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The process-based forest growth model 3-PG for use in forest management: A review

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ABSTRACT

Forests are a critical resource, and need proper management in the face of dire climatic changes facing the world today. Advances in modelling system result in the formulation of numerous forest modelling approaches to provide an estimation of forests services. One such useful and straightforward forest modelling approach is process-based modelling, relying on physiological processes and biophysical parameters of forest ecosystems. It is based on parametric calculations and allometric equations, delivering crucial outputs for forest management. The dynamic 3-PG (Physiological Principles in Predicting Growth) is a process-based model (PBM) based on an ecosystem physiological process-based modelling approach. The various applications and flexible nature of the 3-PG model have resulted in its adoption and utilization over several regions of the world. The 3-PGS (Physiological Principles in Predicting Growth with Satellite) model is a modified and spatial version of the 3-PG model that took advantages of remote sensing & GIS (Geographical Information System) for estimation of biophysical variables like FAPAR (Fraction of absorbed photosynthetically active radiation), LAI (Leaf area index), and Canopy water content (CWC), which are tedious and laborious to calculate manually. The integration of remote sensing & GIS with PBMs offers insights to predict forest biomass and productivity at a regional level. Also, coupling of the 3-PG/3-PGS model with other modelling and statistical approaches in a GIS environment provides insights into the prediction of species distributions and potential disturbances due to climatic changes. The 3-PG model was originally designed for relatively homogenous forests; but with the recent development, the 3-PGmix has extended its use to mixed species forests. In this review, we have tried to emphasize the general overview, structure, applications, and efficacy of the process-based 3-PG model for forest management. In future, forests and their ecosystem services are expected to be rigorously influenced by climatic variations. Therefore, it is important to understand the role and effectiveness of the forest growth model 3-PG under the influence of climate change. The 3-PG model performs well for a diverse range of conditions for many forest types and species, and could be integrated with other models and approaches in order to widen its functions and applications. Areas such as Fertility Rating (FR), sensitivity and uncertainty of outputs to the model inputs in the 3-PG model requires attention to remove the weaker side, and to increase the effectiveness and accuracy of model outputs. In addition, the model performance can be improved by calculating its parameters from the population of interest, rather than using default values or values from extant literature. Furthermore, high-resolution remote sensing datasets and accurate input field data could increase the accuracy of the 3-PG/3-PGS model predictions at a broad regional level. In general, the simple forest growth model 3-PG delivers practical outputs, which are directly used in forest management. Additionally, the functions and applications of the 3-PG/3-PGS/3-PGmix model could be explored to deal with the impacts of climate change on forests and to ensure the sustainable management of forests.

1. Introduction

Forests are one of the most genetically diversified and biologically productive ecosystems, covering about one-third of the global land area (Aerts and Honnay, 2011; FAO, 2015; Köhl et al., 2015). They provide numerous benefits including commercial benefits, contributing to a nation's economic growth, maintaining the hydrology of catchments, maintaining and conservation of ecological balance in regional biodiversity (Coops et al., 1998). They form a structurally and functionally well-established ecosystem, framed in different types of mechanisms

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and driving forces. A critical understanding is required to investigate Carbon (C) dynamics, ecosystem development and management practices (Zhu et al., 2010; Wu et al., 2014). The covered area by a forest's ecosystem is a direct indicator of the global ecological health (Keenan et al., 2015). At present, nearly 30% of the anthropogenic emissions from the atmosphere are removed annually by forests and other ecosystems (Le Quéré et al., 2016); in the future, additional C could be sequestered and removed by raising conservation efforts and sustainable management of forests (Keith et al., 2014; Houghton and Nassikas, 2018). In order to maximize 'ecosystem multifunctionality' by maximizing forest services and benefits to users, is the main challenge for forest managers (Hector and Bagchi, 2007; Brockerhoff et al., 2017).

Process-based forest growth modelling is a technique by which the ecosystem behavior has been examined from individual physical and biological functional components, vis a vis their interactions within themselves and the environment, through varying physical and mechanistic procedures (Godfrey, 1983; Bossel, 1994; Mäkelä et al., 2000; Vacchiano et al., 2012). The physiological processes centered forest growth and prediction models are powerful tools (Korzukhin et al., 1996; Battaglia and Sands, 1998; Mäkelä et al., 2000; Johnsen et al., 2001; Wei et al., 2014b) to understand the C dynamics in forest ecosystems, because these models can be incorporated, and could explicitly describe the natural behavior of systems (Adams et al., 2013; Xia et al., 2013; Wu et al., 2014). Having a broad scope, the PBMs can be relatively simple forest growth models; they have been operationalized as a practical tool for forest management in various countries in recent years (Mäkelä et al., 2000; Lasch et al., 2005; Fontes et al., 2010). PBMs are dependent on allometric equations to derive empirical relations of various underlying processes that provide multiple outputs (Fontes et al., 2010), and have the potential to estimate and quantify the impacts of climate change on forest productivity (Bossel, 1996; Almeida et al., 2004b). The range of ecological functions and processes are interrupted by climate change, whereby different forests differ in their sensitivity to climatic changes (Keenan, 2015). Thus, the role of PBMs is crucial for forest biomass and productivity assessment in the changing climatic conditions (Coops et al., 2005; White et al., 2006; Almeida et al., 2010; Adhikari and White, 2016); which are key outputs in research related to forest growth, management, and sustainability.

The performance of the empirical growth models is somewhat less decisive as compared to the performance of the PBMs (Fontes et al., 2006; Miehle et al., 2009; Fontes et al., 2010), because the former are not generally applicable, as they do not take into account the mechanisms and environmental impacts underlying plantation growth for instance (Pinjuv et al., 2006). On the other hand, PBMs have a broad range of applicability encompassing various mechanisms and environmental conditions relating to tree growth (Coops and Waring, 2011a). Generally, an important issue with empirical models is the requirement of large input datasets to parameterize, whereas PBMs can be parameterized with only a small number of datasets, use-able across many more sites (Adams et al., 2013). In the case of 3-PG for instance, Forrester et al. (2017) showed that it could be used to predict many climate and site effects on growth that couldn't be predicted by empirical analyses of the same data set (Pretzsch et al., 2015b). Process-based forest growth modelling approach provides new insights to researchers, modellers and forest managers to explore their ideas on forest sustainability. PBMs are practically compatible research tools for silvicultural regimes, which help in decision-making policies for sustainability in forest services (Landsberg et al., 2003, 2005; Almeida et al., 2004b). An accurate assessment of forest growth and yield is required for quantifying the influence of silvicultural regimes on productivity, profitability and risk assessment (Dye, 2001). According to Johnsen et al. (2001), risk assessment in the changing climatic conditions is an important study area, which could be explored using process-based modelling.

The 3-PG model is a monospecific, simple, freely available and monthly time-step stand level PBM (Landsberg and Waring, 1997; Coops et al., 1998; Landsberg et al., 2001). The 3-PGS model is a modified and spatial version of the 3-PG model (Coops et al., 1998). The 3-PG model was further modified into the 3-PGmix model by Forrester and Tang (2016), having a small number of new and improved parameters that enable it to predict mixing effects in forests. The credit for 3-PG model development goes to Landsberg and Waring (1997). The 3-PG model is merely a grouping of concepts like radiation-use efficiency, C balance model, partitioning and simple stand nutritional parameters. These parameter values are obtained either by direct measurements or by studies available on the species to be parameterized (Landsberg and Waring, 1997; Xenakis et al., 2008). 3-PG is a deterministic model, which calculates physiological processes like photosynthesis, transpiration, biomass partitioning to tree parts and litter production (Coops et al., 2009, 2011a). Additionally, it provides simulation on the affects of climatic changes, forest management practices, site attributes impacts on stand growth, species interactions, biomass dynamics and hydrological impacts on forests (Coops and Waring, 2001a; Landsberg et al., 2001; Sands and Landsberg, 2002; Stape et al., 2004; Coops et al., 2010; Bryars et al., 2013; Gonzalez-Benecke et al., 2014; Forrester et al., 2017; Meyer et al., 2017, 2018; Xie et al., 2017).

The 3-PG model is a combination of empirical relations and physiological processes, calculated from experimental measurements and field calculations, into the C balance model. Thus, it facilitates and reduces both data in terms of its quantity, and the complexity in data calculations steps (Silva et al., 2013). The process-based 3-PG model bridges the gap between traditional mensuration centered models and complex PBMs (Landsberg et al., 2003, 2005; Zhao et al., 2009). So far, several PBMs have been developed, based more or less on physiological principles; however, simple structure, readily obtainable input data and not very high number of parameters mark the 3-PG model, a widely used forest growth model. The variables generated by the 3-PG model are directly beneficial for forest managers (Rodríguez-Suárez et al., 2010). Coupling of the 3-PG model with other models (Xenakis et al., 2008; Feikema et al., 2010; Minunno et al., 2010; Waring et al., 2011), to different approaches (Zalesny et al., 2012; Nolé et al., 2013; Waring and Gao, 2016), and integration of remote sensing and GIS (Coops and Waring, 2001a, 2001c) can be useful in predicting large scale C sequestration (Nolé et al., 2009), evaluation of trees migration under changing climate (Coops et al., 2005, 2016), regional wildlife conservation (Adhikari and White, 2016), and for ecological investigations (Landsberg and Waring, 1997). 3-PG offers excellent access to calculate the impacts of hydrology and the availability of soil water on the growth of forests species (Dye, 2001).

It has been applied to various forest species in different countries such as Australia, Finland, Brazil, Canada, Spain, New Zealand, China, South Africa, and the United States as shown in Table 4. While much work has been done on the 3-PG model in plantations, it has also performed well in natural forests, which tend to be much more complex than plantations. Therefore, the 3-PG model needs to applied on a larger scale and parameterized in natural forests, which are the significant C absorbers (Potithep and Yasuoka, 2011). The 3-PG/3-PGS model in current form is simple, as it works on basic allometric equations and requires a minimal input dataset. The delivered outputs show a good correlation between observed and predicted data values. The 3-PG_{PJS} *vsn* 2.7 is the latest version of the 3-PG model available, written in Visual Basic for Applications, offering greater flexibility to users in operation (Sands, 2010); it can be easily downloaded from the 3-PG official website "http://3pg.forestry.ubc.ca/3-pg-for-excel/".

A recent update of the 3-PG_{PJS} *vsn* 2.7 is the 3-PGmix model, almost identical to 3-PG_{PJS} *vsn* 2.7, freely available, and can be run to provide nearly the same outputs (with the same inputs) as 3-PG_{PJS} *vsn* 2.7. The 3-PGmix model can be used for mixed-species forests (by dividing the population into a small number of age or species cohorts), uneven-aged forests, deciduous species, allows different versions of water balance calculations, light calculations and includes diameter distributions.

Also, the 3-PGmix model includes some of the more recent developments such as the work by (Wei et al., 2014a, 2014b) to allow stable C isotope data to be used for parameterization. The 3-PGmix model is described in detail by Forrester and Tang, 2016 and is freely downloaded from "https://sites.google.com/site/davidforresterssite/home/projects/3PGmix/3pgmixdownload".

Formerly, Landsberg and Sands (2010) reviewed the 3-PG model in a book chapter, the 3-PG process-based model. In this study, we have provided comprehensive coverage of all the major studies on the 3-PG model. The objective of this study is to review earlier studies, which use 3-PG/3-PGS model and identify the types of applications a simple process-based 3-PG model can offer in forest management. Moreover, this study underlines the role and importance of remote sensing & GIS in the process-based 3-PG/3-PGS model. The 3-PGmix model, a recent modification of the 3-PG model, has also been highlighted in this review. Furthermore, we have attempted to introduce the role and need of the 3-PG model in changing climatic conditions to widen the range of model prediction from simple, shorter-term climatic changes to complex and longer-term climatic changes affects on forest ecosystems. While the scope of this review is somewhat limited to the 3-PG/3-PGS/3-PGmix model, at the same time, it would be of interest to many researchers, not only modellers, as well as forest managers.

2. Methods

This review paper is reviews extant literature covering the process-based 3-PG/3-PGS/3-PGmix model. Fig. 2 contains some main references, which are helpful in finding out additional literature about the 3-PG/3-PGS/3-PGmix model. We have searched extant literature through the Google search engine, Google Scholar, Research gate and Web of Science. Besides, the 3-PG homepage "http://3pg.forestry.ubc.ca/publications/" listed major references on the 3-PG/3-PGS/3-PGmix model. We have found a major portion of literature on the 3-PG/3-PGS/3-PGmix model in two Elsevier journals, one is Forest Ecology and Management, and the other is Ecological Modelling. From 1997 to 2017, the total number of publications on the 3-PG/3-PGS/3-PGmix model and cited in this review is 89 as shown in Fig. 1. An overview of the 3-PG/3-PGS model, its various applications and usefulness is the primary focus of this review. We have adopted a straightforward way of reviewing the 3-PG model (Fig. 2). Firstly, we have provided a general overview and structure of the process-based 3-PG/3-PGS model. Then, we have discussed the need of the PBM like the 3-PG model for forest management in the changing climatic conditions. After that, we have discussed the sensitivity analysis (SA) and parameterization in the 3-PG/3-PGS model. Finally, we have focused on the application part of the 3-PG/3-PGS model. The various studies on the 3-PG/3-PGS/3-PGmix model and their main findings are shown in Table 4.

3. Need for forest growth modelling in changing climate

To understand the global changes taking place in the forests and their services is a complicated task (MacDicken, 2015). Climate change is one of the most severe and significant problems that we are facing nowadays. It is a great challenge for scientists and researchers to make future predictions about its impacts on the forests' ecosystem. Climate change disturbs forest growth, Net Primary Productivity (NPP), forest functions such as C inputs and decomposition rates (Morison and Morecroft, 2006; Ashraf et al., 2015), as well as the distribution of invasive species (Storkey et al., 2014). Moreover, climate change has the potential to disrupt the entire natural forest ecosystem and transform the old structure of forest ecosystem into a new structure, such as from spruce to pine forest, forest to savannah ecosystem (Mendes, 2007).

Forest growth and productivity are hindered by many factors such as deforestation, stocking density, species composition and competition (Zhang et al., 2015), as well as diameter distribution (Coomes and Allen, 2007; MacDicken, 2015). From 1990 to 2015, a 3% net drop in forest area occurred; the total forest area in 2015 was 31% of the global land area, or 0.6 ha per individual (FAO, 2015; Keenan et al., 2015). Reducing deforestation would result in an expansion of forest cover, which in turn would provide an excellent option for levelling Carbon dioxide (CO_2) concentration, and mitigating climate change (Fang et al., 2007; Kanninen et al., 2007). A sufficient modelling approach that estimates forests productivity across regions (Headlee et al., 2013), predicts physiological changes in trees and species shifting, measures mechanisms rates and disturbances in ecosystems as well as develop relations among these has been required in the changing climatic conditions (Turner et al., 1995; Loehle and LeBlanc, 1996; Tilman, 1998; Scheller and Mladenoff, 2005). Process-based modelling can estimate long-term growth, examine and quantify environmental variables that influence tree growth, and also inspects the consequences of stocking and the silvicultural regime on yield.

