earlier (Landsberg and Waring 1997; Sands 2004). Previously, the 3-PG model was parameterised for teak in Brazil (Pontes 2011) and Costa Rica (Nolte et al. 2018); however, it is not suitable to use all those parameters in the current study. Firstly, those studies ignored the fact that teak is deciduous. Secondly, the problem with those parameter sets from Brazil or Costa Rica is that the provenance of teak in those studies could significantly differ from the current study. Sensitivity analysis is an important step for understanding the behaviour of PBM's (Song et al. 2013) because it shows the sensitivity of model outputs to specific parameters. Parameter's uncertainty could be reduced through accurate observations and a better understanding of modelling components (Makler-Pick et al. 2011; Song et al. 2012, 2013; Gupta and Sharma 2019).

This research focused on modelling climate change and thinning regimes implications on teak growth. We ran 3-PGmix incorporated with GCM Community Climate System Model (CCSM4) projected Representative Concentration Pathways (RCPs) scenarios (baseline, RCP4.5, and RCP8.5) and thinning (G-quality, P-quality, and no thinning) regimes up to the year 2100 at different teak planted locations in three states. The obtained outputs were averaged from all locations to demonstrate our final result as a single set based on the model developed in native and planted teak distributed locations. Furthermore, the model was calibrated and validated at different sites against observed values, using a defined set of averaged site-specific parameters. Performance and sensitivity analysis were made, after which the performance was assessed, using statistics such as coefficient of determination (R^2), standard error (SE), mean squared error (MSE), root mean square error (RMSE), and sum of squared error (SSE). The model predicted mean annual increment (MAI), biomass, and NPP should help in recognizing the timber production potential, along with C stock and sequestration of teak in the future.

2 Materials and methods

2.1 Study area

Teak plots in three Indian states, namely Madhya Pradesh, Gujarat, and Rajasthan were selected for the current study (Fig. 1). Madhya Pradesh lies in central India, Gujarat on the western coast of India, and Rajasthan is the north-western part of India. The central latitude of Madhya Pradesh, Gujarat, and Rajasthan is between 21°17′ N and 26°52′ N, 20°07′N and 24°43′N, and 23°4′N and 30°11′N and longitude is 74°08′ E to 82°49′ E, 68°10′E to 74°29′E, and 69°29′E to 78°17′ E respectively. Madhya Pradesh has a sub-tropical climate, while Gujarat has moderate, and Rajasthan has semi-arid to an arid climate. Mean annual precipitation (MAP) ranges between 800 and 1800 mm, 800 and 1000 mm, and 500 and 750 mm in Madhya Pradesh, Gujarat, and Rajasthan, respectively. Mean annual temperature (MAT) varies from 22 to 25 °C, 25 to 28 °C, and 0 to 50 °C in Madhya Pradesh, Gujarat, and Rajasthan, respectively. In Madhya Pradesh, the dry teak forest is 26.40%, the very dry teak forest is 0.86%, and the slightly moist teak forest is 2.28% of the total forest cover. In Gujarat, the moist teak forest is 4.50%, slightly moist teak forest is 3.83%, very dry teak forest is 4.60%, and the dry teak forest is 11.77%, and in Rajasthan, the very dry teak forest is 5.63%, and the dry teak forest is 0.21% of the total forest cover (FSI 2019).

2.2 The 3-PGmix model

3-PGmix (Forrester and Tang 2016) is an improved version of the 3-PG model (Landsberg and Waring 1997). The main concern in 3-PG was that it was designed for evergreen species, but teak is a deciduous species. Therefore, in 3-PG, the simulated trees would shed its foliage gradually and not all at once. This, in turn, would significantly misrepresent the growth dynamics of teak plantations as they are largely leafless during the dry season (Kadambi 1972). 3-PGmix has a modified light-absorption routine, vertical canopy structural gradients, and a water balance routine that allows for competition for water between species (Forrester and Tang 2016). Also, 3-PGmix calculates mean annual increment (MAI), as it is usually calculated in forestry, such that MAI is calculated from the cumulative volume (including all volume growth of live trees and any volume that has been removed in the past due to thinning or that was lost when trees died). In contrast, the original 3-PG calculated MAI as a standing volume divided by age, which ignores all the volume of growth that has been removed by thinning

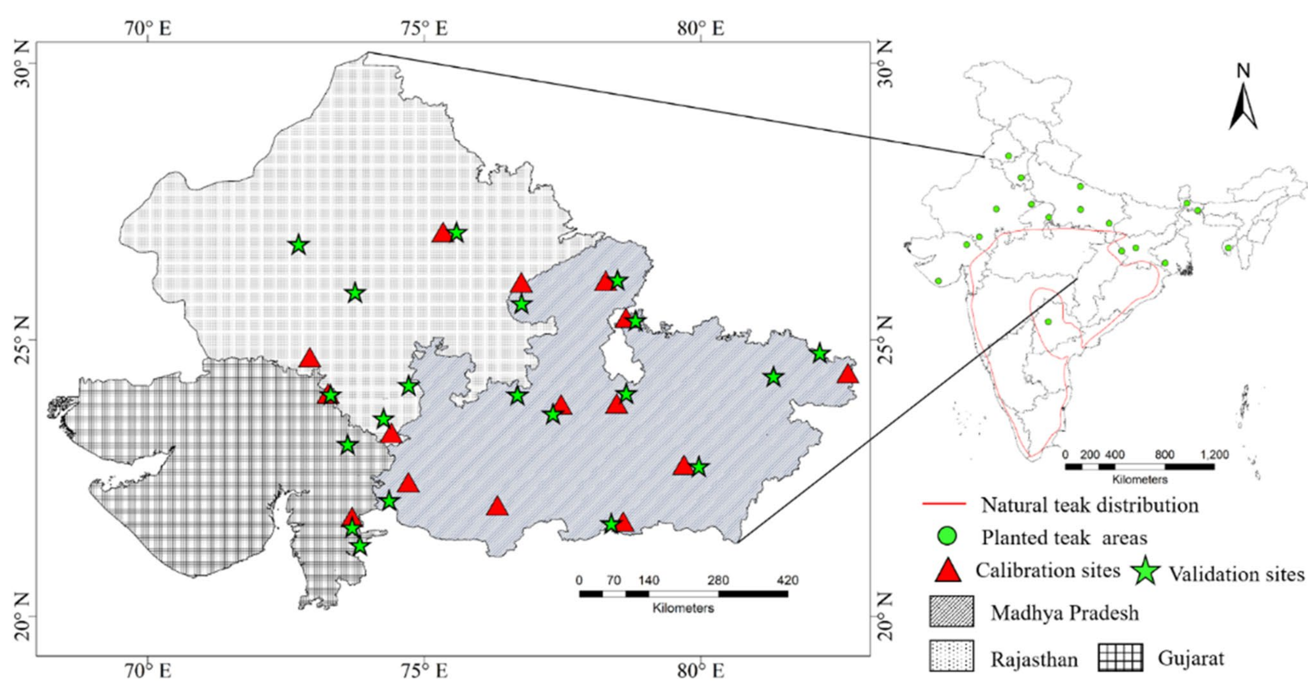

Fig. 1 Locations of the selected teak natural stands and plantations from Madhya Pradesh, Gujarat, and Rajasthan states of India (map was created using ArcGIS Desktop version 10.1)

or mortality; therefore, it would underestimate MAI that is typically calculated in forestry.

