



International Journal of Research in Agronomy

E-ISSN: 2618-0618

P-ISSN: 2618-060X

© Agronomy

www.agronomyjournals.com

2024; SP-7(8): 390-399

Received: 28-06-2024

Accepted: 30-07-2024

Manojkumar S

Department of Silviculture &
Agroforestry, College of Forestry,
Kerala Agricultural University,
Vellanikkara, Thrissur, Kerala,
India

Jamaludheen V

Department of Silviculture &
Agroforestry, College of Forestry,
Kerala Agricultural University,
Vellanikkara, Thrissur, Kerala,
India

Envisioning future forests through simulation models

Manojkumar S and Jamaludheen V

DOI: <https://doi.org/10.33545/2618060X.2024.v7.i8Se.1416>

Abstract

Forest is a dynamic entity, keep on changing spatially and temporally. In the recent past rapid changes in the composition, structure, function and health was observed in the global forests primarily due to human induced climate change processes. In this scenario, Forest Simulation Models (FSM) are emerging as essential aids for predicting future changes and for choosing the appropriate management strategies. They are digital prototypes that simulate the behavior of real-world processes or systems, allowing decision-makers to evaluate various scenarios and situations. These FSMs are basically categorized into empirical models, process-based models and gap models based on their approach. Each approach has its own advantage and disadvantage which is dealt in detail in the article. It also elaborates the basic steps involved in simulation model application such as model initiation, parameterization and prediction. Available forest growth models largely differ from each other in many ways and they provide a large range of future growth estimates. Thus, selection of relevant model for a required end use is most critical.

Keywords: Simulation models, forest modelling, empirical model, process-based model, climate change

1. Introduction

Forest is one of the vital components of earth ecosystem. It houses more than 80% of the world's terrestrial biodiversity, provides livelihood for more than 1.6 billion people ^[1] and it is a source for approximately 75% accessible fresh water of the world. Typically, forests are very complex systems constituting large amount of biodiversity and interactions among the components. Moreover, forest is a dynamic entity. It changes structure of the communities spatially and temporally. Naturally, the temporal changes in forest are at very slow pace, climate has compounded effect on forest dynamics. These human induced climate change in the recent decades accelerated forest structural and functional dynamics ^[2].

Climate change has massive impact on forest by affecting it both directly and indirectly. Directly climate change affects forest in all different levels starting from the cellular/tissue level to the geographical level. At cellular level climate change directly impacts the basic physiological processes like photosynthesis and respiration. Further it has cascading effect in the organism level as those physiological process governs the health, growth, phenology and survival of the individual organisms. Eventually, survival and growth of organisms in the area contributes to community changes and ultimately ecosystem structure, function of the area changes. Indirectly, climate change also has quite a large impact as it favours the incidence of insect and pest attack, frequent wildfires and other natural calamities such as drought, cyclone, landslides and floods etc. ^[3].

Changing climate has both positive and negative effects on trees based on their nature, while, it affects negatively as a whole to the forest system (Fig. 1). Phenological change is the best proxy of climate change, the changing climatic conditions postpone or advances the phenological expressions of the species like leaf shedding, flowering, fruiting, leaf flush, etc. As many other organisms also have synchronised life cycle with some particular plant species indirectly this climate change again threatens those organisms ^[4]. At a larger scale changing phenology also disturb ecosystem functioning and services.

Corresponding Author:

Manojkumar S

Department of Silviculture &
Agroforestry, College of Forestry,
Kerala Agricultural University,
Vellanikkara, Thrissur, Kerala,
India