According to Franklin et al. (2016), it is crucial to incorporate the dimension of climatic changes in the growth and productivity prediction models, in order to understand the impact of climatic variations on the forest's ecosystem thoroughly. Forest growth models are basic tools that can be applied in simulating the C dynamics in forests (Vanderwel et al., 2013; Jin et al., 2016). The reliability of outcomes from forest growth models is severely limited because very few models take account of climate change-induced alterations like forest fire hazards, extreme events like windstorms and invasion of insects and pathogens. Further, the models used by ecologists to assess the climate change-induced impacts on forests and models used by forest managers to determine the forest growth and yield have shown inconsistencies between themselves (Kirilenko and Sedjo, 2007). According to Seidl et al. (2011), we require an integrated modelling approach that integrates

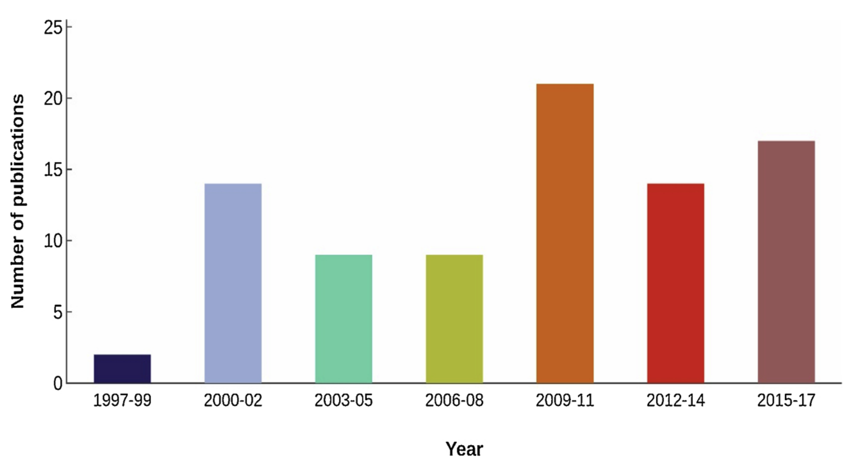

Fig. 1. Number of publications on the 3-PG/3-PGS/3-PGmix model.

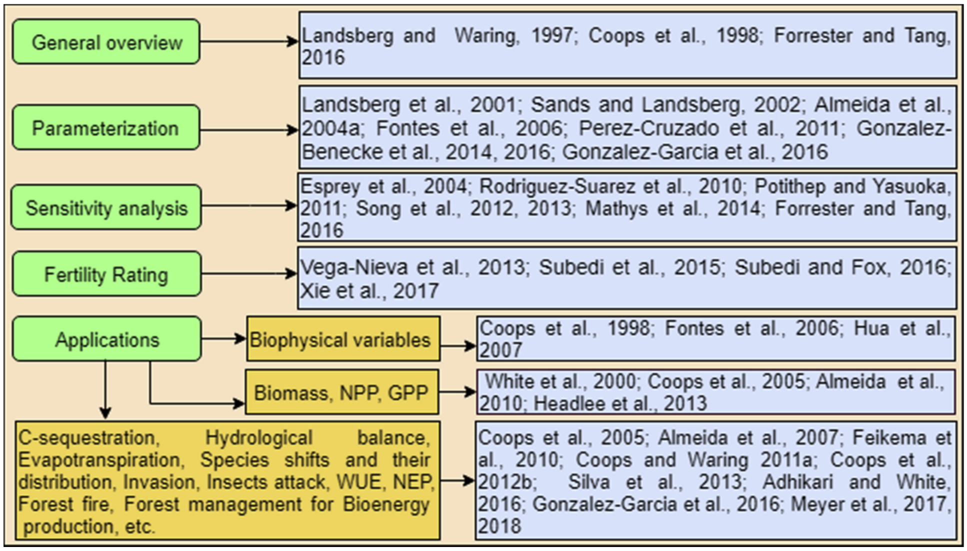

Fig. 2. Discussed topics (green) in this review and their useful references (light blue) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

environmental disturbances and vegetation physiological processes. Thus, that integrated modelling approach has the predictive ability to address interactions between these inclusions over a wide range of spatiotemporal scales.

Primarily, there are three forms of PBMs: 'simple physiological', 'complex physiological', and 'hybrid empirical-physiological', categorized based on complexity among physiological processes (Jin et al., 2016). Since the natural system involves complex and incorporated mechanisms of ecosystems, PBMs offer useful means to understand the complexity and linkages in the functionality of the ecosystem (Johnsen et al., 2001). Physiological processes, such as photosynthesis are impacted by rising concentration of atmospheric CO_2, which effectively alters tree growth and productivity. Thus, PBMs offer an opportunity to assess the impact of rising CO_2 concentration on forest's growth, productivity and functioning (Cropper et al., 1998; Weinstein et al., 1998; Johnsen et al., 2001). It is difficult for any modelling approach to address the entire gamut of complex mechanisms, involving interactions between environmental variables, growth, and the developmental processes in vegetation. Hence, even if all models were to make accurate predictions, they would merely simplify reality (Silva et al., 2013).

4. The process-based model 3-PG

Modelling is a robust approach to understand the growth dynamics of forests (Balandier et al., 2000). Fontes et al. (2010) provide a comprehensive explanation of empirical, process-based and hybrid models for forest management in changing climate environments. Further, they stated that because of wide-ranging environmental applicability and outputs, PBMs are the most versatile; the strength of PBMs lies in their competency to forecast responses to changing climatic conditions. Johnsen et al. (2001) reviewed the significance of PBMs as tools in forest management and discussed the components that need to be enhanced to raise model accuracy and applications. According to Johnsen et al. (2001), PBMs intended for research purposes, generally require complex and intensive data; whereas, PBMs intended for forest management practices, require more straightforward and readily accessible data. Pretzsch et al. (2015a) made a comprehensive analysis of forest growth models to examine the growth dynamics in mixed forests. According to them, out of large number of forest growth models, only a few can be suitably adjusted to evaluate the mixing effects of plantations. The 3-PG is one such model, and it has been adjusted for mixtures in the form of 3-PGmix (Forrester and Tang, 2016; Forrester et al., 2017).

PBMs can become more complex by increasing the parameter numbers and allometric equations (Battaglia and Sands, 1998). Thus, while accuracy is to be gained by adding more parameters, it increases model complexity, reducing thereby its simplicity and feasibility (Johnsen et al., 2001). Light is a chief driver for ecosystem functioning (Forrester, 2014); its interception by the forest canopy cover plays a vital role in growth and biomass production (Bai et al., 2016). The central concept in the 3-PG model is the conversion of Absorbed Photosynthetically Active Radiations (APAR) into NPP. APAR has been calculated from global solar radiations, and LAI using Beer's law; utilized APAR (APARu) has been evaluated by reducing APAR to an amount determined by environmental modifiers (Landsberg and Waring, 1997). These modifiers are Temperature (f_T), Vapor Pressure Deficit (f_{VPD}), Frost (f_F), Available Soil Water (f_{ASW}), and Soil FR (f_{FR}). All these growth modifiers lie between zero (fully limiting) to one (not limiting) (Landsberg and Waring, 1997; Coops et al., 2001b; Landsberg and Sands, 2010; Coops et al., 2011a, 2011b). The analyses and quantification of these monthly-imposed growth modifiers can offer an understanding of confinements in growth and productivity; thus, directed forest management strategies towards sustainable production (Almeida et al., 2010; González-García et al., 2015; Hung et al., 2016). 3-PG model offers a comprehensive and integrated modelling framework. The primary structure of the 3-PG model is presented in Fig. 3; mainly consisting of the following five sub-models:

- Biomass production sub-model based on C balance model (McMurtrie and Wolf, 1983)
- Assimilation and allocation sub-model based on fundamental laws and observations
- Mortality and thinning sub-model
- Soil water balance sub-model
- Management and outputs sub-model

On multiplying APARu with canopy quantum efficiency, it gives Gross Primary Productivity (GPP). NPP is calculated as a fraction of GPP with a constant value of 0.47 ± 0.04. This constant value assumption avoids the requirement to calculate respiration rates (Waring et al., 1998; Landsberg et al., 2003). This constant ratio is found to be almost equal for various types of forests, and for the range of geographical sites and regions (Waring et al., 1998; Rodríguez et al., 2002). In the second sub-model, allocation of NPP to various parts of the plant

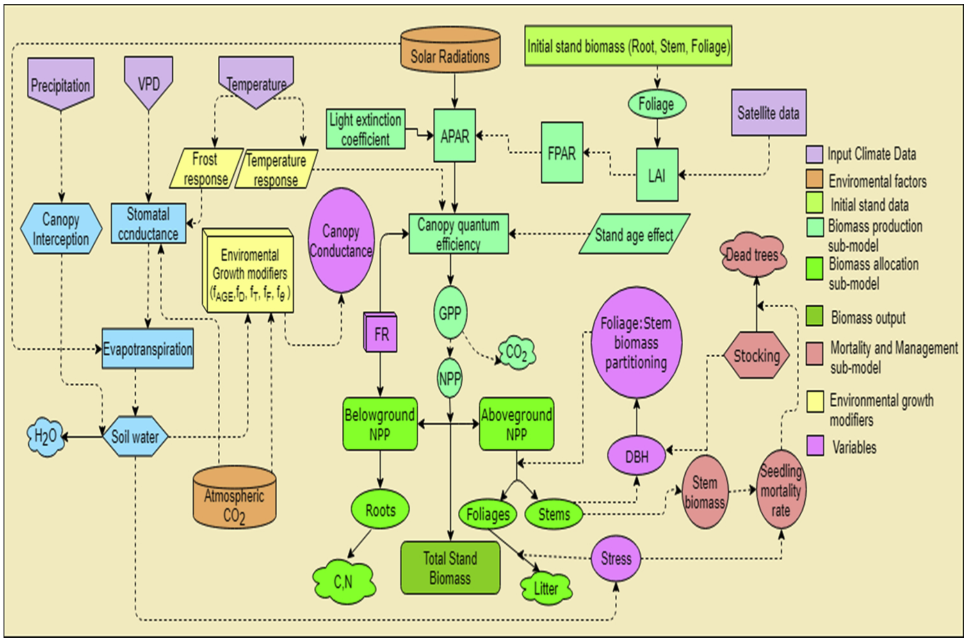

Fig. 3. The primary structure of the 3-PG model showing different inputs, processes, variables, and outputs (adopted and modified from Sands, 2004).

or tree such as stems, foliages, and roots occur. Tree size influences the partitioning of NPP to foliages and stems; large tree size means less partitioning to foliages and stems. Factors such as Vapour Pressure Deficit (VPD), soil moisture, and soil fertility (Landsberg and Waring, 1997; Sands and Landsberg, 2002) influence NPP partitioning to roots. In soil water balance sub-model, canopy conductance is calculated using a species-specific maximum canopy conductance and LAI measurements, adjusting the values according to the VPD modifier and available soil water content (ASWC). The Penman-Monteith equation (Allen, 2005) has been applied to compute the stand transpiration in the 3-PG model (Landsberg et al., 2003), and the canopy evaporation has been computed by the use of LAI, canopy interception, and the rainfall data. Stand evapotranspiration can be evaluated by adding canopy evaporation and transpiration. ASWC is also limited by upper and lower limits, and that runoff is included in the calculation, in addition to rainfall and evapotranspiration. If ASWC exceeds its maximum value, runoff occurs. The difference between rainfall and evapotranspiration gives ASWC (Gonzalez-Benecke et al., 2014).

Stand density has been adjusted for density-dependent mortality using the -3/2 thinning law (Drew and Flewelling, 1977; Sands and Landsberg, 2002; Bryars et al., 2013). Stand Basal Area (BA) has been calculated from the Diameter at Breast Height (DBH) and tree density. The growth rate of the stand may be tuned to the age of stand to consider the age effect on stand growth. Mean tree height (h) has been calculated using a height-diameter function (Gonzalez-Benecke et al., 2014). Data was required as an input to initialize the model; the major outputs generated from the 3-PG model are shown in Table 1. Many studies (Landsberg and Waring, 1997; Coops et al., 2001a,b,2009; Fontes et al., 2006; Gonzalez-Benecke et al., 2014, 2016; Hung et al., 2016; Forrester and Tang, 2016; Meyer et al., 2017) have elaborated on the 3-PG model.

4.1. Parameterization in the 3-PG model

Accuracy and efficacy of any model majorly depend on estimating the representative parameter value (Dye, 2001). Parameterization is the method to delineate the value of species-specific parameters and can be assigned using the allometric relationship and tuning the growth modifiers. It is important to measure (or to obtain from the literature) as many parameters as possible, and only tune the minimum number of

Table 1
The 3-PG model inputs, initial data to run the 3-PG model, and the major derived outputs with their respective symbols and units (adopted and modified from Almeida et al., 2004a).

State variables	Symbol	Units
Inputs		
Total monthly rainfall	P	mm
Monthly mean temperature	T	˚C
Solar radiation	R_s	MJ m^2 /day
Monthly daylight means of VPD	D_{day}	mb
Site latitude/longitude	$Lat/Long$	
Maximum and minimum available soil water	θ_{sx}, θ_{sn}	mm
Site fertility rating	FR	–
Initialization		
Start or initial and end age	S_A,E_A	yr
Available soil water	θ_{si}	mm
Stem number	N_i	trees ha^{-1}
Soil class (C, CL, SL, S)	SC	–
Foliage, root and stem biomass at starting age	w_{Fi},w_{Ri},w_{Si}	trees DM ha^{-1}
Main outputs (monthly)		
Stand basal area	BA	m^2 ha^{-1}
Stand volume	SV	m^3 ha^{-1}
Mean monthly increment	MAI	m^3 ha^{-1} mn^{-1}
Stem number	N_N	trees ha^{-1}
Leaf area index	LAI	–
Foliage biomass	w_F	t DM ha^{-1}
Root biomass	w_R	t DM ha^{-1}
Stem biomass	w_s	t DM ha^{-1}
Litterfall	w_L	t DM ha^{-1}
Growth modifiers (age, VPD, temperature, frost, soil water)	f_{AGE}, f_D, f_T,f_F,f_θ	–
Physiological canopy conductance	φ	–
GPP	P_G	t DM ha^{-1}
NPP	P_N	t DM ha^{-1}
Light-use efficiency(LUE)	ε	g DM MJ^{-1}
Water-use efficiency	WUE	g DM mm^{-1}
Evapotranspiration	E_T	mm
ASWC	θ	mm
Wood density	ρ	t m^{-3}

Table 2
List of the 3-PG model input parameter with their respective symbol, unit and other characteristics (Adopted and modified from Sands, 2004).