Another main advantage of 3-PGmix is its simplicity in parameterisation compared to other PBMs (Du et al. 2016). 3-PGmix can also be freely downloaded from the website https://sites.google.com/site/davidforrestersite/home/projects/3PGmix/3pgmixdownload (Forrester 2020). The implementation strategy of the 3-PGmix model in this study is presented in Fig. 2. The model is comprised of five basic submodels, and various growth modifiers such as temperature, CO_2, vapour pressure deficit, frost, available soil water, and soil fertility can offer confinements to estimate NPP. All these growth modifiers range from zero (fully limiting) to one (non-limiting) (Landsberg and Waring 1997; Gupta and Sharma 2019). In 3-PGmix, for deciduous species, we need merely two extra parameters, comprising the month when foliage is produced (leafP) and the month when they were shed (leafL) (Forrester and Tang 2016).

2.3 Model inputs

2.3.1 Data collection

The main site inputs include latitude, elevation, fertility rating (FR), soil texture, CO_2 concentration, and minimum and maximum available soil water (ASW). Field surveys were done in thirty-five teak sample plots, selected from three states for different climatic and growth conditions (Fig. 1). Out of 35 plots, we used an average data value of 15 plots for calibration and 20 plots for validation purposes. Average stand data from 2001 to 2010 was used for calibration, while data from 2011 to 2020 was used for validation against mean observed data. We overlaid a 0.1 ha plot in each sample site, post which, the inventory data for teak was recorded. The location in terms of latitude and longitude, and elevation were recorded by handheld Global Positioning System (GPS, Garmin etrex10). The height (m) of trees was measured using the Haga altimeter (Bharat Emporium, Haridwar, India), and the diameter at breast height (DBH) (cm) (1.38 m above ground) was measured using a measuring tape in sample plots. CO_2 concentration (ppm) was downloaded from the RCP Database (v2.0.5) (Meinshausen et al. 2011) available through (https://tntcat.iiasa.ac.at/RcpDb/) website. ASW was derived from the Harmonized World Soil Database (HWSD v1.2) (FAO 2012). The soil texture generally varies from sandy loam to clay loam in the study sites. FR was measured using a method suggested by Subedi et al. (2015) based on site index and volume. Allometric model-based equations (Eqs. 1–8) derived for teak species (FSI 2019) were used to estimate stand volume (SV), stem biomass (WS), foliage biomass (WF), above-ground biomass (AGB), below-ground biomass (BGB), and total biomass (TotalW) (Table 1).

$$SV_{\text{Madhya Pradesh}} = -0.003673 - 0.379175 \times DBH + 6.368282 \times DBH^2 \quad (1)$$

$$SV_{\text{Gujarat}} = 0.032011 - 0.995414 \times DBH + 9.91129 \times DBH^2 \quad (2)$$

Table 1 Observed mean of stand variables in 10-year-old teak stands (compiled using Eqs. 1 to 8)

Stand variable	Minimum	Maximum	Mean
Height (m)	1.40 ± 0.14	4.88 ± 4.71	3.11
DBH (cm)	2.90 ± 0.20	8.80 ± 7.57	5.88
Basal area (m^2/ha)	1.43 ± 0.75	12.16 ± 2.88	6.37
SV (m^3/ha)	3.25 ± 2.22	41.40 ± 5.82	20.4
WS (t/ha)	2.63 ± 1.49	18.75 ± 6.85	10.36
WR (t/ha)	0.72 ± 0.58	11.6 ± 1.65	5.27
WF (t/ha)	0.33 ± 0.27	1.62 ± 1.38	0.94
TotalW (t/ha)	3.58 ± 2.25	58 ± 19.45	26.33

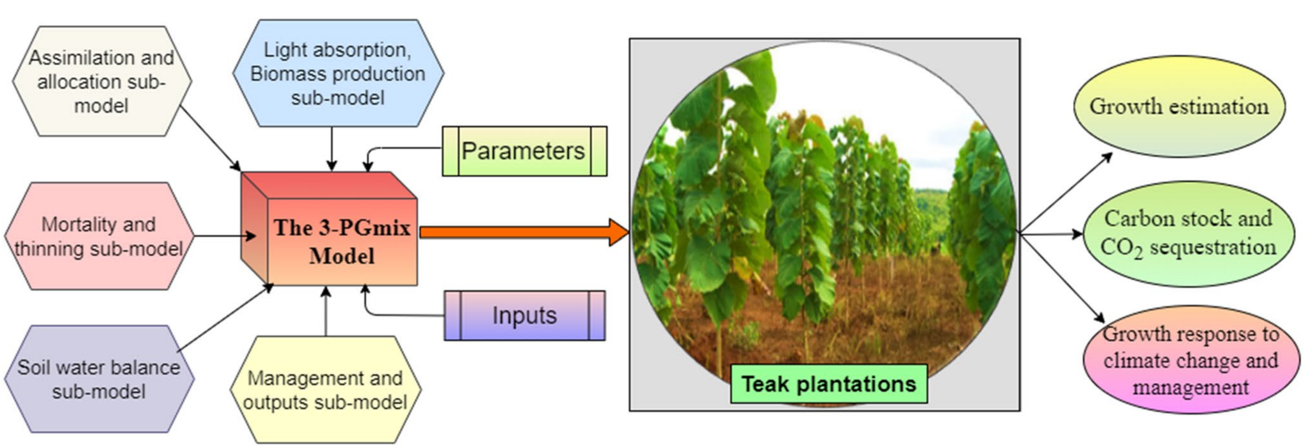

Fig. 2 Implementation scheme of the 3-PGmix model to determine teak response under change climate change and management

$$SV_{Rajasthan} = 0.062108 - 0.927983 \times DBH + 6.613031 \times DBH^2 \quad (3)$$

$$WS = 0.1701 \times DBH^2 - 0.5602 \times DBH + 1.3209 \quad (4)$$

$$WF = 0.0080 \times DBH^2 + 0.0186 \times DBH + 0.0245 \quad (5)$$

$$AGB = 0.0904 \times DBH^{2.551} \quad (6)$$

$$BGB = 0.097 \times DBH^{2.023} \quad (7)$$

$$TotalW = AGB + BGB \quad (8)$$

2.3.2 Model initialisation data

3-PGmix needed stand data, including the planting date, model initialisation and end date, initial stem biomass, initial foliage biomass, initial root biomass, initial available soil water, and initial stocking (tree/ha). Teak is generally planted during the month of June–July in the study sites. Model estimates are initialised from May, as teak is a deciduous species, and no new foliage biomass is produced in the dormant season (November to March). Stand data from 2001 to 2010 was selected for calibration, while data from 2011 to 2020 were chosen to validate model outputs. Initial mean DBH and tree height data from each study plot were extracted and cleaned from e-Green Watch (http://egreenwatch.nic.in/) and verified in field surveys. Stocking and stand age data were compiled from field surveys, e-Green Watch, and secondary sources (forest survey reports, literature, and management companies).