1.1 Effects of climate change on forest ecosystem

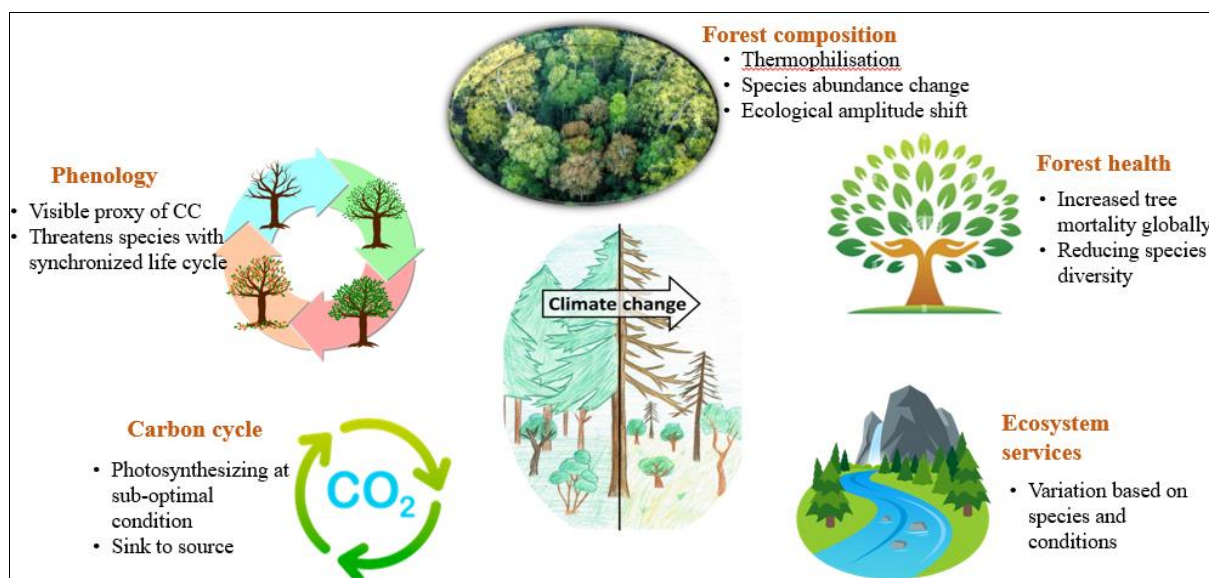


Fig 1: Effects of climate change on forest ecosystem

Climate change alters species distributions, causing variations in the makeup of plant communities. Specifically, it is known as 'thermophilization'; it is a process in which relative number of warm-adapted species increases while the relative abundance of cold-adapted species decreases. This phenomenon was directly related with warming rate of the biome and was quicker in moderately warm ecoregions of the world [5]. Moreover, climate change drastically influences ecological amplitude of the species.

Climatic extremes such as heat and drought have increased tree mortality across the world [6]. In some cases, climatically affected forests have not yet recovered [7], yet, as previously mentioned, fundamental modifications in tree species composition are taking place [8]. Climate change affects forest health in numerous ways. Rising temperatures alter ecosystems, triggering shifts in plant and animal habitats. Droughts become more frequent, stressing trees and making them vulnerable to diseases and pests. Extreme weather events like storms and wildfires become more common, causing damage and destruction to forests. Changes in rainfall patterns affect water availability, crucial for forest survival. Overall, these impacts weaken forests, making them less resilient and more susceptible to further damage, endangering biodiversity and ecosystem stability.

Scholes and Settele [9] found that most ecosystems are sensitive to climate change, even in low and medium-range scenarios of global warming. Climatic change driven functional and structural change of forest results in its potential of ecosystem service provision [10]. Climate change can impact local and regional ecosystem services including water control and timber production, affecting dependent societies [11]. Moreover, it also affects biogeochemical cycles by changing the patterns and rates of nutrient cycling, altering the balance of elements in ecosystems, and interfering with the general operation of processes. Forests are the key player in global carbon cycle and it holds a significant role in maintaining the global carbon sink. Carbon sink-source dynamics in the forest ecosystem are highly influenced by human induced climate change conditions [12]. Due to increasing temperature tropical forests are already photosynthesize at suboptimal conditions, if it perpetuates, soon trees in these forests may dies and turns ecosystem into carbon

source [13].

1.2 Changing forests: challenge for forest mangers

The uncertainty in the recent years in forest growth and development has become a major challenge for the forest stakeholders to take up further planning and decision making for meeting their future needs. Despite shrinking forest area intensified by climate change and biodiversity loss, forest managers are confronting to meet the demands of growing population. Climate change, ecosystem conservation, biodiversity, and sustainable management are complex concerns at stand level that lack historical precedents for solutions [14, 15]. The concerns also existed at the landscape level, affecting patterns of change across multiple scales. Monitoring and predicting change in forest structure and function, and taking action to minimize bad repercussions or capitalize on potential benefits is much needed to fulfil the interests of management [16]. Hence, the paradigm shift in the forest management from traditional systems to the climate mitigating and adaptive management systems are need of the hour. But certainly, prediction of forest response to different management regimes to the novel combination of climatic stressors is highly risky [17]. At this difficult scenario, forest simulation models are one of the reliable options for future prediction and planning.