Parameters description	Symbol	3-PG$_{PJS}$ name	Units	Site or species-specific	Default/Fitted/Observed
Biomass partitioning and turnover					
Foliage: stem partitioning ratio (DBH = 2 cm)	p_2	pFS2	–	Species	Fitted
Foliage: stem partitioning ratio (DBH = 20 cm)	P_{20}	pFS20	–	Species	Fitted
Constant in the stem biomass and DBH relationship	a_S	stemConst	–	Species	Observed
Power in the stem biomass and DBH relationship	n_S	stemPower	–	Species	Observed
Maximum fraction of NPP to root	η_{Rx}	pRx	–	Species	Default
Minimum fraction of NPP to roots	η_{Rn}	pRn	–	Species	Default
Litterfall & root turnover					
Maximum litterfall rate	γ_{Fx}	gammaF1	mn^{-1}	Both	Observed
Litterfall rate when age = 0	γ_{F0}	gammaF0	mn^{-1}	Both	Default
Age at which litterfall rate has a median value	$t_{\gamma F}$	tgammaF	months	Both	Fitted
Average monthly root turnover rate	γ_R	gammaR	mn^{-1}	Both	Default
Temperature modifier (f_T)					
Minimum temperature, optimum temperature and maximum temperature for growth	T_{min}, T_{opt}, T_{max}	Tmin, Topt, Tmax	°c	Species	Fitted
Frost modifier (f_{frost})					
Days production lost per frost day	k_F	kF	days	Species	–
Soil water modifier (f_{ASW})					
Moisture ratio deficit for soil water content = 50%	c_θ	SWconst	–	Site	Default
Power of moisture ratio deficit	n_θ	SWpower	–	Site	Default
Atmospheric CO_2 modifier					
Assimilation enhancement factor at 700 ppm	–	fCalpha700	–	Site	Observed
Canopy conductance enhancement factor at 700 ppm	–	fCg700	–	Site	Observed
Fertility effects (f_N)					
Value of m when FR = 0	m_0	m0	–	Species	Default
Value of f_N when FR = 0	f_{N0}	fN0	–	Species	Default
Power of (1-FR) in f_N	n_{fN}	fNn	–		
Age modifier (f_{age})					
Maximum stand age used in age modifier	t_x	MaxAge	yrs	Species	Default
Power of relative age in function for f_{age}	n_{age}	nAge	–	Species	Default
Relative age to give f_{age} = 0.5	r_{age}	rAge	–	Species	Default
Stem mortality & self-thinning					
The mortality rate for large age	γ_{N1}	gammaNx	yr^{-1}	Species	Observed
Seedling mortality rate at age = 0	γ_{N0}	gammaN0	yr^{-1}	Species	Observed
Age at which mortality rate has a median value	$t_{\gamma N}$	tgammaN	yrs	Species	Observed
Max. Stem mass per tree at 1000 trees ha^{-1}	w_{Sx1000}	Ws × 1000	Kg $trees^{-1}$	Species	Default
Power in self-thinning rule	n_N	thinPower	–	Species	Default
The fraction of mean single-tree for foliage, root and stem biomass lost per dead tree	m_F,m_R,m_s	mF,mR, mS	–	Species	Default
Specific leaf area					
Specific leaf area at age 0	σ_0	SLA0	m^2kg^{-1}	Species	Observed
Specific leaf area for mature leaves	σ_1	SLA1	m^2kg^{-1}	Species	Observed
Age at which specific leaf area = (σ_0 + σ_1)/2	t_σ	tSLA	yrs	Species	Observed
Light interception					
The extinction coefficient for absorption of PAR by a canopy	k	k	–	Species	Default
Age at canopy cover	t_c	fullCanAge	yrs		–
Canopy quantum efficiency	α_{Cx}	alpha	molC/molPAR	Species	Fitted
Rainfall interception					
The maximum proportion of rainfall intercepted by the canopy	i_{Rx}	MaxIntcptn	–	Both	Default
LAI for maximum rainfall interception	L_{ix}	LAImaxIntcptn	m^2m^{-2}	Species	Default
Production and respiration					
Ratio NPP/GPP	Y	Y	-	None	Default
Conductance					
Maximum stomatal conductance	gSx	–	ms^{-1}	Species	Default
Maximum canopy conductance	g_{Cx}	MaxCond	ms^{-1}	Species	Default
LAI for maximum canopy conductance	L_{Cx}	LAIgcx	m^2m^{-2}	Species	Default
Defines stomatal response to VPD	k_D	CoeffCond	$MBar^{-1}$	Species	Default
Canopy boundary layer conductance	g_B	BLcond	ms^{-1}	Both	Default
Branch and bark fraction (p_{BB})					
Branch and bark fraction at age = 0	p_{BB0}	fracBB0	–	Species	Observed
Branch and bark fraction for mature stands	p_{BB1}	fracBB1	–	Species	Observed
Age at which p_{BB} = (p_{BB0} + p_{BB1})/2	t_{BB}	tBB	yrs	Species	Observed
Basic Density					
Minimum basic density for young trees	ρ_0	rhoMin	tm^{-3}	Both	Observed
Maximum basic density for older trees	ρ_1	rhoMax	tm^{-3}	Both	Observed
Age at which ρ = ½ density of old and young trees	t_ρ	tRho	yrs	Both	Observed
Stem height					
Constant in stem height relationship	a_H	aH	–	Species	Observed
Power of DBH in the stem height relationship	n_{HB}	nHB	–	Species	Observed
Power of stocking in the stem height relationship	n_{HN}	nHN	–	Species	Observed
Stem volume					

(continued on next page)

Table 2 (*continued*)

Parameters description	Symbol	3-PG$_{PJS}$ name	Units	Site or species-specific	Default/Fitted/Observed
Constant in stem volume relationship	a_V	aV	–	Species	Observed
Power of DBH in stem volume relationship	n_{VB}	nVB	–	Species	Observed
Power of stocking in stem volume relationship	n_{VN}	nVN	–	Species	Observed
Conversion factors					
An intercept of net versus solar radiation relationship	Q_a	Qa	Wm^{-2}	–	Default
The slope of net versus solar radiation relationship	Q_b	Qb	–	–	Default
The molecular weight of dry matter		gdm_mol	$gmol^{-1}$	–	Default
Conversion of solar radiation to PAR		molPAR-MJ	$molMJ^{-1}$	–	Default

parameters that could not be obtained (Sands, 2004). Tuning of parameters may be achieved by adjusting the values of model parameters to give good fit of model output to observed data. The 3-PG model may be parameterized for specific species or different genotypes of same species. Different type of parameters in the 3-PG model is shown in Table 2. The 3-PGmix model has an additional number of parameters and allometric equations, mainly to allow the prediction of APAR by canopies of mixed species forests. Sands and Landsberg (2002) derived values for a set of parameters that provide good fit to stem biomass, LAI, and litterfall across a diverse range of *E. globulus* species. Landsberg et al. (2003) described the procedures for calibration in the 3-PG model and estimated the values of different parameters to best fit for widely ranged forest growth datasets. Almeida et al. (2004a) performed the 3-PG model parameterization for *E. grandis* species by applying input parameter values from direct observation, default values and by applying the best-fit method. According to Amichev et al. (2010), parameterization of the 3-PG model for fast-growing hybrid poplar clones (Walker variety) has multiple benefits. The most significant benefit includes longer-term biomass supply data, which could be predictable and accessed by farmland managers along with commercial sector industries that are keen to grow hybrid poplars on cultivated land for the bioenergy production. Bryars et al. (2013) modified various allometric equations of 3-PG to get outputs associated with the observed growth of *P. taeda* species for the calibrated site. According to them, a generic set of parameters in the 3-PG model increases its effectiveness as an analytical tool to evaluate the growth and yield response to different silvicultural and fertilization regimes. Some studies suggested that the directly calculated parameters from population of interest and adjustments in default and optional parameters values could improve the performance of the 3-PG model. Rodríguez-Suárez et al. (2010) adjusted the default values of two 3-PG parameters (*fullCanAge* and *nS*).

They ranged *fullCanAge* from 3.5 to 7 years (default value is 0), and *nS* ranged from 2.25 to 2.35 (default value is 2.4) for *E. globulus* species. According to their observations, 3-PG exhibited an improved growth prediction on modifying default values of 3-PG parameters (*fullCanAge* and *nS*). Amaral et al. (2006), Fontes et al. (2006) also applied 3-PG in Portugal for the estimation of biomass and volume of *E. globulus*. They showed that 3-PG provides improved initial results when default values of parameters (alpha and pFS2) were replaced with directly measured values for species under study.

4.2. Sensitivity analysis

Complexity and limited knowledge about the ecosystem structure and function, cause parameter uncertainty (Song et al., 2013). Accuracy in measurements and a better understanding of modelling procedures could reduce the uncertainty of parameters (Makler-Pick et al., 2011; Song et al., 2012, 2013). SA has been performed to examine the sensitivity of model outputs to input parameters. It is related with allometric equations and biophysical processes; therefore, it offers an approach to understand and improve the 3-PG/3-PGS model variables and to extend the applications of the 3-PG model (Esprey et al., 2004; Nightingale et al., 2008; Zhao et al., 2009). Fig. 2 shows some important studies, which have focused on sensitivity and uncertainty analysis of outputs to 3-PG inputs. Esprey et al. (2004) performed a detailed and first inclusive description of SA for the 3-PG model parameters by taking *Eucalyptus grandis* species from 31 sites in South Africa, which were widely different in climatic and site conditions. They performed the SA of stand volume and LAI outputs for over twenty-four 3-PG input parameters. The sensitivity of model outputs to inputs, such as monthly mean rainfall and temperature, site fertility, and maximum ASWC was also examined by them, wherein they revealed that the 3-PG model outputs like stand volume (SV) and w_R are significantly sensitive to FR.

Almeida et al. (2004a) performed SA for outputs like DBH, water use efficiency (WUE), SV, root, stem and foliage biomass by variating the values of input parameters (a_S, n_S, g_{Cx}, D, k_g, η_{Rn}, a and L_{Cx}) between −20% to + 20% and demonstrated that the ouputs like DBH and foliage biomass (w_F) were most affected by these variations in inputs. A similar SA was done for 3-PGmix by Forrester and Tang (2016), which indicated that this modified version had very similar behavior to the 3-PG model. Amichev et al. (2010) made the sensitivity of the 3-PG model outputs to input paramters like Topt, SLA1 (specific leaf area for mature leaves), fullCanAge, and minimum ASW for hybrid Poplar (Walker), and revealed that the predictions of outputs like height (h) and Diameter at Breast Height (DBH) are highly sensitive to variations in these inputs. Song et al. (2013) stated that the stand age of vegetation markedly affects the sensitivity values of most of the 3-PG model parameters. Moreover, climatic variations and soil properties are also found to be responsible for fluctuation in the sensitivity values of some of the 3-PG model parameters. They described the time-dependence sensitivity of the 3-PG model outputs to the 3-PG model inputs; further, the calculation of the 3-PG model sensitvity of outputs to input parameters only at a single simulation period (Lu and Mohanty, 2001; Esprey et al., 2004; Makler-Pick et al., 2011) is somewhat biased, and thus they (Song et al., 2013) proposed the time-dependent SA, which provide much better insights into the structure, analysis and performance of the 3-PG model. Hung et al. (2016) also supported the time-dependent SA in his study on Acacia hybrid at two different simulation ages. A study by Potithep and Yasuoka (2011) on deciduous broadleaf forests in Japan varied the range of input parameters between -20% to + 20% and observed the affects of these variations on the 3-PG model outputs. They found that the 3-PG model outputs are more sensitive to the 3-PG model input parameters (α_{Cx}, T_{min} and T_{opt}) than other 3-PG inputs parameters. Therefore, these highly sensitive inputs need more attention for calculating their values in order to improve accuracy in outputs. GPP was found to be highly sensitive and positively related with input parameters (α_{Cx} and T_{min}); whereas with the input parameter (T_{opt}), GPP has shown an inverse relation. Overall, the output (GPP) derived by Potithep and Yasuoka (2011) using the 3-PG model was found to be sensitive to each selected and varied input parameter (a_S, n_S, p_2, p_{20}, α_{Cx}, T_{min}, T_{opt}, ws and w_F). According to Vega-Nieva et al. (2013), the variations in FR values would significantly alter the 3-PG model estimation of forest biomass and productivity. Therefore, they developed a general modelling approach for the prediction of FR from soil profile Relative Nutrient Contents (RNCs), by comparing several general modelling frameworks of FR from RNCs. Sensitivity and uncertainty analysis of the 3-PG model outputs to input parameters needs further attention. Moreover, attention also is required on the role of parameters' value distributions on the uncertainties and sensitivities of input parameters for the model outputs as well as the affects of site-specific data on parameters sensitivities to attain a more unbiased and representative model's sensitivity (Song et al., 2013).

4.3. Fertility rating (FR)

Fertility Rating (FR) is an essential and complicated site-specific parameter that relates to the soil fertility to stand productivity (Subedi et al., 2015). FR affects outputs of the 3-PG model; moreover, FR directly affects the partitioning coefficient, 'm' that is used to estimate NPP partitioning to roots (Landsberg and Waring, 1997; Subedi et al., 2015). It is a challenging task to determine FR value, whereby the FR is labelled as the weakest feature of the 3-PG model in various studies (Esprey et al., 2004; Almeida et al., 2010; Landsberg and Sands, 2010; Bryars et al., 2013). Lack of knowledge about FR's role in forest growth will inevitably affect the quality of decision-making practices based on model outputs, both for productivity and management (Almeida et al., 2004a; Hung et al., 2016). Several studies such as Dye et al. (2004); Stape et al. (2004); Fontes et al. (2006); Paul et al. (2007); Pérez-Cruzado et al. (2011); Vega-Nieva et al. (2013); Gonzalez-Benecke et al. (2014); Subedi et al. (2015), and Subedi and Fox, (2016) have made significant contributions to improve the FR aspect of the 3-PG model.

4.4. Integration of remote sensing and GIS in the 3-PG model

Remote sensing and GIS technology play a remarkable role in the process-based forest growth modelling. These technologies offer a quick and synoptic view of things, assessing the spatio-temporal variations in the concerned attributes; seen in combination, both remote sensing and GIS technology have become an important tool for assessing forest biomass at a broad scale (Kumar et al., 2015; Kumar and Mutanga, 2017). Advances in geospatial technology and their integration with forest growth models offer promising advantages in forest assessment, modelling, management and research. The 3-PGS model is a spatial version of the 3-PG model, which derives results by taking advantages of remote sensing & GIS technology; further, there are different types of sensors located on satellites, which provide data on a wide range of topographic features and climatic regions on the earth surface. This satellite data can then be integrated with PBMs like 3-PGS. Therefore, remote sensing & GIS technology provides a promising opportunity to initialise, run, and test the model's outputs (Waring et al., 2010) (Table 3).