2.3.3 Climatic data

We used six climatic variables (Fig. 3) for baseline (1981–2010), historical (2001–2020), and future (2011–2100) climatic conditions (RCP4.5 and RCP8.5) in the 3-PGmix model. We extracted the value of each climate variable from each sample plot location and then put it into the model. The model generated outputs were averaged from each site to obtain the growth response to climate change. We downloaded data variables including monthly mean maximum temperature (Tmax), monthly mean minimum temperature (Tmin), MAT, MAP, and frost days from Climate Asia Pacific (CAP) (ClimateAP v2.30) software (Wang et al. 2017) (Table 2). In CAP, baseline data was down-scaled and gridded (4×4 km), with monthly climate data extracted from PRISM (Daly et al. 2008) and WorldClim (Hijmans et al. 2005) to scale-free point locations. Historical data has 0.5°×0.5° spatial resolution, obtained from the Climate Research Unit (CRU) (Harris et al. 2014). Future climatic scenarios (RCP4.5 and RCP8.5) were used based on GCM CCSM4 of the Coupled Model Inter-comparison Project (CMIP5), developed in the Fifth Assessment Report (IPCC 2014) of the Intergovernmental Panel on Climate Change (IPCC). Gridded solar radiation data (Gent et al. 2011) under historical and future scenarios were based on GCM CCSM4 and were downloaded from the Copernicus climate change service portal (https://cds.climate.copernicus.eu/). Monthly mean vapour pressure deficit

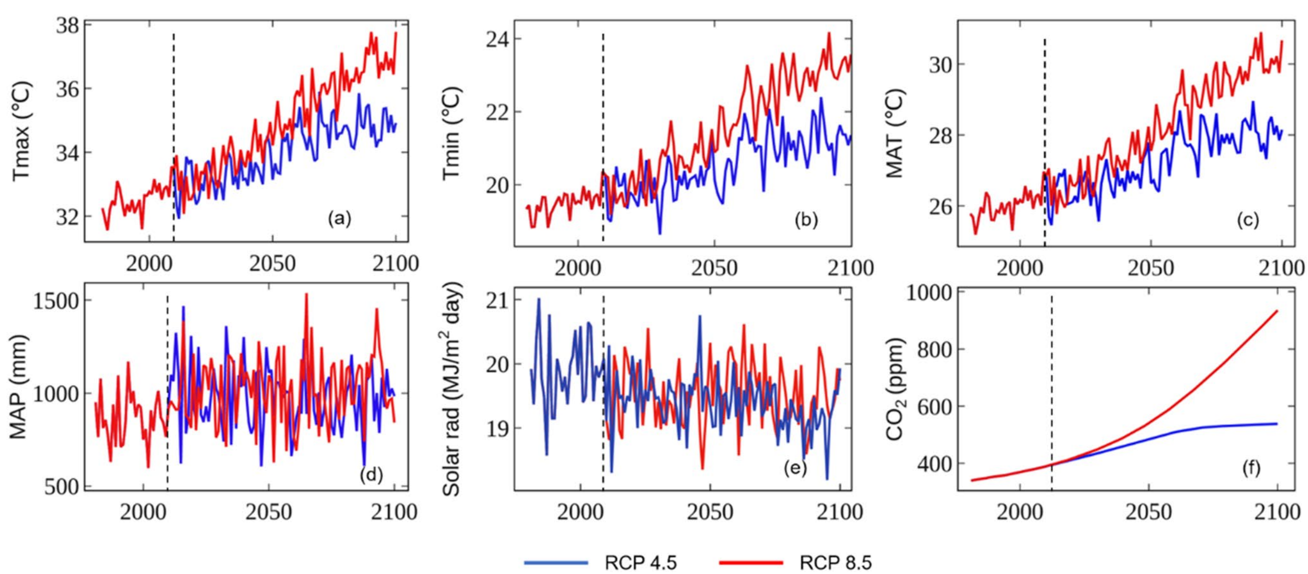

Fig. 3 Mean variations in Tmax (a), Tmin (b), MAT (c), MAP (d), solar radiations (e), and CO_2 (f) across study sites under different climate scenarios (baseline, RCP4.5, and RCP8.5)

Table 2 Variations in mean annual temperature (MAT), mean annual precipitation (MAP), and CO_2 under different climate scenarios (baseline, RCP4.5, and RCP8.5)

Climate scenarios	Period	MAT (°C)	MAP (mm)	CO_2 (ppm)
Baseline	1981–2010	26.03 (±0.74)	72.16 (±19.29)	362.47
RCP4.5	2011–2100	27.3 (±0.69)	78.8 (±19.61)	484.91
RCP8.5	2011–2100	29.83 (±0.65)	81.51 (±20.87)	606.94

Table 3 Thinning regimes for teak in the current study (adopted from Sagreiya (1957) and Kadambi (1972))

Thinning	G-quality Frequency (yr)	P-quality Frequency (yr)	Stocking/ha	Thinning intensity (%)
First	5	10	1250	50
Second	10	20	750	30
Third	20	40	500	20
Fourth	40	60	300	12

(VPD) data values were downloaded from Terraclimate (Abatzoglou et al. 2018). Monthly climatic data were used as input to the 3-PGmix model, but the annual climate information was used to describe the different climate scenarios considered in this study.

2.4 Thinning regimes

An increase in stocking and DBH growth cannot be done simultaneously (Chaturvedi 1995). DBH is increased proportionally on increasing crown size in teak, e.g. by reducing stocking. The high stem volume in teak can be obtained on frequent thinnings (Chaturvedi 1995). Generally, the first two thinnings are mechanical, and each aims to remove 50% of the total stocking. However, thinning intervals need to be varied with silvicultural requirements and teak development on sites of different quality (Kadambi 1972). For Madhya Pradesh teak plantations, the thinning regimes suggested by Sagreiya (1957) are shown in Table 3. We adopted the same thinning regimes in this study and categorised them as good (G)-quality and poor (P)-quality. In G-quality, the first thinning was performed at the age of 5 years, and then the remaining three thinnings were at the age of 10, 20, and 40 years. In G-quality, the first thinning was performed at the age of 10 years, and then the remaining three thinnings were at the age of 20, 40, and 60 years. The thinning intensity in both G-quality and P-quality was 50%, 30%, 20%, and 12% in first, second, third, and fourth thinning operations respectively. Therefore, an earlier thinning was performed under G-quality than P-quality; however, the thinning intensity would be the same (Table 3). Under the ‘no thinning’ scenario, there were no thinning treatments in teak stands.

2.5 Parameterisation

In the current study, the 3-PGmix model parametrisation for teak plantation was performed in four ways: (1) finding parameters value in literature (*L*) on Indian teak; (2) good fitted (*F*) values of model output to observed growth data; (3) taking an average of observed (*O*) parameters from sampling plots; and (4) using default (*D*) values. In literature, we were able to find some site-specific related parameters from Pandey and Brown (2000); Gangopadhyay (2005); Gopalakrishnan et al. (2011); Mehta et al. (2012); and Behera et al. (2017, 2019). Most of the parameters related to biomass partitioning, root turnover, and stem height were estimated from modelled values fitted to observed data. Parameters for deciduous species in 3-PGmix were used from direct observations. The remaining parameters were used as default values from the 3-PG mix model.

2.6 Sensitivity analysis

Sensitivity analysis is performed to determine the sensitive parameters that give fitted modelled data to observed data from the study site. We used r3PG (Trotsiuk et al. 2020b), a recent R (R Core Team 2019) package of Fortran re-implementations of the 3-PG model, to perform Morris screening (Morris 1991). The results obtained from sensitivity analysis are shown in Fig. 4. The descending trend of influential parameter names is plotted on the *y*-axis against iterations on the *x*-axis. Higher $\mu*$ indicates a factor with a significant overall effect on model outputs. Higher σ specifies either a factor interacting with other factors or a factor whose influence is non-linear (Trotsiuk et al. 2020b) (Fig. 4).

2.7 Model performance

The goodness of fit test has been performed by applying linear regression between observed and simulated data variables. Different statistics equations (Eqs. 9 to 12) were used to determine SE, SSE, MSE, and RMSE for calibration and validation outputs as shown in Fig. 5.

$$\mathrm{SE} = \left(x_i - \overline{x}_i\right)^2 \tag{9}$$

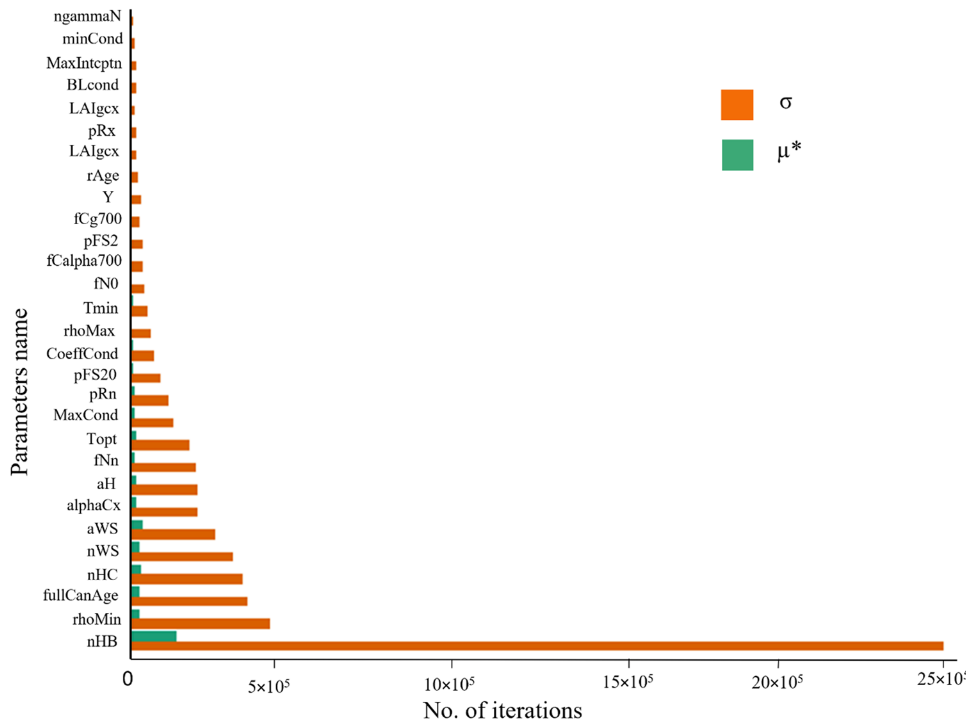

Fig. 4 Sensitivity analysis plot of model parameters (*y*-axis) and number of iterations (*y*-axis)

$$\mathrm{SSE} = \sum_{i=1}^{n} \left(x_i - \overline{x}_i\right)^2 \tag{10}$$

$$\mathrm{MSE} = \frac{1}{n} \sum_{i=1}^{n} \left(x_i - \overline{x}_i\right)^2 \tag{11}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(x_i - \overline{x}_i\right)^2} \tag{12}$$

where x_i is observed data; $\overline{x}_i$ is predicted data; and n is the number of data observations.

2.8 Growth and carbon dynamics

After successful calibration and validation (Fig. 5) of the 3-PGmix model for various outputs with a defined set of parameters for teak plantations, we performed a projection of teak growth variables for over 20 years (2001–2020) using historical climatic data (Fig. 6). Next, we simulated TotalW, MAI, and NPP of teak plantations under the climate change scenarios and thinning regimes with constant (Fig. 7) and increasing CO_2 (Fig. 8) up to 2100. By keeping constant CO2 conditions, we can estimate what effect other climate variables can cause on teak growth in the future. About 50% of total biomass is C stock (IPCC 2006), while CO_2 sequestration is the long-term storage of carbon in teak calculated by multiplying C stock by 3.67 (Fig. 9).

3 Results

3.1 Calibration and validation

An excellent correlation ($R^2 > 0.95$) was found between simulated and observed growth variables (Fig. 5). In both calibration and validation steps, the p value between simulated and observed data is < 0.0001, which reveals that the model outputs are significant for the predicted values. Low SE, MSE, RMSE, and higher R^2 in between observed and simulated outputs indicate that the 3-PG mix model can accurately predict teak growth.

3.2 Sensitivity analysis

Figure 4 reveals that the model outputs are generally sensitive to stand parameters such as the power of DBH in the stem height relationship (nHB), constant in stem height relationship (aH), and power of stocking in the stem height relationship (nHC); and biomass accumulation and partitioning parameters such as power in the stem biomass and DBH relationship (nWS), constant in the stem biomass and DBH relationship (aWS), and foliage and stem partitioning ratio (DBH = 20 cm) (pFS20). Also, outputs are sensitive to canopy structure and properties such as age at canopy cover (fullCanAge), canopy quantum efficiency (alphaCx), maximum canopy conductance (MaxCond), and stomatal response to VPD (CoeffCond). Moreover, the teak growth is sensitive to modifiers such as optimum temperature (Topt), assimilation enhancement factor at 700 ppm (fCalpha700),