Moreover, changes in phenology and the indirect estimation of soil water storage capacity using the relation between soil water balance calculations and seasonal reductions in LAI over a vast region spanning decades, could be achieved through remote sensing and GIS (Landsberg and Waring, 1997). Development of PBMs that works with the combination of remote sensing and GIS technology raise the efficiency and measurement from the plot or stand level to a broad regional level, and could be compared with estimations derived from remote sensing independently (Landsberg and Waring, 1997). Coops and Waring (2001a) used the 3-PGS model to find the primary production of coniferous forest across Southwest Oregon and obtained r^2 of 0.76, Standard Error (SE) of $1.2\,m^3\,ha^{-1}\,yr^{-1}$, and $P < 0.01$ between the 3-PGS modelled maximum annual above ground production and predictions made from yield tables. Nightingale et al. (2008) estimated *f*PAR (Fractional Photosynthetically Active Radiations) from NDVI (Normalized Difference Vegetation Index) using NOAA (National Oceanic and Atmospheric Administration), and AVHRR (Advanced Very High-Resolution Radiometer) sensors and applied in the 3-PGS model for spatial assessment and growth dynamics of mature, old-growth Australian tropical rainforest bioregion. Above ground biomass (AGB) prediction from 3-PGS model and ground measurements are significantly correlated (Coops et al., 1998; Nightingale et al., 2008). Six vegetation indices (VI) are calculated from ten days MODIS (Moderate Resolution Imaging Spectroradiometer) composite image to calculate the GPP of deciduous broadleaf forest in two sites of Japan (Potithep et al., 2009). A study by Nolé et al. (2009) to estimate the C sequestration in Italian forests coupled with the 3-PGS model along with improved soil respiration model, show that the 3-PGS model efficiently simulates forest GPP and Net Ecosystem Production (NEP). Coops et al. (2012a) applied an inverse model approach, whereby they inverted the 3-PG model to calculate FR and ASWC from growth potential (LAImax) using MODIS imagery at $1\,km^2$ spatial resolution across forest region in western North America.

Imagery generated by remote sensing are useful in spatial prediction of productivity, therefore, determines the planning and management of resources such as bioenergy production and its distribution (Ahamed et al., 2011). Waring et al. (2010), briefly described the use of remote sensing and GIS technology and their scope, and discussed improvements in PBM like the 3-PG/3-PGS model for forest growth. They reviewed the 3-PGS model, and also discussed satellite sensors, which may be suitable for generating information required to run the 3-PGS model (Table 3). All these abovesaid examples and discussion reveal that remote sensing and GIS were widely used and integrated with the 3-PG/3-PGS model for measurements; this integrated approach could be further explored in order to improve outputs for forest management in changing the climatic conditions.

Sensors collect data over a range of the electromagnetic spectrum: UV and visible range (200–700 nm), IR range (700–3000 nm), thermal (3–10 mm) and microwave range (up to 1 m) and provide information to define forests with related structural properties, nutritional limits on forest growth, and interaction of soil properties with stand height that influence above ground Net Primary Productivity (NPPA) (Waring et al., 2010). High-resolution imagery is crucial for estimating the variables accurately. Several types of sensors are designed, differing in their resolution power, and their ability to describe the characteristics within a process-based modelling approach as shown in Table 3. Sensors having coarse spatial resolution do not provide species-level information (Sinha et al., 2015); high-resolution imagery is required for that purpose. Hyperspectral remote sensing is the latest advancement in remote sensing and GIS, which can be very useful for providing accurate information and quantification at the species level.

5. Applications of the 3-PG model

A wide range of applications have been identified by reviewing literature on 3-PG/3-PGS/3-PGmix model (Table 4). Outputs that are generated by the 3-PG/3-PGS/3-PGmix model are commonly related to forest managers. Moreover, outputs like biomass, productivity, ASWC, LAI, and evapotranspiration are very beneficial in environmental assessments, monitoring, and research. Biomass estimation of any forest is a well-established scientific attempt, which helps in calculating C stock, NPP and additional biophysical parameters (Deb et al., 2017). Vegetation productivity (gross and net) is a critical biophysical variable, which can be evaluated using the 3-PG/3-PGS model. This variable recognizes the spatial and temporal distribution of C along with its source, sink and cycling, which eventually help to understand climate change (Zhao et al., 2012). Spatial version (3-PGS) of the 3-PG model offers a better opportunity than the standard 3-PG model to evaluate the GPP and NPP. The 3-PGS model can be more proficient in simulating the above and below ground productivity correctly if there are characteristic parametric values of Canopy Quantum Efficiency (α) and ASWC (θ) are supplied in the 3-PG model (Coops et al., 2001a). LAI is also a crucial variable and can be calculated from either a direct method or remote sensing technique. LAI is useful in the calculation of variables like APAR; it determines the parameters' value along with 3-PG variables (Fontes et al., 2006).

Table 3
Remote sensing sensors, their characteristics, and their potential role in the 3-PG/3-PGS model (Adopted and modified from Waring et al., 2010).

Features and variables	Role in model	Sensors name	Spatial resolution (m)	Spectral resolution (No. of bands)	Temporal resolution (days)
Forest covered area and disturbances such as invasion, forest fire, drought, and defoliation	Initialization of model, confirm disturbance under stable climatic conditions	Landsat-TM	30	7	16
		Landsat-7ETM+	30	8	16
		ASTER	15, 30, 90	4	16
		AVHRR	1000	4 or 5	daily
		MODIS	250, 500, 1000	36	daily
Climatic variables	Drive PBMs	SPOT	2.5-20	15	3-5
Seasonal variations in LAI and APAR	Distinguish vegetative types, fix limits on the light absorbed by the canopy cover, and calculate Light use efficiency (LUE)	IRS-1	23.5	15	16
		QUICKBIRD	0.61-2.44	4	5
		IKONOS	1-4	4	5
		RESOURSESAT	5.8	3	24
		WORLDVIEW	0.55	1	1.7- 5.9
		RAPID EYE	6.5	5	1-2
Nitrogen content, light absorbance in foliage chlorophyll	Index to nutrient cycling, maximum photosynthetic capacity	HYPERION	30	196	16
		AVIRIS-classic	20	224	–
		AVIRIS-NG	15	425	–
Photosynthetic efficiency	Confirm model estimates of maximum canopy conductance and canopy photosynthetic capacity				
Aboveground Biomass (AGB), height and structural properties	Model Initialization, validation of NPP_A and LUE	RADARSAT-2	3, 3	–	24
		ENVISAT ASAR	10, 30	–	35
		ALOS PALSAR	5, 10	–	46

LAI is useful in the calculation of variables like APAR; it determines the parameters' value along with 3-PG variables (Fontes et al., 2006). Coops et al. (2005) calculated LAI for the 3-PG model from estimated foliage mass and specific leaf area of vegetation. According to Gonzalez-Benecke et al. (2016), a more realistic LAI evaluation has occurred through 3-PG when equations on the seasonal dynamics of needle fall rate introduced in it. A successful occurrence of forest species and their productivity over the landscape largely depends on ASWC. The 3-PG model thereby provides an opportunity to compute species' fluctuations and reactions to hydrological changes (Weltzin et al., 2003; Mathys et al., 2014). The 3-PG model and other PBMs are also useful to evaluate the shifts in the distribution of species, by identifying seasonal limits on photosynthesis, whereby its affects are assessed in the extent of absorbed radiations by the forest canopy cover (Waring et al., 2014). Various researchers performed biomass and productivity predictions using 3-PG/3-PGS/3-PGmix (Table 4). Today, there is an increasing interest in biodiversity and mixed-species plantations; however, there are often no mixed-species plantations to provide empirical information about which species to mix, on which sites and which silvicultural methods to employ for their management. Therefore, Forrester and Tang (2016) to answer these questions developed the 3-PGmix model. It can be parameterized using data from monocultures and used to predict the dynamics of mixed forests. One of the primary objectives of many modellers appears to be that their models are used in practice by foresters (i.e. not only by researchers). Battaglia et al. (2007) also provided some examples on the 3-PG model for its use as a practical forestry tool.

6. Conclusion

Broad acceptance and successful performance of the 3-PG model and its spatial version (3-PGS) indicate that the process-based 3-PG/3-PGS model has a tremendous predictive ability for forest management, along with practical research applications. Process-based modelling can be further useful in simulating CO_2 induced climatic changes, and their potential disturbances in forest ecosystems (Almeida et al., 2009). Additionally, appropriate hybrid approaches, such as the hybridization of the process-based 3-PG model and decision tree analysis (Coops et al., 2009, 2011b) could be useful in predicting the distribution of species, offering thorough understanding about the confines of growth and species shifts than purely any empirical approach. Therefore, the applications and performances of the process-based model 3-PG could be augmented by coupling with other forest growth models/sub-models, statistical calculations and supplementary methods for estimation of variables. For instance, coupling the 3-PG model with decision tree model, use of inversion method to determine FR and ASWC from LAImax, use of equations to determine unknown inputs, and use of the 3-PG model in a GIS environment to evaluate outputs at a regional level. Following the increasing interest in biodiversity and mixed-species plantations, the 3-PG model was recently modified into the 3-PGmix model, and was used to examine the dynamics of mixed forests, variability in mixed forests across sites and climates, having implications even for silvicultural practices. The 3-PGS model predictions could be accurate when high-resolution remotely sensed dataset have been applied as an input. Additionally, new advances in remote sensing & GIS technology, such as hyperspectral remote sensing, which is to be integrated into process-based modelling approach, could be advantageous in forestry research. The 3-PG/3-PGS model provides a large number of outputs, and proper estimations of variables; however, some features like species-specific parameterization, poor methods for FR evaluation, sensitivity and uncertainty of outputs to input parameters (Song et al., 2013) have required more attention as specified in different studies to establish high accuracy. Moreover, some aspects like light interception calculations, open canopies forest structures, edge effects, growth modifiers, biomass allocation, water balance calculations, site fertility, and silvicultural practices, in the present form of the 3-PG model use either basic or not fully improved allometric equations for calculation of these aspects. Besides, data unavailability at a large region, site conditions and validation of model outputs against independent datasets are some of the issues with the 3-PG model data. Landsberg and Sands (2010) provided some useful insights into some interesting improvement areas of these aspects; however, they also stated that on introducing various complex equations for improving these aspects, the model could lose its simplicity. While modifications and improvements in the 3-PG/3-PGS/3-PGmix model make it a more accurate, there's a possibility that the model becomes more complex, depending on the modifications in its structure, mechanisms and allometric equations. On the other hand, complexity would restrict the 3-PG/3-PGS/3-PGmix model only up to the modelling community. Hence,

Table 4
List of studies using 3-PG/3-PGS/3-PGmix including authors, the name of the study site, the species studied and the author's contribution/findings.

Author's name	Study site	Species studied	Contribution/Findings
Landsberg and Waring (1997)	Eight forest sites in Australia	Eucalyptus species, *Pinus contorta*, *Acer saccharum*, *Populus tremuloides*	The 3-PG model was developed. A practical forestry tool beneficial for forest management and could be integrated with remote sensing & GIS
Coops et al. (1998)	Australia & New Zealand	*C. glaucophylla*, *E. pilularis*, *P. radiata*, *E. maculata*, *E. obliquia*, *E. regnans*	They modified the 3-PG model into spatial version (3-PGS) to assess the broad-scale forest productivity using satellite-derived data on canopy cover light interceptions, LAI and NDVI. Model showed a linear relationship with r^2 of 0.82 between the 3-PGS model predicted NPP_A and field estimated NPP_A
White et al. (2000)	New Zealand	Podocarp species, woody shrubs, Beech plants, Broadleaf plants	They used soil maps of $1Km^2$ resolution to estimate the forest and shrubs biomass. They found a significant correlation between predicted and observed data values of biomass (r^2 = 0.98). Moreover, the 3-PG model predicted AGB and remote sensing estimated AGB shows significant correlation for both calibration and validation tests with r^2 of 0.78 and 0.93 respectively
Coops et al. (2001a)	Six sites in Oregon transect, USA	Coniferous forest species	Forest productivity was estimated using the 3-PGS model. This study suggested to work with decades of spatial data to find out the long-term climatic variations
Coops et al. (2001b)	Siskiyou mountains,Southern Oregon, USA	Coniferous forest species	They compared two forest growth models (3-PGS and BIOME-BCG) to evaluate the NPP. Also, made predictions of climatic limits on the growth of species using these models. Both models gave nearly the same annual estimates of total NPP with r^2 of 0.85. They stated that these two models differed in their displaying of photosynthetic activity seasonally. However, the 3-PGS model provides better intuitions than BIOME-BCG for seasonal photosynthetic limits because of the presence of optimum temperature (T_{opt}) function in it.
Coops and Waring (2001a)	18 sites in Siskiyous, Southwestern Oregon	Coniferous forest species	They applied GIS in the 3-PG model for data displaying, data manipulation, and for the prediction of soil water availability as well as AGB growth
Coops and Waring (2001b)	Southwestern Oregon, USA	Six forest types	They projected the 3-PG model to compute the forest responses from current and future climate scenarios, forest management as well as silvicultural practices
Coops and Waring (2001c)	Southwestern Oregon, USA	14 forest types	A good correlation with r^2 value of 0.82 was recorded between estimated and observed forest growth capacity
Dye (2001)	Southern Africa	*Pinus patula*	The 3-PG model was applied for simulating the growth and water use in *P. patula* species
Landsberg et al. (2001)	Scotland County, North Carolina	Loblolly pine	They calibrated the 3-PG model for Loblolly pine species. Also, evaluated the role of fertility (nutrition) in plantations growth
Tickle et al. (2001)	Bago-Maragle state forests, Australia	Eucalyptus species	They used the spatial version of the 3-PG (3-PGS) model to estimate the growth and productivity of native Eucalyptus species using fine resolution data and for a large geographical site
Coops et al. (2002)	New Zealand	Regional forest and Shrubs	They coupled 3-PG with SPOT-4 satellite data measurements. A high correlation was recorded between the values of NPP_A obtained from coupled (3-PG and SPOT-4 data) and estimated NPP_A from stem biomass field records
Rodríguez et al. (2002)	Chile	Radiata pine	They studied the effects of silvicultural regimes on the productivity of *P. radiata* using the 3-PG model. According to them, thinning and site resources play a substantial role in forest growth
Sands and Landsberg (2002)	Different sites in Tasmania & Western Australia	*Eucalyptus globulus*	The 3-PG model was parameterized for *Eucalyptus globulus* plantation. They concluded that if the 3-PG model is

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Table 4 (*continued*)