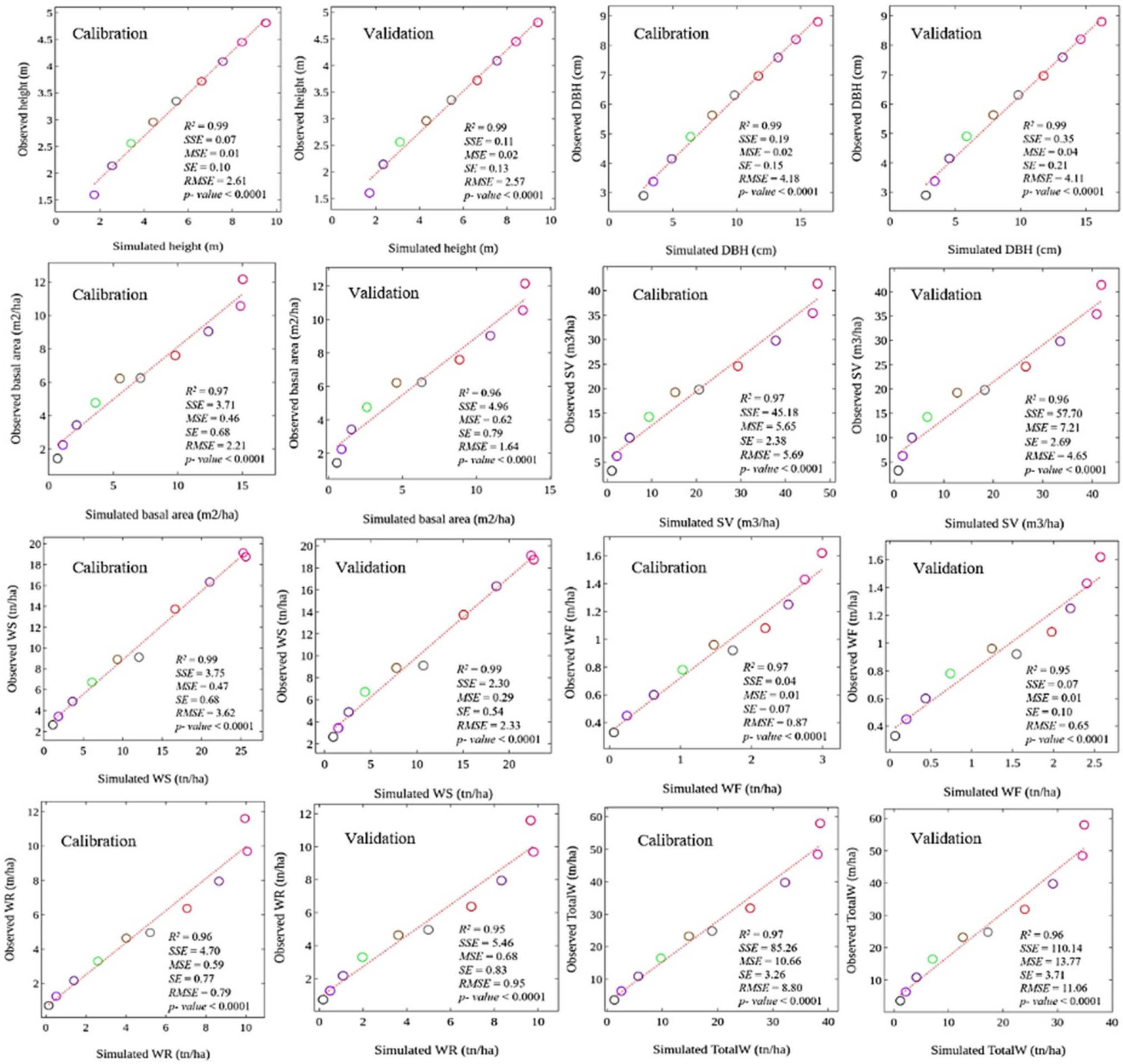

Fig. 5 Calibration and validation of the 3-PGmix model between annual average simulated and observed values for variables including height, mean DBH, basal area, stand volume, foliage biomass (WF), root biomass (WR), stem biomass (WS), and total biomass (TotalW) with different statistics values

and canopy conductance enhancement factor at 700 (fCg700) (Table 4).

3.3 Projected average growth over 20 years (2001–2020)

Height (m) and mean DBH reach 17.81 m and 29.06 cm respectively at the projected age of 20 years. Stem biomass (WS) is projected to be 75.49 t/ha at 20 years. The model projected total biomass (TotalW) is 100.11t/ha at 20 years. The projected mean annual increment (MAI) is 7.48 m^3/ha/year at the stand age of 20 years. Also, net primary productivity (NPP) reached 11.28 t/ha/year at 20-year-old teak plantations (Fig. 6).

3.4 Growth response to climate and thinning regimes under constant CO_2

Relative to baseline conditions, predicted MAI, TotalW, and NPP were lower under RCP4.5, RCP8.5, and

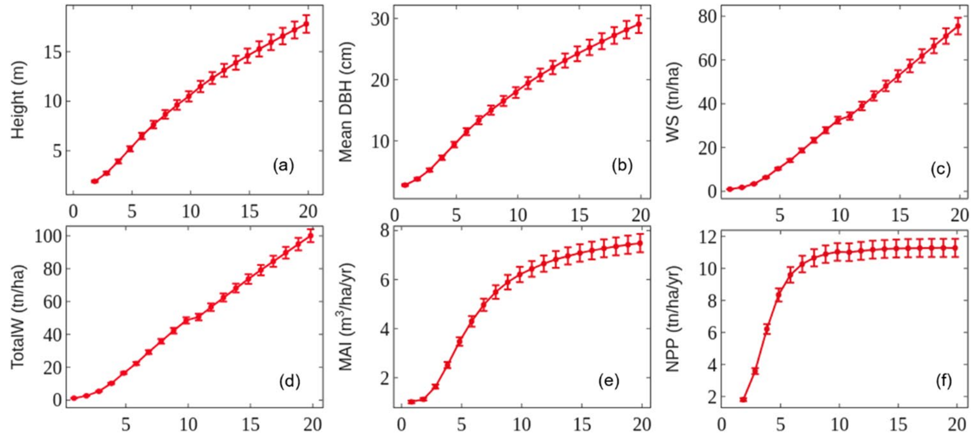

Fig. 6 Projected growth variables (*y*-axis) over stand age (*x*-axis) for 20 years (2001–2020). Error bars represent the standard deviation in data

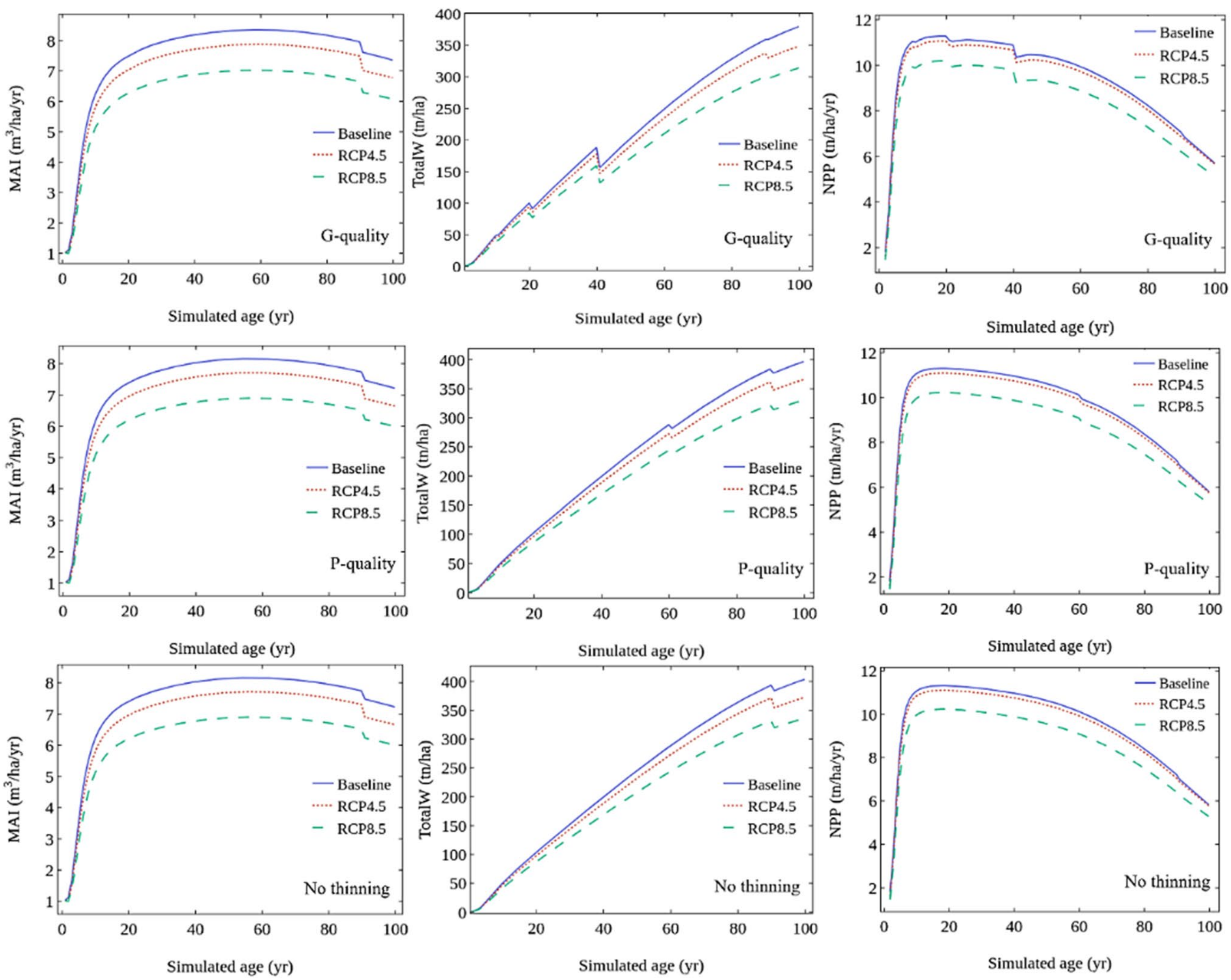

Fig. 7 Mean variations in MAI, TotalW, and NPP over simulated age of 100 years under different climate scenarios (baseline, RCP4.5, and RCP8.5) and management (G-quality, P-quality, and no thinning) treatments