Author's name	Study site	Species studied	Contribution/Findings
			initialized with observed biomass and stem number of species, it works as a tool for modelling the time-course of future growth of intensively managed fertilized stands of *E. globulus*. However, if the 3-PG model is initialized with typical seedling biomass at planting, it works as a useful tool for modelling long-term stand development, even if early stand development is quite sensitive to assumed initial biomass data
Waring et al. (2002)	Oregon, USA	Woody plant species	The species richness of woody plant species in intermediate productivity sites of Oregon, USA was predicted and elucidated using the 3-PGS model
Whitehead et al. (2002)	South Westland, New Zealand	Rimu (*Dacrydium cupressinum* Sol. ex Lamb.)	They estimated the species productivity and identified the environmental elements that regulate the forest growth. Besides, they integrated the canopy C uptake model with the 3-PG model.
Landsberg et al. (2003)	Australia, and Northern Europe	Sitka spruce, Douglas fir Pinus species, Eucalyptus species, *C. maculata, A. cunninghamii*	This study supported the 3-PG model for its applicability over a large area and range of species with high accuracy in generated outputs
Almeida et al. (2004a)	Atlantic coast, Eastern Brazil	*E. grandis*	The 3-PG model was parameterized for *Eucalyptus grandis*. Linear regression between predicted versus observed values of LAI for *E. grandis* showed a good correlation with r^2 of 0.71
Almeida et al. (2004b)	Espirito Santo & Bahia States, East coast of Brazil	*E. grandis*	Role and importance of the 3-PG model was underlined in the commercial sector and its use as a practical foresty tool for short rotation commercial plantations
Dye et al. (2004)	Zululand, South Africa	*E. grandis* × *E. camaldulen-sis* hybrid	According to them, the 3-PG model is handy in the prediction of growth and water use over a varied range of rotation ages and growth conditions
Esprey et al. (2004)	Distinct sites in South Africa	*E. grandis*	They performed and analyzed the sensitivity of outputs to various input parameters of the 3-PG model
Stape et al. (2004)	Brazil	*Eucalyptus grandis* × *urophylla*	According to them, the 3-PG model performed better than the empirical models. The 3-PG model could capture the response to fertilization and variations in wet and dry periods
Coops et al. (2005)	Pacific Northwest, North America	*P. ponderosa*	The prediction of potential shifts (1900-2100) in the distribution of species and potential productivity of *P. ponderosa* species was evaluated using the 3-PG model
Coops et al. (2005)	Pacific Northwest, North America	*P. ponderosa*	Prediction of potential shifts (1900-2100) in the distribution of species and potential productivity of *P. ponderosa* species was evaluated using the 3-PG model
Landsberg et al. (2005)	Southern Finland	*Pinus sylvestris*	They suggested that the input parameters of 3-PG could be estimated as independently as possible from the locations where the 3-PG model has been applied
Swenson et al., 2005	Oregon, USA	Douglas-fir	The 3-PG model was applied for the prediction of potential growth and site index mapped at a $1Km^2$ resolution in Oregon, USA
Fontes et al. (2006)	Australia & Portugal	*E. globulus*	They calibrated, parameterized, and tested the 3-PG model for *E. globulus* plantations. The 3-PG model efficiency for *E. globulus* woody biomass and leaf biomass was 0.98 and 0.96, with RMSE (Root mean square error) of 5.9 and 0.4 Mg ha^{-1} respectively
Pinjuv et al. (2006)	South-eastern New Zealand	*Pinus radiata*	They compared four model types (simplified PBM, a statistical state-space, statistical difference, and hybrid model) for the estimation of forest growth. The estimated BA using the 3-PG model shows more accurate and relevant results than an older statistical state-space model

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Table 4 (*continued*)

Author's name	Study site	Species studied	Contribution/Findings
White et al. (2006)	Legal Amazon	Amazonian forests	NPP estimated using the 3-PG model was correlated well with the MODIS derived algorithms ($r^2 = 0.77$)
Almeida et al. (2007)	Atlantic rainforest, Brazil	*E. grandis*	The 3-PG model was used in a simulation of water balance, evapotranspiration, water-use efficiency, runoff and forest growth averaged monthly for six years
Hua et al. (2007)	Southern China	Eucalyptus plantations	Accurate outputs like stand volume, DBH, h, water use, stem and leaf biomass were obtained using the 3-PG model which revealed that the model is robust and stable
Nightingale et al. (2007)	USA	Nine ecoregions forest species across the USA	The comparison was made for GPP estimated by MODIS and GPP estimated using the 3-PGS model. A good agreement (within 20%) was observed for all nine forest regions across the USA
Paul et al. (2007)	Temperate regions of Australia	*E. cladocalyx, Corymbia maculata*	3-PG was calibrated for these two species, which were mainly found in low rainfall regions. They revealed that the stand age in the 3-PG model is the most significant variable for *E. cladocalyx* and *C. maculata* species in describing mean DBH across a wide range with an efficiency of 0.81 and 0.82 respectively. Moreover, accurate site data and coupling with a suitable modelling approach could improve the performance of the 3-PG model
Nightingale et al. (2008)	North Queensland, Australia	A mix of 50 tropical rainforest species in that region	3-PGS was calibrated and applied for the spatial estimation of forest growth and C dynamics in widely distributed matured rainforest species. 3-PG and 3-PGS predicted AGB and estimated AGB from field was found significantly correlated ($r^2 = 0.99$, RMSE = 25.41 and $r^2 = 0.99$, RMSE = 5.13 respectively). It suggested that the measurements from the 3-PGS model are somewhat more accurate than the 3-PG model
Xenakis et al. (2008)	Scotland	Scots pine (*Pinus sylvestris*)	They incorporated the 3-PG model and Introductory C balance model (ICBM) and named as 3-PGN. Also, added some new parameters in the list of the 3-PG model parameters
Almeida et al. (2009)	Atlantic coast, Brazil	*E. grandis* × *E. urophylla*	The 3-PG model was modified to evaluate the impacts of rising levels of CO_2 and the effects of the future climate situations on potential productivity and WUE in the region
Coops et al. (2009)	Pacific Northwest, USA	Ponderosa pine, Western juniper, Sitka spruce, Lodgepole pine, Western hemlock, Douglas fir	They used the 3-PG model and regression tree analysis approach to evaluate the relative significance of four climate-related variables in the prediction of species distributions over a large geographical region
Miehle et al. (2009)	Southern Australia	*E. globulus*	Performance of the four (3-PG, 3-PG+, CABALA, and Forest-DNDC) PBMs were compared with empirical regression models to evaluate the growth of *E. globulus*
Nolé et al. (2009)	Five sites in Italy	Mixed deciduous forest, *P. abies, P. pinaster, Quercus ilex, Fagus sylvatica*	They evaluated the C sequestration and NEP at a regional level by combining the 3-PGS model and modified soil respiration model. They suggested that the species-specific parameterization and fine resolution datasets are required to improve the model efficiency
Potithep et al. (2009)	Takayama & Hitsujigaoka sites, Japan	Deciduous broadleaf forest	They parameterized the 3-PG model for the deciduous broadleaf forest and coupled the remote sensing based observations into the 3-PG model to determine the GPP
Zhao et al. (2009)	Huitong County, Hunan Province, Southern China	Chinese fir	The 3-PG model was calibrated and validated to estimate the C sequestration in Chinese fir plantations. Also, predicted the shifts in C allocation due to stand age, FR and climatic factors
Amichev et al. (2010)	Saskatchewan, Canada	*Populus deltoides x P. nigra*	The 3-PG model was first time modelled and applied for hybrid

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Table 4 (*continued*)

Author's name	Study site	Species studied	Contribution/Findings
			poplar plantation grown in a short-rotation production system
Almeida et al. (2010)	Eastern Brazil near the Atlantic Coast	*E. grandis* × *E. urophylla*	They performed the mapping of soil and climatic record in a GIS environment and run into the 3-PG model for the prediction of growth variables, LAI, and ASWC
Coops et al. (2010)	British Columbia, Canada	Douglas-fir	In this study, they evaluated the current and future variations in the growth of Douglas Fir species in British Columbia under the changing climatic conditions
Feikema et al. (2010)	South-eastern Australia	*E. globulus, E. nitens, E. grandis, E. regnans, P. radiata*	They integrated enhanced 3-PG (3-PG+) and Catchment Analysis Tool (CAT) to simulate and assess the soil water balance and transpiration in a detailed multi-layered model, with a daily time step
Minunno et al. (2010)	Scotland	Sitka spruce (*Picea sitchensis*)	They parameterized and validated the 3-PGN model to evaluate the C sequestration. This study also highlighted the significance of soil properties in altering the site productivity
Rodríguez-Suárez et al. (2010)	Mabegondo, Northwest Spain	*E. globulus*	They estimated DBH and height of plantations using 3-PG. They found that the r^2 was always greater than 0.97 between observed data and the predicted value, RMSE of 0.45–1.05 cm and 0.46–0.85 cm for DBH and h respectively. Model Efficiency (EF) lies between 0.98–0.99. The 3-PG model results could be improved by varying the default values of *fullCanAge* and *nS* parameter.
Waring et al. (2010)	–	–	Advances in remote sensing technology helpful for calculating variables with good accuracy and ultimately powered the 3-PG/3-PGS model and its applicability
Amichev et al. (2011)	Saskatchewan, Canada	Willow species	They calibrated the 3-PG model for multi-stem willow species. They made changes in allometric measurements of the multistem structure of willow species to find production using 3-PG
Coops et al. (2011a)	Pacific Northwest, USA and Canada	Five coniferous forest species	The 3-PG model was applied to predict site indices spatial variations under current and future climate change scenarios
Coops et al. (2011b)	Pacific Northwest of North America, USA and Canada	15 native coniferous tree species	They used the 3-PG model and decision tree analyses, a hybrid approach to predict the species distribution. This hybrid approach offers more understanding about the confines of growth and tree shifts than a purely empirical approach
Coops and Waring (2011a)	Pacific Northwest of North America	*Pinus contorta* Dougl.	This study predicted the distribution of *P. contorta* Dougl. species under the changing climate conditions through a hybrid approach (3-PG, Canadian Climate Centre Model (CGCM2) and decision tree analysis)
Coops and Waring (2011b)	Pacific Northwest, North America	15 native tree species	This study estimated the vulnerability of 15 native species across the region by hybrid approach (3-PG, Canadian Climate Centre model (CGCM3) and decision tree analysis)
Pérez-Cruzado et al. (2011)	Northern Spain	*Eucalyptus nitens*	The 3-PG model was parameterized for *E. nitens* plantations. Besides, they made a comparison between 3-PG predicted outputs and empirically derived outputs
Potithep and Yasuoka (2011)	Hitsujigaoka & Takayama, Japan	Deciduous broadleaf forests	They applied 3-PG in mature, non-water limited deciduous broadleaf forests for the estimation of GPP. The estimated stem (w_S) and foliage (w_F) biomass demonstrated a strong correlation between estimated and observed dataset (r^2 = 0.89 and r^2 = 0.94 for w_S and w_F respectively) and both relationships were close to one-to-one linear relationship
Waring et al. (2011)	Pacific Northwest Region, USA	15 coniferous tree species	A hybrid model approach (climatically driven decision tree model and the 3-PG

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Table 4 (*continued*)

Author's name	Study site	Species studied	Contribution/Findings
			model) was used to determine the large-scale forests disturbances due to the current change in climatic conditions
Coops et al. (2012a)	western North America, USA	Douglas-fir, Ponderosa pine	They made improvements in the associated soil factors for species productivity measurement by the 3-PG model and outputs derived from remote sensing
Coops et al. (2012b)	western North America, USA	*Pinus contorta* Dougl., *Pinus banksiana* Lamb.	They modelled the vulnerability of these species to mountain pine beetle expansion over the region. This approach is useful both for long-term risk assessment and planning of future monitoring programs
Zalesny et al. (2012)	Minnesota and Wisconsin, USA	Poplars (Populus species and their hybrid)	They estimated the poplars productivity by integrating local site information and biophysical data at a large-scale. This approach is useful in siting bioenergy production and forests services
Bryars et al. (2013)	Ware County, Georgia	Loblolly pine	The 3-PG model was used to estimate the growth and productivity of Loblolly pine across a wide range of soils and climatic conditions. Some modifications were also performed in the 3-PG model to improve estimations on stand volume, mortality, and initial biomass increment
Headlee et al. (2013)	Minnesota and Wisconsin, USA	Hybrid poplars	The 3-PG model was calibrated, parameterized and validated for hybrid poplars to predict the biomass growth. Model revealed a strong fit (r^2 = 0.89, RMSE = 8.1 Mg ha^{-1}, mean bias = 5.3 Mg ha^{-1} or 14.3 % of mean observed biomass) between observed versus predicted total AGB for the validation datasets
Nolé et al. (2013)	Two Mediterranean forest sites in Italy	*Quercus ilex* L., *Juniperus phoenicea* L., *Pistacia lentiscus* L., *Phyllirea angustifolia* L.	They upgraded 3-PG to a daily time step called 3-PG_{day}, which include soil-water balance routines. Also, evaluated seasonal variations in GPP and Net Ecosystem Exchange (NEE) as well as quantify the potential of C source and sink in drought-prone sites
Song et al. (2013)	Queensland, Australia	*Corymbia maculata, Eucalyptus cladocalyx*	This study introduced and quantified the time-dependent sensitivity of outputs to inputs of the 3-PG model
Vega-Nieva et al. (2013)	Northwestern Spain	*Eucalyptus globulus*	They formulated a general model for the evaluation of FR from soil profile Relative Nutrient Contents (RNCs).
Silva et al. (2013)	Rio doce basin, Brazil	Eucalyptus plantation	This study attempted to form a new tool in the basic 3-PG model to improve the water balance measurements to make the energy balance, and transpiration process more efficient and effective
Gonzalez-Benecke et al. (2014)	South & south-eastern America & Uruguay	*Pinus elliottii*	The 3-PG model was first time parameterized for *P. elliottii*, and some new improvements were made for the measurements of biomass pools, FR, canopy closure and allocation dynamics
Mathys et al. (2014)	Pacific Northwest of North America, USA	20 tree species	This study underlined the importance of soil properties such as availability of soil water content in successful species occurrence over the landscape. Results indicated that the 30% of species were highly sensitive and 45% were slightly sensitive to changes in ASWC
Waring et al. (2014)	western North America	Douglas-fir	They predicted the extent to which the site growth potential and forest function vary between cold, wet (1950-75), warm, dry (2000–09) periods using 3-PG which run using remotely derived soil properties, productivity, and maximum LAI (LAImax)
Wei et al. (2014a)	Northern Idaho, USA	*Abies grandis*	The $\delta^{13}C$ sub-model was tested with the 3-PG model. It provided a consistent simulation of outputs and evaluation of tree

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Table 4 (*continued*)