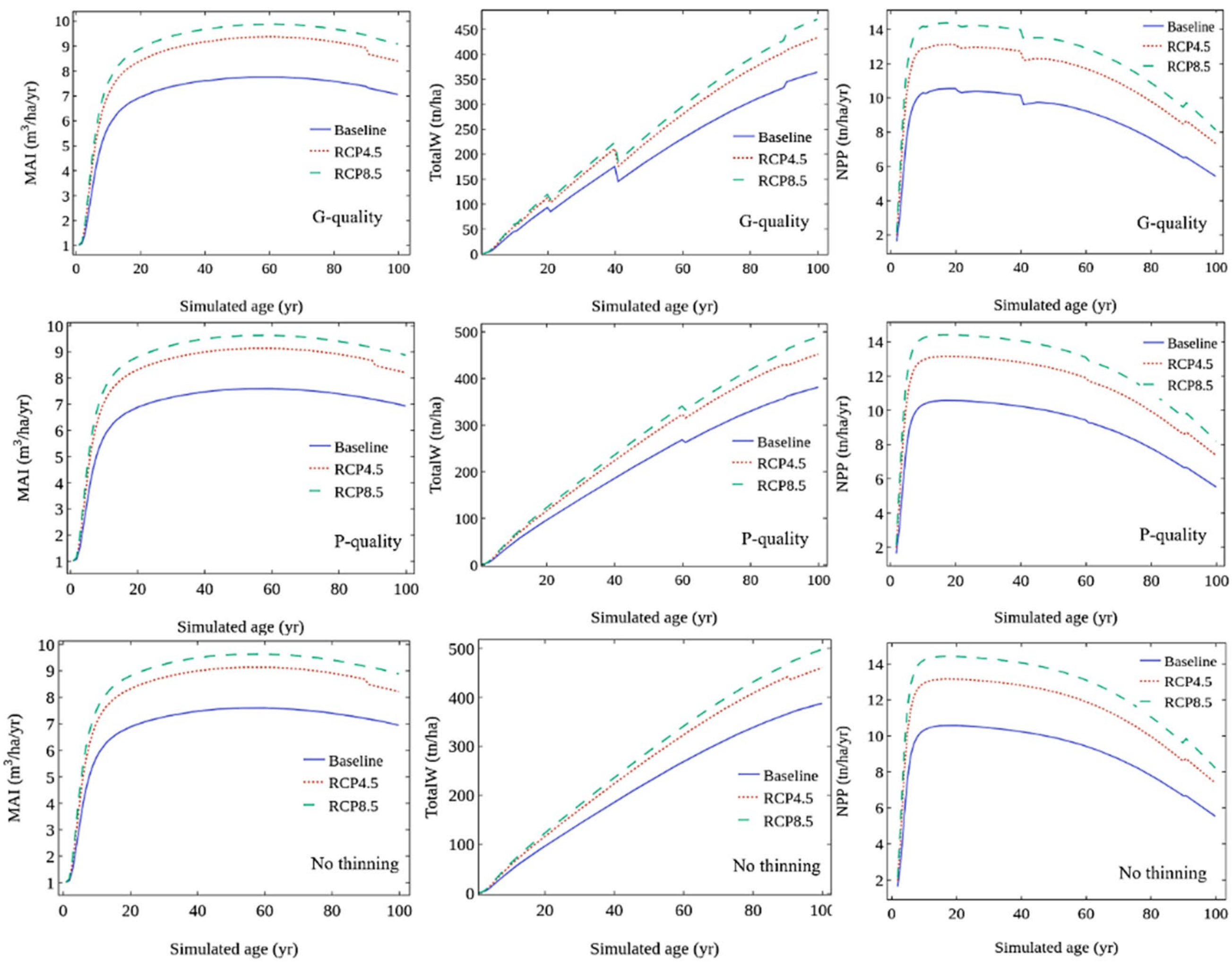

Fig. 8 Impact of increasing CO_2 on mean values of MAI, TotalW, and NPP over simulated age of 100 years under different climate scenarios (baseline, RCP4.5, and RCP8.5) and management (G-quality, P-quality, and no thinning) treatments

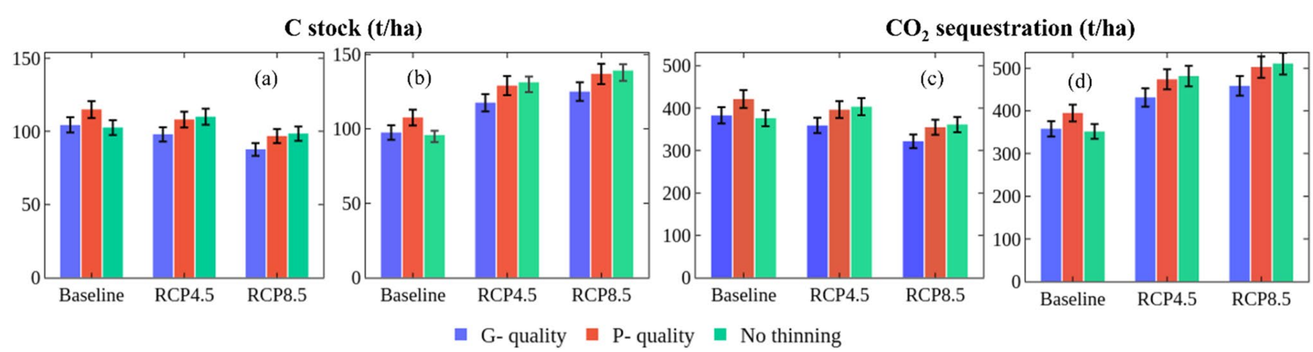

Fig. 9 C stock and CO_2 sequestration potential of teak with constant CO_2 (a, c) and increasing CO_2 (b, d), under climate scenarios (baseline, RCP4.5, and RCP8.5) and management (G-quality, P-quality, and no thinning) treatments

thinning (Fig. 7). Mean NPP over simulated 100 years follows the trend baseline > RCP4.5 > RCP8.5. In 2100 with no thinning, NPP is 5.82 t/ha/year, 5.77 t/ha/year, and 5.28 t/ha/year under baseline, RCP4.5, and RCP8.5 respectively (Fig. 7). Table 6 demonstrates that the predicted mean NPP over 100 years under no thinning is

Table 4 3-PGmix parameter descriptions, their names, symbols, units, values, and sources: Default (*D*) values from the 3-PGmix model/modelled values Fitted (*F*) to observed data/Literature (*L*) related to teak from Indian conditions/Observed (*O*) data from the field used in this study

Parameter's description	Name	Symbol	Unit	Value	Source
Biomass partitioning and turnover					
Foliage: stem partitioning ratio (DBH = 2 cm)	pFS2	p_2	-	0.33	*F*
Foliage: stem partitioning ratio (DBH = 20 cm)	pFS20	P_{20}	-	0.12	*F*
Constant in the stem biomass and DBH relationship	aWS	a_S	-	0.13	*F*
Power in the stem biomass and DBH relationship	nWS	n_S	-	2.01	*F*
Maximum fraction of NPP to root	pRx	η_{Rx}	-	0.6	*F*
Minimum fraction of NPP to roots	pRn	η_{Rn}	-	0.2	*F*
Litterfall and root turnover					
Maximum litterfall rate	gammaF1	γ_{Fx}	mn^{-1}	0.03	*D*
Litterfall rate when age = 0	gammaF0	γ_{F0}	mn^{-1}	0.001	*D*
Age at which litterfall rate has a median value	tgammaF	$t_{\gamma F}$	months	12	*D*
Average monthly root turnover rate	gammaR	γ_R	mn^{-1}	0.015	*D*
If deciduous, leaves are produced at end of this month	leafgrow	leafP	month	4	*O*
If deciduous, leaves all fall at start of this month	leaffall	leafL	month	11	*O*
Temperature modifier (f_T)					
Parameter's description	Name	Symbol	Unit	Value	Source
Minimum temperature, optimum, and maximum temperature	Tmin, Topt, Tmax	$T_{\min}, T_{\text{opt}}, T_{\max}$	°C	13, 25, 43	Pandey and Brown (2000)
Frost modifier (f_{frost})					
Days production lost per frost day	kF	k_F	days	0	*O*
Soil water modifier (f_{ASW})					
Moisture ratio deficit for soil water content = 50%	SWconst	c_θ	-	0.5	*D*
Power of moisture ratio deficit	SWpower	n_θ	-	5	*D*
Atmospheric CO_2 modifier					
Assimilation enhancement factor at 700 ppm	fCalpha700	$fC\alpha 700$	-	1.4	*D*
Canopy conductance enhancement factor at 700 ppm	fCg700	$fCg700$	-	0.3	*D*
Fertility effects $(\boldsymbol{f_N})$					
Value of m when $FR = 0$	m0	m_0	-	0.01	*D*
Value of f_N when $FR = 0$	fN0	f_{N0}	-	0.6	*F*
Power of (1-FR) in f_N	fNn	n_{fN}	-	0.6	*F*
Age modifier $(\boldsymbol{f_{\text{age}}})$					
Maximum stand age used in age modifier	MaxAge	t_x	yrs	120	Gangopadhyay (2005)
Power of relative age in function for f_{age}	nAge	n_{age}	-	4	*D*
Relative age to give $f_{\text{age}} = 0.5$	rAge	r_{age}	-	0.95	*D*
Stem mortality and self-thinning					
The mortality rate for large age	gammaN1	γ_{N1}	yr^{-1}	0.005	Behera et al. (2019)
Seedling mortality rate at age = 0	gammaN0	γ_{N0}	yr^{-1}	0	*D*
Age at which mortality rate has a median value	tgammaN	$t_{\gamma N}$	yrs	2	*D*
Shape of mortality response	ngammaN	$n_{\gamma N}$	-	1	*D*

Table 4 (continued)

Parameter's description	Name	Symbol	Unit	Value	Source
Max. Stem mass per tree at 1000 trees ha^{-1}	wSx1000	w_{Sx1000}	kg $trees^{-1}$	300	*D*
Power in self-thinning rule	thinPower	n_N	-	1.5	*D*
The fraction of mean single-tree for foliage, root, and stem biomass lost per dead tree	mF, mR, mS	m_F, m_R, m_s	-	0.01, 0.1, 0.04	*D*
Specific leaf area					
Specific leaf area at age 0	SLA0	σ_0	m^2kg^{-1}	10.68	Mehta et al. (2012)
Specific leaf area for mature leaves	SLA1	σ_1	m^2kg^{-1}	22.7	Gopalakrishnan et al. (2011)
Age at which specific leaf area = $(\sigma_0 + \sigma_1)/2$	tSLA	t_σ	yrs	3	*D*
Light interception					
Extinction coefficient for absorption of PAR	k	k	-	0.47	*D*
Age at canopy cover	fullCanAge	t_c	yrs	10	*F*
Canopy quantum efficiency	alphaCx	α_{Cx}	molC/molPAR	0.055	*D*
Rainfall interception					
Maximum proportion of rainfall intercepted	MaxIntcptn	i_{Rx}	-	0.15	*D*
LAI for maximum rainfall interception	LAImaxIntcptn	L_{ix}	m^2m^{-2}	3.79	Behera et al. (2017)
LAI for 50% reduction of VPD in canopy	cVPD	L_{50D}	-	5	*D*
Production and respiration					
Ratio NPP/GPP	Y	Y	-	0.47	*D*
Conductance					
Parameter's description	Name	Symbol	Unit	Value	Source
Minimum canopy conductance	MinCond	gSx	ms^{-1}	0.013	*D*
Maximum canopy conductance	MaxCond	g_{Cx}	ms^{-1}	0.08	*F*
LAI for maximum canopy conductance	LAIgcx	L_{Cx}	m^2m^{-2}	3.33	*D*
Defines stomatal response to VPD	CoeffCond	k_D	$MBar^{-1}$	0.04	*D*
Canopy boundary layer conductance	BLcond	g_B	ms^{-1}	0.01	Behera et al. (2019)
Branch and bark fraction (p_{BB})					
Branch and bark fraction at age = 0	fracBB0	p_{BB0}	-	0.75	Pontes (2011)
Branch and bark fraction for mature stands	fracBB1	p_{BB1}	-	0.15	Pontes (2011)
Age at which $p_{BB} = (p_{BB0} + p_{BB1})/2$	tBB	t_{BB}	yrs	2	Pontes (2011)
Minimum basic density for young trees	rhoMin	ρ_0	tm^{-3}	0.45	*D*
Maximum basic density for older trees	rhoMax	ρ_1	tm^{-3}	0.45	Pontes (2011)
Age at which ρ = ½ density of old and young trees	tRho	t_ρ	yrs	4	*D*
Stem height					
Constant in stem height relationship	aH	a_H	-	0.4501	*F*
Power of DBH in the stem height relationship	nHB	n_{HB}	-	1.0892	*F*
Power of stocking in the stem height relationship	nHC	n_{HN}	-	0.002	*F*

9.58 t/ha/year, 9.38 t/ha/year, and 8.59 t/ha/year under baseline, RCP4.5, and RCP8.5 respectively (Table 5).

3.5 Growth response to climate and thinning regimes with increasing CO_2

Relative to baseline conditions, predicted MAI, TotalW, and NPP are increased under RCP4.5 and RCP8.5 with

Table 5 Simulated mean MAI, TotalW, and NPP over 100 years under climate scenarios (baseline, RCP4.5, and RCP8.5) and management (G-quality, P-quality, and no thinning) with constant CO_2

Variables	G-quality			P-quality			No thinning		
	Baseline	RCP4.5	RCP8.5	Baseline	RCP4.5	RCP8.5	Baseline	RCP4.5	RCP8.5
TotalW (t/ha)	208.65	195.71	175.18	229.70	216.08	193.45	204.96	219.74	196.77
MAI (m^3/ha/yr)	7.53	7.07	6.30	7.39	6.94	6.21	7.53	6.95	6.21
NPP (t/ha/yr)	9.43	9.22	8.42	9.56	9.37	8.58	9.41	9.38	8.59

increasing CO_2 (Fig. 8). MAI, TotalW, and NPP under no thinning are increased compared to G-quality and P-quality thinnings. Under RCP8.5, NPP in the year 2100 reaches 8.14 t/ha/year, 8.20 t/ha/year, and 8.22 t/ha/year for G-quality, P-quality, and no thinning respectively. In simulated 100 years and under RCP8.5, the mean TotalW is 250.02 t/ha, 274 t/ha, and 278.48 t/ha; mean NPP is 12.32 t/ha/year, 12.46 t/ha/year, and 12.47 t/ha/year; and mean MAI is 8.98 m^3/ha/year, 8.79 m^3/ha/year, and 8.79 m^3/ha/year in G-quality, P-quality, and no thinning respectively (Table 6).