Author's name	Study site	Species studied	Contribution/Findings
			rings using the $\delta^{13}C$ sub-model
Wei et al. (2014b)	Northern California, USA	Ponderosa pine	The 3-PG model was parameterized for young pine plantations and used the $\delta^{13}C$ sub-model on the gaseous exchange processes. Also, applied some new features on fertilization and competition to improve the 3-PG model outputs
Hart et al. (2015)	Pacific Northwest, USA	Coppiced poplar (Populus species)	This study focused on the economic significance of the 3-PG model by applying it to commercial coppiced poplars plantations. Some modifications were made in the 3-PG model to extend its applicability to coppice management regimes
López-Serrano et al. (2015)	Cuenca Mountains, Spain	*P. pinaster* Ait., *Quercus ilex* L.	The 3-PG model was calibrated for the dominant and subdominant species, and its performance was evaluated under different thinning intensities
Lu et al. (2015)	Southern China	Chinese Fir	3-PG was used to simulate the Chinese fir species productivity and distribution under the changing climatic conditions
Subedi et al. (2015)	Southeastern, USA	Loblolly Pine	The 3-PG model was applied for the estimation of FR from the site index to determines the productivity of Loblolly pine in the region
Adhikari and White (2016)	Lower Rio Grande Valley, Texas, USA	Shrub species	The 3-PG model was applied to estimate the shrubland productivity. This approach is useful to predict C sequestration and wildlife conservation in managed shrublands in current and future climatic conditions
Coops et al. (2016)	Pacific Northwest region of North America	Fifteen tree species	They developed a hybrid modelling approach by integrating the data obtained from remote sensing and migration rates of species to estimate the future distribution of fifteen native forest species
Forrester and Tang (2016)	Shitai County, Anhui province, China	*Castanopsis sclerophylla, Cunninghamia lanceolate, Liquidambar formosana*	The 3-PG model was modified into 3-PG$_{mix}$ for mixed forests by adjusting sub-models, soil water balances and allometric equations accordingly. It provides new insights to forecast the growth dynamics in mixed species forests
Gonzalez-Benecke et al. (2016)	South-eastern and South, US, and Uruguay	*Pinus taeda*	The 3-PG model was parameterized and validated for Loblolly pine. Also, they applied a new set of parameters and improved methods to improve the 3-PG model outputs. The model shows a significant correlation between observed and predicted values of AGB. Based on different site indices, r^2 ranged from 0.85-0.93 in USA and 0.86-0.89 in Uruguay
González-García et al. (2016)	Spain	*Eucalyptus nitens*	The 3-PG model was parameterized for *E. nitens*, which is a bioenergy-based plantation. This approach could be useful in decision-making, analyses, and forests management tactics for bioenergy production
Hung et al. (2016)	Vietnam	Acacia hybrid (*A. Auriculiformis* × *A. mangium*)	The efficiency of the 3-PG model for Acacia hybrid was higher than 0.76. Thus the 3-PG model offers an excellent explanation to estimate productivity across a varied range of climates and soils profiles in Vietnam
Navarro-Cerrillo et al. (2016)	"Sierra de Los Filabres" (Almeria), Spain	*Pinus sylvestris, Pinus nigra*	The observed and estimated DBH values revealed a high correlation ($r^2 > 0.99$), whereas observed and estimated BA increment revealed a low correlation ($r^2 < 0.68$) for both species
Subedi and Fox (2016)	Southeastern, USA	Loblolly pine	This study was the first attempt to model the dynamics of FR and then linked it in the 3-PG model to evaluate the growth and productivity of *P. taeda* in the southeastern USA
Waring and Coops (2016)	Western North America	Forest area of this region	In this study, the LAI and soil moisture data derived from remotely sensed images were

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Table 4 (*continued*)

Author's name	Study site	Species studied	Contribution/Findings
			combined with the process-based model 3-PG. Thus, it provides a useful way to identify and manage forest fire hazards at a large scale
Waring and Gao (2016)	Northwestern China	Spruce forest	They combined the dendrochronological measurements in the 3-PG model to expand the more general understandings about the interactions of environmental variables which disturb the tree growth
Forrester et al. (2017)	26 sites across Europe	*F. sylvatica* and *P. sylvestris*	They studied the mixing effects in mixed forests using the 3-PG_{mix} model. The efficiency of 3-PGmix was usually higher than 0.7 for total biomass. The 3-PG_{mix} model could be applied to evaluate the dynamics of heterogeneous forest
Meyer et al. (2017, 2018)	British Columbia	Lodgepole pine	A modified version of the 3-PG model was used to simulate the effects of mountain pine beetle attack on GPP, WUE and site hydrology
Xie et al. (2017)	North-eastern China	*Larix olgensis*	The 3-PG model was applied to *L. olgensis* plantations. They found that the r^2 was always more than 0.93 between observed and predicted data for outputs like stand density, DBH, biomass partitioning. Besides, they showed that the FR and fullCanAge are the critical parameters of the 3-PG model. They proposed for adjustment in default values of these two parameters to suitably defining the growth rates of *L. olgensis* species to the changeable weather conditions. In conclusion, they indicated that the 3-PG model could be used to determine the stands growth at a regional level and across a wide range of ages and stand characteristics in the future climatic scenarios

the complex nature of the model cannot be easily operationalized by forest managers as a practical tool for forest management. Therefore, improvements, accurateness, and maintenance of simplicity and feasibility of the standard 3-PG model, its spatial and mixed version, are the chief challenges for the 3-PG/3-PGS/3-PGmix model developers. As mentioned in introduction, natural forests play a significant role as a sinker for C emissions. Therefore, there is certainly a need to add other natural and native forest species as well as commercial plantations to parameterize and study under the process-based 3-PG/3-PGS/3-PGmix model. In our next work, we would apply the 3-PG/3-PGS model to investigate the forest growth in India.

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References

Adams, H.D., Williams, A.P., Xu, C., Rauscher, S.A., Jiang, X., McDowell, N.G., 2013. Empirical and process-based approaches to climate-induced forest mortality models. Front. Plant Sci. 4, 1–5. https://doi.org/10.3389/fpls.2013.00438.

Adhikari, A., White, J.D., 2016. Climate change impacts on regenerating shrub land productivity. Ecol. Model. 337, 211–220. https://doi.org/10.1016/j.ecolmodel.2016.07.003.

Aerts, R., Honnay, O., 2011. Forest restoration, biodiversity and ecosystem functioning. BMC Ecol. 11, 1–10. https://doi.org/10.1186/1472-6785-11-29.

Ahamed, T., Tian, L., Zhang, Y., Ting, K.C., 2011. A review of remote sensing methods for biomass feedstock production. Biomass Bioenergy 35, 2455–2469. https://doi.org/10.1016/j.biombioe.2011.02.028.

Allen, R., 2005. Penman–Monteith equation. Encyclopedia of Soils in the Environment. pp. 180–188. https://doi.org/10.1016/B0-12-348530-4/00399-4.

Almeida, A.C.D., Landsberg, J.J., Sands, P.J., 2004a. Parameterisation of 3-PG model for fast-growing *Eucalyptus grandis* plantations. For. Ecol. Manag. 193, 179–195. https://doi.org/10.1016/j.foreco.2004.01.029.

Almeida, A.C.D., et al., 2004b. Needs and opportunities for using a process-based productivity model as a practical tool in Eucalyptus plantations. For. Ecol. Manag. 193, 167–177. https://doi.org/10.1016/j.foreco.2004.01.044.

Almeida, A.C., Soares, J.V., Landsberg, J.J., Rezende, G.D., 2007. Growth and water balance of *Eucalyptus grandis* hybrid plantations in Brazil during a rotation for pulp production. For. Ecol. Manag. 251, 10–21. https://doi.org/10.1016/j.foreco.2007.06.009.

Almeida, A.C., et al., 2009. Use of a spatial process-based model to quantify forest plantation productivity and water use efficiency under climate change scenarios. 18Th World IMACS/MODSIM. Congress. http://mssanz.org.au/modsim09.

Almeida, A.C., Siggins, A., Batista, T.R., Beadle, C., Fonseca, S., Loos, R., 2010. Mapping the effect of spatial and temporal variation in climate and soils on Eucalyptus plantation production with 3-PG, a process-based growth model. For. Ecol. Manag. 259, 1730–1740. https://doi.org/10.1016/j.foreco.2009.10.008.

Amaral, A., Salas-Gonzalez, R., Pa´scoa, F., Tome, M., Tome, J., Soares, P., 2006. Application of the forest growth model 3-PG to eucalyptus globulus stands in the central region of Portugal. In: Reynolds, K.M. (Ed.), Sustainable Forestry in Theory and Practice: Recent Advances in Inventory and Monitoring, Statistics and Modeling, Information and Knowledge Management, and Policy Science. Gen Tech Rep PNW-GTR-688, Portland.

Amichev, B.Y., Johnston, M., Rees, K.C.J.V., 2010. Hybrid poplar growth in bioenergy production systems: biomass prediction with a simple process-based model (3-PG). Biomass Bioenergy 34, 687–702. https://doi.org/10.1016/j.biombioe.2010.01.012.

Amichev, B.Y., Hangs, R.D., Rees, K.C.J.V., 2011. A novel approach to simulate the growth of multi-stem willow in bioenergy production systems with a simple process-based model (3-PG). Biomass Bioenergy 35, 473–488. https://doi.org/10.1016/j.biombioe.2010.09.007.

Ashraf, M.I., Meng, F.-R., Bourque, C.P.-A., MacLean, D.A., 2015. A novel modelling approach for predicting forest growth and yield under climate change. PLoS One 10, e0132066. https://doi.org/10.1371/journal.pone.0132066.

Bai, Z., et al., 2016. Study on light interception and biomass production of different cotton cultivars. PLoS One 11, e0156335. https://doi.org/10.1371/journal.pone.0156335.

Balandier, P., Lacointe, A., Le Roux, X., Sinoquet, H., Cruiziat, P., Le Dizès, S., 2000. SIMWAL: a structural-functional model simulating single walnut tree growth in response to climate and pruning. Ann. For. Sci. 57, 571–585. https://doi.org/10.1051/forest:2000143.

Battaglia, M., Sands, P.J., 1998. Process-based forest productivity models and their application in forest management. For. Ecol. Manag. 102, 13–32. https://doi.org/10.1016/S0378-1127(97)00112-6.

Battaglia, M., Almeida, A.C., O'Grady, A.P., Mendham, D., 2007. Process-based model in Eucalyptus plantation management: reality and perspectives. Boletín del CIDEU 3, 189–205 ISSN 1885-5237.

Bossel, H., 1994. Modeling and Simulation. A.K. Peters Ltd., Wellesley, MA, pp. 484.

Bossel, H., 1996. TREEDYN3 forest simulation model. Ecol. Model. 90, 187–227. https://doi.org/10.1016/0304-3800(95)00139-5.

Brockerhoff, E.G., et al., 2017. Forest biodiversity, ecosystem functioning and the provision of ecosystem services. Biodivers. Conserv. 26, 3005–3035. https://doi.org/10.1007/s10531-017-1453-2.

Bryars, C., Maier, C., Zhao, D., Kane, M., Borders, B., Will, R., Teskey, R., 2013. Fixed physiological parameters in the 3-PG model produced accurate estimates of loblolly pine growth on sites in different geographic regions. For. Ecol. Manag. 289, 501–514. https://doi.org/10.1016/j.foreco.2012.09.031.

Coomes, D.A., Allen, R.B., 2007. Mortality and tree-size distributions in natural mixed-age forests. J. Ecol. 95, 27–40. https://doi.org/10.1111/j.1365-2745.2006.01179.x.

Coops, N.C., Waring, R.H., 2001a. Estimating forest productivity in the eastern Siskiyou Mountains of southwestern Oregon using a satellite-driven process model, 3-PGS. Can. J. For. Res. 31, 143–154. https://doi.org/10.1139/x00-146.

Coops, N.C., Waring, R.H., 2001b. Assessing forest growth across southwestern Oregon under a range of current and future global change scenarios using a process model, 3-PG. Glob. Change Biol. 7, 15–29. https://doi.org/10.1046/j.1365-2486.2001.00385.x.

Coops, N.C., Waring, R.H., 2001c. The use of multiscale remote sensing imagery to derive regional estimates of forest growth capacity using 3-PGS. Remote Sens. Environ. 75, 324–334. https://doi.org/10.1016/S0034-4257(00)00176-0.

Coops, N.C., Waring, R.H., 2011a. A process-based approach to estimate lodgepole pine (*Pinus contorta* Dougl.) distribution in the Pacific Northwest under climate change. Clim. Change 105, 313–328. https://doi.org/10.1007/s10584-010-9861-2.

Coops, N.C., Waring, R.H., 2011b. Estimating the vulnerability of fifteen tree species under changing climate in Northwest North America. Ecol. Model. 222, 2119–2129. https://doi.org/10.1016/j.ecolmodel.2011.03.033.

Coops, N.C., Waring, R.H., Landsberg, J.J., 1998. Assessing forest productivity in Australia and New Zealand using a physiologically based model driven with averaged monthly weather data and satellite-derived estimates of canopy photosynthetic capacity. For. Ecol. Manag. 104, 113–127. https://doi.org/10.1016/S0378-1127(97)00248-X.

Coops, N.C., Waring, R.H., Landsberg, J.J., 2001a. Estimation of potential forest productivity across the Oregon transects using satellite data and monthly weather records. Int. J. Remote Sens. 22, 3797–3812. https://doi.org/10.1080/01431160010014710.

Coops, N.C., Waring, R.H., Brown, S.R., Running, S.W., 2001b. Comparisons of predictions of net primary production and seasonal patterns in water use derived with two forest growth models in Southwestern Oregon. Ecol. Model. 142, 61–81. https://doi.org/10.1016/S0304-3800(01)00279-4.

Coops, N.C., White, J.D., Scott, N.A., 2002. Assessment of regional forest and scrub productivity using a coupled vegetation process model with remote sensing. Geocarto Int. 17, 5–14. https://doi.org/10.1080/10106040208542249.

Coops, N.C., Waring, R.H., Law, B.E., 2005. Assessing the past and future distribution and productivity of ponderosa pine in the Pacific Northwest using a process model, 3-PG. Ecol. Model. 183, 107–124. https://doi.org/10.1016/j.ecolmodel.2004.08.002.

Coops, N.C., Waring, R.H., Schroedera, T.A., 2009. Combining a generic process-based productivity model and a statistical classification method to predict the presence and absence of tree species in the Pacific Northwest, U.S.A. Ecol. Model. 220, 1787–1796. https://doi.org/10.1016/j.ecolmodel.2009.04.029.

Coops, N.C., Hember, R.A., Waring, R.H., 2010. Assessing the impact of current and projected climates on Douglas-Fir productivity in British Columbia, canada, using a process-based model (3-PG). Can. J. For. Res. 40, 511–524. https://doi.org/10.1139/X09-201.

Coops, N.C., Gaulton, R., Waring, R.H., 2011a. Mapping site indices for five Pacific Northwest conifers using a physiologically based model. Appl. Veg. Sci. 14, 268–276. https://doi.org/10.1111/j.1654-109X.2010.01109.x.

Coops, N.C., Waring, R.H., Beier, C., Roy-Jauvin, R., Wang, T., 2011b. Modeling the occurrence of fifteen coniferous tree species throughout the Pacific Northwest of North America using a hybrid approach of a generic process-based growth model and decision tree analysis. Appl. Veg. Sci. 14, 402–414. https://doi.org/10.1111/j.1654-109X.2011.01125.x.

Coops, N.C., Waring, R.H., Hilker, T., 2012a. Prediction of soil properties using a process-based forest growth model to match satellite-derived estimates of leaf area index. Remote Sens. Environ. 126, 160–173. https://doi.org/10.1016/j.rse.2012.08.024.

Coops, N.C., Wulder, M.A., Waring, R.H., 2012b. Modeling lodge pole and jack pine vulnerability to mountain pine beetle expansion into the western Canadian boreal forest. For. Ecol. Manag. 274, 161–171. https://doi.org/10.1016/j.foreco.2012.02.011.

Coops, N.C., Waring, R.H., Plowright, A., Lee, J., Dilts, T.E., 2016. Using remotely-sensed land cover and distribution modeling to estimate tree species migration in the Pacific Northwest Region of North America. Remote Sens. 8, 1–15. https://doi.org/10.3390/rs8010065.

Cropper Jr, W.P., Peterson, K., Teskey, R.O., 1998. MAESTRO simulations of the response of loblolly pine to elevated temperatures and Carbon dioxide. In the productivity and sustainability of southern forest ecosystems in a changing environment. Ecol. Stud. 128, 327–339. https://doi.org/10.1007/978-1-4612-2178-4_18.