3.6 Carbon stock and CO_2 sequestration

It is observed from Fig. 9 that with constant CO_2, the potential C stock and CO_2 sequestration for teak follow the trend baseline > RCP4.5 > RCP8.5 for both G-quality and P-quality. However, with increasing CO_2, the trend is RCP8.5 > RCP4.5 > baseline. The maximum C stock with constant CO_2 is under RCP8.5, and no thinning reached 98.38 t/ha; with increasing CO2, under RCP8.5 and no thinning, it reached 139.24 t/ha. Also, the maximum CO_2 sequestration with constant CO_2, RCP8.5, and no thinning is 361.07 t/ha; with increasing CO_2, RCP8.5, and no thinning, the maximum CO_2 sequestration is 511.01 t/ha (Fig. 9).

4 Discussion

Formerly, only a few studies were conducted on estimating teak growth with climate change and management scenarios. Therefore, it is unclear that how the teak growth varies with climate change and management. Our results showed that there would be a decrease in MAI, TotalW, and NPP under RCP 4.5 and RCP8.5 scenarios with thinning regimes compared to baseline under constant CO_2 conditions. The C stock and CO_2 sequestration potential of teak are also decreased under constant CO_2 concentration. However, simulations showed that with increasing CO_2 concentration, the MAI, TotalW, NPP, C stock, and CO2 sequestration in teak would increase in the future. Comparison of MAI, Total W, and NPP in G-quality and P-quality revealed low MAI, TotalW, and NPP in G-quality thinning, indicating that climate change can become slightly unfavourable to G-quality thinning. Our results suggest that increasing CO_2, temperature, and precipitation under RCP 4.5 and RCP8.5 scenarios can increase teak growth through the 'carbon fertilisation effect' (Kirilenko and Sedjo 2007; Jana et al. 2009; García-Valdés et al. 2020; Favero et al. 2021). Climate change scenarios show that under RCP4.5 and RCP8.5, an increase in temperature and precipitation in the deciduous forests of the study site. The rise in temperature and precipitation is generally linked to increasing the NPP by enhancing photosynthesis, provided that the temperature is optimum. However, an extreme temperature possibly causes a reduction in NPP of teak in future RCP4.5 and RCP8.5 scenarios. One advantage with deciduous forests is that they are already adapted to dry and wet conditions; however, a possible increase in the length of dry or colder season, extreme temperature, and high rate of evapotranspiration could cause a reduction in NPP, increased droughts frequency, and wildfire risk.

A sensitivity analysis showed that parameters related to biomass allocation, stand structure and canopy properties, temperature, and CO_2 modifiers are very sensitive to growth outputs and need to be calculated as accurately as possible. However, the CO_2 modifier parameters had default values, which were not species-specific; therefore, even if the parameters are important in the sensitivity analysis, they were also those that were estimated most reliably. Gopalakrishnan et al. (2011) revealed that NPP and biomass in teak might increase in the future because of elevated CO_2; however, they did not explore management treatments. Xie et al. (2020a) found that the NPP of deciduous plantations *Larix olgensis* at a simulated age of 90 years would increase under RCP 4.5 and RCP 8.5. Furthermore, they showed that climate change and thinning did not significantly interact with each other. Xie et al. (2020b) showed that the future variations in temperature, precipitation, and atmospheric CO_2 concentration are favourable in raising C stock and follow the RCP 8.5 > RCP 4.5 > current conditions in larch plantations. However, increase in C stock would be mainly sensitive to CO_2 and depends locally on climatic and site conditions (Trotsiuk et al. 2020a). Our results also revealed that the C stock would be increased under rising CO_2 concentrations in RCP4.5 and RCP8.5 scenarios and thinning regimes. Empirical observations from Purwanto et al. (2003) showed that total biomass ranged from 2.76 to 55.39 t/ha, while NPP varied from 11.88 to 36.05 t/ha/

Table 6 Simulated mean MAI, TotalW, and NPP over 100 years under climate scenarios (baseline, RCP4.5, and RCP8.5) and management (G-quality, P-quality, and no thinning) with increasing CO_2

Variables	G-quality			P-quality			No thinning		
	Baseline	RCP4.5	RCP8.5	Baseline	RCP4.5	RCP8.5	Baseline	RCP4.5	RCP8.5
TotalW (t/ha)	194.95	235.14	250.02	215.21	258.32	274.00	191.71	262.62	278.48
MAI (m^3/ha/yr)	7.02	8.47	8.98	6.89	8.30	8.79	7.02	8.30	8.79
NPP (t/ha/yr)	8.78	11.17	12.32	8.92	11.29	12.46	8.77	11.31	12.47

year for 2–7-year-old teak plantations. Negi et al. (1995) estimated the value of AGB in 10-, 20-, and 30-year-old teak was 74.6 t/ha, 90.7 t/ha, and 164.1 t/ha respectively. This shows that there is an increase of biomass with stand age, similar to our study. According to Nirala et al. (2018), the age at which a tree stand is harvested has an impact on timber quality, biomass production, and C stock potential of the teak stands. In teak forests, where temperature or precipitation is not limiting, CO_2 concentration plays a role in the increase of NPP. Our results revealed that the thinning schedules possibly impact C stock and CO_2 sequestration capacity in teak. With reduced intensity or no thinning, an increased rotation period, teak plantations have more C in the simulations. Similar results were shown by Nölte et al. (2018) and Quintero-Méndez and Jerez-Rico (2019) for teak as well.

5 Conclusion

We used the process-based 3-PGmix model to address the impacts of climate change and management treatments on teak plantations in India. Using climate scenarios and 3-PGmix, we showed that in the year 2100, with increasing CO_2, teak growth and potential to store C will increase. We showed that simulated MAI, biomass, and NPP rise with increasing CO_2; however, these are lowered under constant CO_2 conditions. Furthermore, low-intensity thinning, late thinning (P-quality), and no thinning would increase the C stock in teak. Sensitivity analysis showed that site- and species-specific parameters are related to biomass, stand canopy, and structural properties, and modifiers related to optimum temperature and CO_2 are very influential in teak growth. This study provides an opportunity to manipulate variables through improved parameterisation for attaining management objectives of teak stands in India. The model offers simulations of growth outputs that are generally foreseen under climate change and management; however, it is also a possibility of abnormal growth patterns under extreme temperature and drought conditions in future, as pointed out in recent studies. Furthermore, such work can be explored using ensemble GCMs datasets, accurate observed site-specific parameters, and integrating RS & GIS to extend the applicability of the 3-PGmix model across moisture gradients and varying climatic patterns in India.

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Author contribution Rajit Gupta: data collection, methodology design, software run, formal analysis, data curation, writing field data collection, visualisation.

Laxmikant Sharma: supervision, writing, review, editing, conceptualisation, resources, methodology design, analysis.

Availability of data and material The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Code applicability Not applicable.

Declarations

Ethics approval The authors declare that they follow the rules of good scientific practice.

Consent for publication All authors gave their informed consent to this publication and its content.

Conflict of interest The authors declare no competing interests.

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