Deb, D., Singh, J.P., Deb, S., Datta, D., Ghosh, A., Chaurasia, R.S., 2017. An alternative approach for estimating aboveground biomass using Resourcesat-2 satellite data and artificial neural network in Bundelkhand region of India. Environ. Monit. Assess. 189, 576. https://doi.org/10.1007/s10661-017-6307-6.

Drew, T.J., Flewelling, J.W., 1977. Some recent Japanese theories of yield–density relationship and their applications to Monterey pine plantations. For. Sci. 23, 517–534.

Dye, P.J., 2001. Modelling growth and water use in four *Pinus patula* stands with the 3-PG model. S. Afr. For. J. 191, 53–63. https://doi.org/10.1080/20702620.2001.10434151.

Dye, P.J., Jacobsa, S., Drewa, D., 2004. Verification of 3-PG growth and water-use predictions in twelve Eucalyptus plantation stands in Zululand, South Africa. For. Ecol. Manag. 193, 197–218. https://doi.org/10.1016/j.foreco.2004.01.030.

Esprey, L.J., Sands, P.J., Smith, C.W., 2004. Understanding 3-PG using a sensitivity analysis. For. Ecol. Manag. 193, 235–250. https://doi.org/10.1016/j.foreco.2004.01.032.

Fang, S., Xue, J., Tang, L., 2007. Biomass production and Carbon sequestration potential in poplar plantations with different management patterns. J. Environ. Manag. 85, 672–679. https://doi.org/10.1016/j.jenvman.2006.09.014.

FAO, 2015. Global Forest Resources Assessment 2015: How Have the World's Forests Changed? Rome, Italy. .

Feikema, P.M., Morris, J.D., Beverly, C.R., Collopy, J.J., Baker, T.G., Lane, P.N.J., 2010. Validation of plantation transpiration in south-eastern Australia estimated using the 3-PG+ forest growth model. For. Ecol. Manag. 260, 663–678. https://doi.org/10.1016/j.foreco.2010.05.022.

Fontes, L., Landsberg, J., Tomé, J., Tomé, M., Pacheco, C.A., Soares, P., Araujo, C., 2006. Calibration and testing of a generalized process-based model for use in Portuguese eucalyptus plantations. Can. J. For. Res. 36, 3209–3221. https://doi.org/10.1139/x06-186.

Fontes, L., et al., 2010. Models for supporting forest management in a changing environment. Forest Syst. 19, 8–29. https://doi.org/10.5424/fs/201019S-9315.

Forrester, D.I., 2014. A stand-level light interception model for horizontally and vertically heterogeneous canopies. Ecol. Model. 276, 14–22. https://doi.org/10.1016/j.ecolmodel.2013.12.021.

Forrester, D.I., Tang, X., 2016. Analyzing the spatial and temporal dynamics of species interactions in mixed-species forests and the effects of stand density using the 3-PG model. Ecol. Model. 319, 233–254. https://doi.org/10.1016/j.ecolmodel.2015.07.010.

Forrester, D.I., et al., 2017. Predicting the spatial and temporal dynamics of species interactions in *Fagus sylvatica* and *Pinus sylvestris* forests across Europe. For. Ecol. Manag. 405, 112–133. https://doi.org/10.1016/j.foreco.2017.09.029.

Franklin, J., Serra-Diaz, J.M., Syphard, A.D., Regan, H.M., 2016. Global change and terrestrial plant community dynamics. PNAS 113, 3725–3734. https://doi.org/10.1073/pnas.1519911113.

Godfrey, K., 1983. Compartmental Models and Their Applications. Academic Press, New York, USA, pp. 291.

Gonzalez-Benecke, C.A., Jokela, E.J., Cropper Jr., W.P., Bracho, R., Leduc, D.J., 2014. Parameterization of the 3-PG model for *Pinus elliottii* stands using alternative methods to estimate fertility rating, biomass partitioning and canopy closure. For. Ecol. Manag. 327, 55–75. https://doi.org/10.1016/j.foreco.2014.04.030.

Gonzalez-Benecke, C.A., Teskey, R.O., Martin, T.A., Jokela, E.J., Fox, T.R., Kane, M.B., Noormets, A., 2016. Regional validation and improved parameterization of the 3-PG model for *Pinus taeda* stands. For. Ecol. Manag. 361, 237–256. https://doi.org/10.1016/j.foreco.2015.11.025.

González-García, M., et al., 2016. Application of a process-based model for predicting the productivity of *Eucalyptus nitens* bioenergy plantations in Spain. Glob. Change Biol. Bioenergy 8, 194–210. https://doi.org/10.1111/gcbb.12256.

Hart, Q.J., Tittmann, P.W., Bandaru, V., Jenkins, B.M., 2015. Modeling poplar growth as a short rotation woody crop for biofuels in the Pacific Northwest. Biomass Bioenergy 79, 12–27. https://doi.org/10.1016/j.biombioe.2015.05.004.

Headlee, W.L., Zalesny Jr, R.S., Donner, D.M., Hall, R.B., 2013. Using a process-based model (3-PG) to predict and map hybrid poplar biomass productivity in Minnesota and Wisconsin, USA. Bioenergy Res. 6, 196–210. https://doi.org/10.1007/s12155-012-9251-x.

Hector, A., Bagchi, R., 2007. Biodiversity and ecosystem multi functionality. Nature 448, 188–190. https://doi.org/10.1038/nature05947.

Houghton, R.A., Nassikas, A.A., 2018. Negative emissions from stopping deforestation and forest degradation, globally. Glob. Change Biol. 24, 350–359. https://doi.org/10.1111/gcb.13876.

Hua, L.Z., Morris, J., He, X.B., Jaing, X.D., 2007. Predicting Eucalyptus production in China using the 3-PG model. J. Trop. For. Sci. 19, 127–140. http://www.jstor.org/stable/43594528.

Hung, T.T., Almeida, A.C., Eyles, A., Mohammed, C., 2016. Predicting productivity of Acacia hybrid plantations for a range of climates and soils in Vietnam. For. Ecol. Manag. 367, 97–111. https://doi.org/10.1016/j.foreco.2016.02.030.

Jin, W., He, H.S., Thompson, F.R., 2016. Are more complex physiological models of forest ecosystems better choices for plot and regional predictions? Environ. Model. Softw. 75, 1–14. https://doi.org/10.1016/j.envsoft.2015.10.004.

Johnsen, K., Samuelson, L., Teskey, R., McNulty, S., Fox, T., 2001. Process models as tools in forestry research and management. For. Sci. 47, 2–8. https://doi.org/10.1093/forestscience/47.1.2.

Kanninen, M., Murdiyarso, D., Seymour, F., Angelsen, A., Wunder, S., German, L., 2007. Do Trees Grow on Money? The Implications of Deforestation Research for Policies to Promote REDD. CIFOR, pp. 61–Bogor, Indonesia. https://doi.org/10.17528/cifor/002347.

Keenan, R.J., 2015. Climate change impacts and adaptation in forest management: a review. Ann. For. Sci. 72, 145–167. https://doi.org/10.1007/s13595-014-0446-5.

Keenan, R.J., Reams, G.A., Achard, F., de Freitas, D.V., Grainger, A., Lindquist, E., 2015. Dynamics of global forest area: results from the FAO global forest resources assessment 2015. For. Ecol. Manag. 352, 9–20. https://doi.org/10.1016/j.foreco.2015.06.014.

Keith, H., et al., 2014. Managing temperate forests for carbon storage: impacts of logging versus forest protection on carbon stocks. Ecosphere 5, 1–34. https://doi.org/10.1890/ES14-00051.1.

Kirilenko, A.P., Sedjo, R.A., 2007. Climate change impacts on forestry. PNAS 104, 19697–19702. https://doi.org/10.1073/pnas.0701424104.

Köhl, M., et al., 2015. Changes in forest production, biomass and carbon: results from the 2015 UN FAO Global Forest Resource Assessment. For. Ecol. Manag. 352, 21–34. https://doi.org/10.1016/j.foreco.2015.05.036.

Korzukhin, M.D., Ter-Mikaelian, M.T., Wagner, R.G., 1996. Process versus empirical models: which approach for forest ecosystem management? Can. J. For. Res. 26, 879–887. https://doi.org/10.1139/x26-096.

Kumar, L., Mutanga, O., 2017. Remote sensing of above-ground biomass. Remote Sens. 9, 2–8. https://doi.org/10.3390/rs9090935.

Kumar, L., Sinha, P., Taylor, S., Alqurashi, A.F., 2015. Review of the use of remote sensing for biomass estimation to support renewable energy generation. J. Appl. Remote Sens. 9, 1–28. https://doi.org/10.1117/1.JRS.9.097696.

Landsberg, J., Sands, P., 2010. Physiological Ecology of Forest Production: Principles, Processes and Models. Elsevier, Amsterdam.

Landsberg, J.J., Waring, R.H., 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. For. Ecol. Manag. 95, 209–228. https://doi.org/10.1016/S0378-1127(97)00026-1.

Landsberg, J.J., Johnsen, K.H., Albaugh, T.J., Allen, H.L., McKeand, S.E., 2001. Applying 3-PG, a simple process-based model designed to produce practical results, to data from loblolly pine experiments. For. Sci. 47, 43–51.

Landsberg, J.J., Waring, R.H., Coops, N.C., 2003. Performance of the forest productivity model 3-PG applied to a wide range of forest types. For. Ecol. Manag. 172, 199–214. https://doi.org/10.1016/S0378-1127(01)00804-0.

Landsberg, J., Mäkelä, A., Sievänen, R., Kukkola, M., 2005. Analysis of biomass accumulation and stem size distributions over long periods in managed stands of *Pinus sylvestris* in Finland using the 3-PG model. Tree Physiol. 25, 781–792. https://doi.org/10.1093/treephys/25.7.781.

Lasch, P., Badeck, F.W., Suckow, F., Lindner, M., Mohr, R.P., 2005. Model-based analysis of management alternatives at stand and regional level in Brandenburg (Germany). For. Ecol. Manag. 207, 59–74. https://doi.org/10.1016/j.foreco.2004.10.034.

Le Quéré, C., et al., 2016. Global Carbon budget 2016. Earth Syst. Sci. Data 8, 605–649. https://doi.org/10.5194/essd-8-605-2016.

Loehle, C., LeBlanc, D., 1996. Model-based assessments of climate change effects on forests: a critical review. Ecol. Model. 90, 1–31. https://doi.org/10.1016/0304-3800(96)83709-4.

López-Serrano, F.R., Martínez-García, E., Dadi, T., Rubio, E., García-Morote, F.A., Lucas-Borja, M.E., Andrés-Abellán, M., 2015. Biomass growth simulations in a natural mixed forest stand under different thinning intensities by 3-PG process-based model. Eur. J. For. Res. 134, 167–185. https://doi.org/10.1007/s10342-014-0841-3.

Lu, Y.C., Mohanty, S., 2001. Sensitivity analysis of a complex proposed geologic waste disposal system using the Fourier amplitude sensitivity test method. Reliab. Eng. Syst. Safe. 72, 275–291. https://doi.org/10.1016/S0951-8320(01)00020-5.

Lu, Y., Coops, N.C., Wang, T., Wang, G., 2015. A process-based approach to estimate Chinese Fir (*Cunninghamia lanceolata*) distribution and productivity in southern China under climate change. Forests 6, 360–379. https://doi.org/10.3390/f6020360.

MacDicken, K.G., 2015. Global forest resources assessment 2015: what, why and how? For. Ecol. Manag. 352, 3–8. https://doi.org/10.1016/j.foreco.2015.02.006.

Mäkelä, A., et al., 2000. Process-based models for forest ecosystem management: current state of the art and challenges for practical implementation. Tree Physiol. 20, 289–298. https://doi.org/10.1093/treeps/20.5-6.289.

Makler-Pick, V., Gal, G., Gorfine, M., Hipsey, M.R., Carmel, Y., 2011. Sensitivity analysis for complex ecological models – a new approach. Environ. Model. Softw. 26, 124–134. https://doi.org/10.1016/j.envsoft.2010.06.010.

Mathys, A., Coops, N.C., Waring, R.H., 2014. Soil water availability effects on the distribution of 20 tree species in western North America. For. Ecol. Manag. 313, 144–152. https://doi.org/10.1016/j.foreco.2013.11.005.

McMurtrie, R.E., Wolf, L., 1983. Above- and below-ground growth of forest stands: a carbon budget model. Ann. Bot. 52, 437–448. https://doi.org/10.1093/oxfordjournals.aob.a086599.

Mendes, H., 2007. Brazil faces forecast of heat and dust Sci. Dev. Net. http://www.scidev.net/en/features/brazil-faces-forecast-of-heat-and-dust.html.

Meyer, G., et al., 2017. Measurements and simulations using the 3-PG model of the water balance and water use efficiency of a lodgepole pine stand following mountain pine beetle attack. For. Ecol. Manag. 393, 89–104. https://doi.org/10.1016/j.foreco.2017.03.019.

Meyer, G., et al., 2018. Simulation of net ecosystem productivity of a lodgepole pine forest after mountain pine beetle attack using a modified version of 3-PG. For. Ecol. Manag. 412, 41–52. https://doi.org/10.1016/j.foreco.2018.01.034.

Miehle, P., Battaglia, M., Sands, P.J., Forrester, D.I., Feikema, P.M., Livesley, S.J., Morris, J.D., Arndt, S.K., 2009. A comparison of four process-based models and a statistical regression model to predict growth of Eucalyptus globulus plantations. Ecol. Model. 220, 734–746. https://doi.org/10.1016/j.ecolmodel.2008.12.010.

Minunno, F., Xenakis, G., Perks, M.P., Mencuccini, M., 2010. Calibration and validation of a simplified process-based model for the prediction of the carbon balance of Scottish Sitka spruce (*Picea sitchensis*) plantations. Can. J. For. Res. 40, 2411–2426. https://doi.org/10.1139/X10-181.

Morison, J.I., Morecroft, M.D., 2006. Plant Growth and Climate Change. Blackwell Publishing, Oxford, UK, pp. 213.

Navarro-Cerrillo, R.M., Beira, J., Suarez, J., Xenakis, G., Sánchez-Salguero, R., Hernández-Clemente, R., 2016. Growth decline assessment in *Pinus sylvestris* L. and *Pinus nigra*Arnold. forests by using 3-PG model. For. Syst. 25, e068. https://doi.org/10.5424/fs/2016253-08610.

Nightingale, J.M., Coops, N.C., Waring, R.H., Hargrove, W.W., 2007. Comparison of MODIS gross primary production estimates for forests across the U.S.A. With those generated by a simple process model, 3-PGS. Remote Sens. Environ. 109, 500–509. https://doi.org/10.1016/j.rse.2007.02.004.

Nightingale, J.M., Hill, M.J., Phinn, S.R., Davies, I.D., Held, A.A., Erskine, P.D., 2008. Use of 3-PG and 3-PGS to simulate forest growth dynamics of Australian tropical rainforests I. Parameterisation and calibration for old-growth, regenerating and plantation forests. For. Ecol. Manag. 254, 107–121. https://doi.org/10.1016/j.foreco.2007.03.041.

Nolé, A., Law, B.E., Magnani, F., Matteucci, G., Ferrara, A., Ripullone, F., Borghetti, M., 2009. Application of the 3-PGS model to assess carbon accumulation in forest ecosystems at a regional level. Can. J. For. Res. 39, 1647–1661. https://doi.org/10.1139/X09-077.

Nolé, A., et al., 2013. Assessing temporal variation of primary and ecosystem production in two Mediterranean forests using a modified 3-PG model. Ann. For. Sci. 70, 729–741. https://doi.org/10.1007/s13595-013-0315-7.

Paul, K.I., Booth, T.H., Jovanovic, T., Sands, P.J., Morris, J.D., 2007. Calibration of the forest growth model 3-PG to eucalypt plantations growing in low rainfall regions of Australia. For. Ecol. Manag. 243, 237–247. https://doi.org/10.1016/j.foreco.2007.03.029.

Pérez-Cruzado, C., Muñoz-Sáez, F., Basurco, F., Riesco, G., Rodríguez-Soalleiro, R., 2011. Combining empirical models and the process-based model 3-PG to predict *Eucalyptus nitens* plantation growth in Spain. For. Ecol. Manag. 262, 1067–1077. https://doi.org/10.1016/j.foreco.2011.05.045.

Pinjuv, G., Mason, E.G., Watt, M., 2006. Quantitative validation and comparison of a range of forest growth model types. For. Ecol. Manag. 236, 37–46. https://doi.org/10.1016/j.foreco.2006.06.025.

Potithep, S., Yasuoka, Y., 2011. Application of the 3-PG model for gross primary productivity estimation in deciduous broadleaf forests: a study area in Japan. Forests 2, 590–609. https://doi.org/10.3390/f2020590.

Potithep, S., Endo, T., Takeuchi, W., Sawada, H., Yasuoka, Y., 2009. Coupling remote sensing with spatial 3-PG model for gross primary productivity estimation in deciduous broadleaf forest: Hokkaido, Japan. Seisan-Kenkyu 61, 755–759. https://doi.org/10.11188/seisankenkyu.61.755.

Pretzsch, H., Forrester, D.I., Rötzer, T., 2015a. Representation of species mixing in forest growth models. A review and perspective. Ecol. Model. 313, 276–292. https://doi.org/10.1016/j.ecolmodel.2015.06.044.

Pretzsch, H., del Río, M., Ammer, C., et al., 2015b. Growth and yield of mixed versus pure stands of Scots pine (*Pinus sylvestris* L.) and European beech (*Fagus sylvatica* L.) analysed along a productivity gradient through Europe. Eur. J. Forest Res. 134, 927–947. https://doi.org/10.1007/s10342-015-0900-4.

Rodríguez, R., Espinosa, M., Real, P., Inzunza, J., 2002. Analysis of productivity of Radiata pine plantations under different silvicultural regimes using the 3-PG process-based model. Aust. For. 65, 165–172. https://doi.org/10.1080/00049158.2002.10674869.

Rodríguez-Suárez, J.A., Soto, B., Iglesias, M.L., Diaz-Fierros, F., 2010. Application of the 3-PG forest growth model to a *Eucalyptus globulus* plantation in Northwest Spain. Eur. J. For. Res. 129, 573–583. https://doi.org/10.1007/s10342-010-0355-6.

Sands, P., 2004. Adaptation of 3-PG to Novel Species: Guidelines for Data Collection and Parameter Assignment. Technical Report No.141. CRC for Sustainable Production Forestry. Hobart. .

Sands, P.J., 2010. 3-PGPJS User Manual.

Sands, P.J., Landsberg, J.J., 2002. Parameterization of 3-PG for plantation grown Eucalyptus globulus. For. Ecol. Manag. 163, 273–292. https://doi.org/10.1016/S0378-1127(01)00586-2.

Scheller, R.M., Mladenoff, D.J., 2005. A spatially interactive simulation of climate change, harvesting, wind, and tree species migration and projected changes to forest composition and biomass in northern Wisconsin, USA. Glob. Change Biol. 11, 307–321. https://doi.org/10.1111/j.1365-2486.2005.00906.x.

Seidl, R., et al., 2011. Modelling natural disturbances in forest ecosystems: a review. Ecol. Model. 222, 903–924. https://doi.org/10.1016/j.ecolmodel.2010.09.040.

Silva, Da, W.C.M., Ribeiro, A., Neves, J.C.L., de Barros, N.F., Leite, F.P., 2013. Water balance model and eucalyptus growth simulation in the Rio doce basin, Brazil. Acta Scientiarum 35, 403–412. https://doi.org/10.4025/actasciagron.v35i4.16955.

Sinha, S., Jeganathan, C., Sharma, L.K., Nathawat, M.S., 2015. A review of radar remote sensing for biomass estimation. Int. J. Environ. Sci. Technol. 12, 1779–1792. https://doi.org/10.1007/s13762-015-0750-0.

Song, X., Bryan, B.A., Paul, K.I., Zhao, G., 2012. Variance-based sensitivity analysis of a forest growth model. Ecol. Model. 247, 135–143. https://doi.org/10.1016/j.ecolmodel.2012.08.005.

Song, X., Bryan, B.A., Almeida, A.C., Paul, K., Zhao, G., Ren, Y., 2013. Time-dependent sensitivity of a process-based ecological model. For. Ecol. Manag. 256, 114–123. https://doi.org/10.1016/j.ecolmodel.2013.06.013.

Stape, J.L., Ryan, M., Binkley, D., 2004. Testing the utility of the 3-PG model for growth of *Eucalyptus grandis* x *urophylla* with natural and manipulated supplies of water and nutrients. For. Ecol. Manag. 193, 219–234. https://doi.org/10.1016/j.foreco.2004.01.031.

Storkey, J., Stratonovitch, P., Chapman, D.S., Vidotto, F., Semenov, M.A., 2014. A process-based approach to predicting the effect of climate change on the distribution of an invasive allergenic plant in Europe. PLoS One 9, e88156. https://doi.org/10.1371/journal.pone.0088156.

Subedi, S., Fox, T.R., 2016. Modeling repeated fertilizer response and one-time midrotation fertilizer response in loblolly pine plantations using FR in the 3-PG process model. For. Ecol. Manag. 380, 90–99. https://doi.org/10.1016/j.foreco.2016.08.040.

Subedi, S., Fox, T.R., Wynne, R.H., 2015. Determination of fertility rating (FR) in the 3-PG model for loblolly pine plantations in the southeastern United States based on site index. Forests 6, 3002–3027. https://doi.org/10.3390/f6093002.

Swenson, J.J., Waring, R.H., Fan, W., Coops, N.C., 2005. Predicting site index with a physiologically based growth model across Oregon, USA. Can. J. For. Res. 35, 1697–1707. https://doi.org/10.1139/x05-089.

Tickle, P.K., Coops, N.C., Hafner, S.D., The Bago Science Team, 2001. Assessing Forest Productivity at local scales across a native eucalypt forest using a process model, 3PG-SPATIAL. For. Ecol. Manag. 152, 275–291. https://doi.org/10.1016/S0378-1127(00)00609-5.
Tilman, D., 1998. Species composition, species diversity, and ecosystem processes: understanding the impacts of global change. In: Pace, M.L., Groffman, P.M. (Eds.), Successes, Limitations, and Frontiers in Ecosystem Science. Springer-Verlag, New York, pp. 452–472. https://doi.org/10.1007/978-1-4612-1724-4_19.
Turner, M.G., Gardner, R.H., O'Neill, R.V., 1995. Ecological dynamics at broad scales ecosystems and landscapes. BioScience 45 (Supplement), 29–35. http://www.jstor.org/stable/1312440.
Vacchiano, G., Magnani, F., Collalti, A., 2012. Modeling Italian forests: state of the art and future challenges. iForest 5, 113–120. https://doi.org/10.3832/ifor0614-005.
Vanderwel, M.C., Coomes, D.A., Purves, D.W., 2013. Quantifying variation in forest disturbance, and its effects on aboveground biomass dynamics, across the eastern United States. Glob. Chang. Biol. 19, 1504–1517. https://doi.org/10.1111/gcb.12152.
Vega-Nieva, D.J., et al., 2013. Developing a general method for the estimation of the fertility rating parameter of the 3-PG model: application in Eucalyptus globulus plantations in northwestern Spain. Can. J. For. Res. 43, 627–636. https://doi.org/10.1139/cjfr-2012-0491.
Waring, R.H., Coops, N.C., 2016. Predicting large wildfires across western North America by modeling seasonal variation in soil water balance. Clim. Change 135, 325–339. https://doi.org/10.1007/s10584-015-1569-x.
Waring, R.H., Gao, L., 2016. Recent reduction in the frequency of frost accounts for most of the increased growth of a high elevation spruce forest in northwestern China. Trees 30, 1225–1236. https://doi.org/10.1007/s00468-016-1360-2.
Waring, R.H., Landsberg, J.J., Williams, M., 1998. Net primary production of forests: a constant fraction of gross primary production. Tree Physiol. 18, 129–134. https://doi.org/10.1093/treephys/18.2.129.
Waring, R.H., Coops, N.C., Ohmann, J.L., Sarr, D.A., 2002. Interpreting woody plant richness from seasonal ratios of photosynthesis. Ecology 83, 2964–2970. https://doi.org/10.1890/0012-9658(2002)083[2964:IWPRFS]2.0.CO;2.
Waring, R.H., Coops, N.C., Landsberg, J.J., 2010. Improving predictions of forest growth using the 3-PGS model with observation by remote sensing. For. Ecol. Manag. 259, 1722–1729. https://doi.org/10.1016/j.foreco.2009.05.036.
Waring, R.H., Coops, N.C., Running, S.W., 2011. Predicting satellite-derived patterns of large-scale disturbances in forests of the Pacific Northwest Region in response to recent climatic variation. Remote Sens. Environ. 115, 3554–3566. https://doi.org/10.1016/j.rse.2011.08.017.
Waring, R.H., Coops, N.C., Mathys, A., Hilker, T., Latta, G., 2014. Process-based modeling to assess the effects of recent climatic variation on site productivity and forest function across Western North America. Forests 5, 518–534. https://doi.org/10.3390/f5030518.
Wei, L., Marshall, J.D., Link, T.E., Kavanagh, K.L., Du, E., Pangle, R.E., Gag, P.J., Ubierna, N., 2014a. Constraining 3-PG with a new $\delta^{13}C$ submodel: a test using the $\delta^{13}C$ of tree rings. Plant Cell Environ. 37, 82–100. https://doi.org/10.1111/pce.12133.
Wei, L., Marshall, J.D., Zhang, J., Zhou, H., Powers, R.F., 2014b. 3-PG simulations of young ponderosa pine plantations under varied management intensity: why do they grow so differently? For. Ecol. Manag. 313, 69–82. https://doi.org/10.1016/j.foreco.2013.10.035.
Weinstein, D.A., Cropper Jr, W.P., Mcnulty, S.G., 1998. Summary of simulated forest responses to climate change in the southeastern United States, Mickler, R.A., Fox, S.. the productivity and sustainability of southern forest ecosystems in a changing environment. Ecol. Stud. 128, 479–500. https://doi.org/10.1007/978-1-4612-2178-4_26.
Weltzin, J.F., et al., 2003. Assessing the response of terrestrial ecosystems to potential changes in precipitation. BioScience 53, 941–952. https://doi.org/10.1641/0006-3568(2003)053[0941:ATROTE]2.0.CO;2.
White, J.D., Coops, N.C., Scott, N.A., 2000. Estimates of New Zealand forest and scrub from the 3-PG model. Ecol. Model. 131, 175–190. https://doi.org/10.1016/S0304-3800(00)00251-9.
White, J.D., Scott, N.A., Hirsch, A.I., Running, S.W., 2006. 3-PG productivity modeling of regenerating Amazon forests: climate sensitivity and comparison with MODIS-Derived NPP. Earth Interact. 10, 1–26. https://doi.org/10.1175/EI137.1.
Whitehead, D., et al., 2002. Analysis of the growth of rimu (*Dacrydium cupressinum*) in South Westland, New Zealand, using process-based simulation models. Int. J. Biometeorol. 46, 66–75. https://doi.org/10.1007/s00484-001-0122-y.
Wu, Y., Liu, S., Huang, Z., Yan, W., 2014. Parameter optimization, sensitivity, and uncertainty analysis of an ecosystem model at a forest flux tower site in the United States. J. Adv. Model. Earth Syst. 6, 405–419. https://doi.org/10.1002/2013MS000298.
Xenakis, G., Ray, D., Mencuccini, M., 2008. Sensitivity and uncertainty analysis from a coupled 3-PG and soil organic matter decomposition model. Ecol. Model. 219, 1–16. https://doi.org/10.1016/j.ecolmodel.2008.07.020.
Xia, J., Luo, Y., Wang, Y.P., Hararuk, O., 2013. Traceable components of terrestrial carbon storage capacity in biogeochemical models. Glob. Change Biol. 19, 2104–2116. https://doi.org/10.1111/gcb.12172.
Xie, Y., Wang, H., Lei, X., 2017. Application of the 3-PG model to predict growth of Larix olgensis plantations in northeastern China. For. Ecol. Manag. 406, 208–218. https://doi.org/10.1016/j.foreco.2017.10.018.
Zalesny Jr, R.S., Donner, D.M., Coyle, D.R., Headlee, W.L., 2012. An approach for siting poplar energy production systems to increase productivity and associated ecosystem services. For. Ecol. Manag. 284, 45–58. https://doi.org/10.1016/j.foreco.2012.07.022.
Zhang, J., Huang, S., He, F., 2015. Half-century evidence from western Canada shows forest dynamics are primarily driven by competition followed by climate. PNAS 112, 4009–4014. https://doi.org/10.1073/pnas.1420844112.
Zhao, M., Xiang, W., Peng, C., Tian, D., 2009. Simulating age-related changes in carbon storage and allocation in a Chinese fir plantation growing in southern China using the 3-PG model. For. Ecol. Manag. 257, 1520–1531. https://doi.org/10.1016/j.foreco.2008.12.025.
Zhao, J., Yan, X., Guo, J., Jia, G., 2012. Evaluating spatial-temporal dynamics of net primary productivity of different forest types in north-eastern China based on improved FORCCHN. PLoS One 7, e48131. https://doi.org/10.1371/journal.pone.0048131.
Zhu, Z., et al., 2010. A Method for Assessing Carbon Stocks, Carbon Sequestration, and Greenhouse-gas Fluxes in Ecosystems of the United States Under Present Conditions and Future Scenarios: U.S. Geological Survey Scientific Investigations Report 2010–5233. pp. 190. http://pubs.usgs.gov/sir/2010/5233/.

Websites referred

http://3pg.forestry.ubc.ca/3-pg-for-excel/ (Accessed 26 October 2018)
http://3pg.forestry.ubc.ca/publications/ (Accessed 26 October 2018)
https://sites.google.com/site/davidforrestersite/home/projects/3PGmix/3pgmixdownload (Accessed 10 December 2018)