2. Forest simulation modelling

Foresters understanding about the past and present measurements has got paramount importance in management, but it's been used limitedly [18]. Monitoring the forest throughout time has been challenging due to the high cost and dedication required from individuals and institutions. Traditional methodologies cannot directly address the complex response of forest structure and function to changing environments. While, forest simulation models are good at addressing complex issues and formalize hypotheses that link patterns and processes. Forest Simulation Models (FSMs) are the essential allies for forest stakeholders in predicting future changes. These simulation models are digital prototypes that simulate the behaviour of real-world processes or systems, allowing decision-makers to evaluate various scenarios and situations. These models consist of hardware and software's to produce the virtual

representations likely, images, graphs or tables of the real-world processes of forest ecosystem which is practically impossible to create and study.

2.1 Significance of forest simulation modelling

Modelling for any fields will be carried out for either prediction

of future or to know the past conditions. The future forest modelling will be very helpful in this climate changing scenarios to understand the impact of changing climate on composition, physiological processes, species migration, insect and pest outbreaks, survival, growth, reproduction, phenology, succession and services of forests.

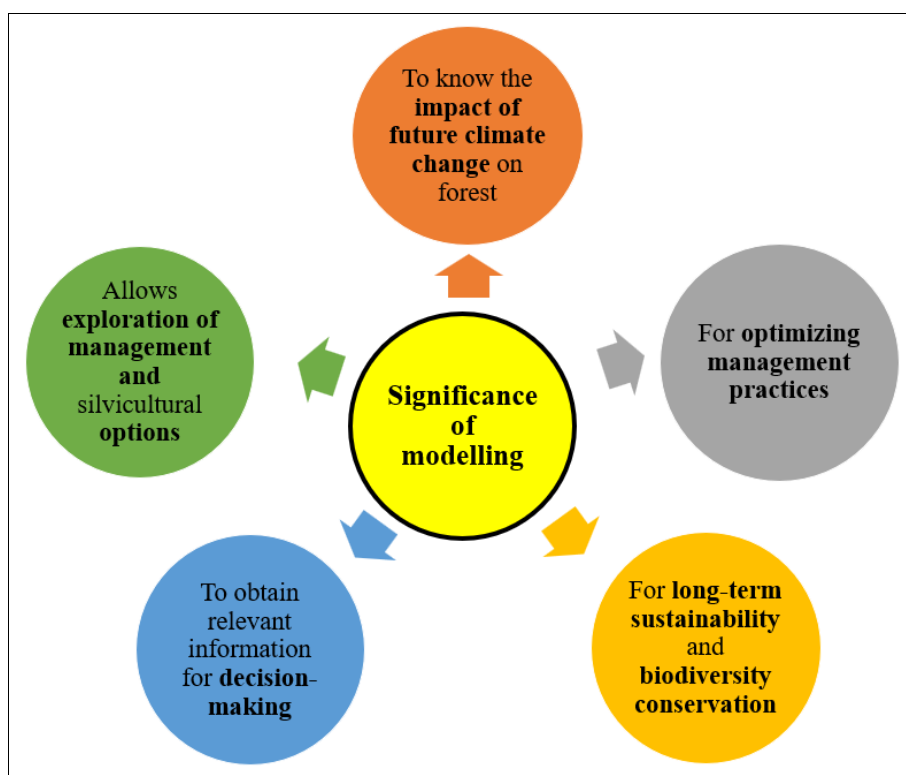


Fig 2: Significance of simulation models in forestry

These simulation models are the available tools to examine and evaluate the management strategies and to optimize the management practices to meet our future needs, few important significances are discussed here (Fig. 2). FSM's aid in anticipating forest dynamics, assessing the effects of various management options, and understanding how climate, disturbances, and management techniques affect forest ecosystems. Forest simulation models, which use empirical or mechanistic methodologies, can provide insights on forest development, yield, succession, carbon storage, nutrient cycling, and energy balance with the atmosphere^[18, 19]. Predicting forest developmental growth, succession, and vegetation dynamics on the basis of climate change, disturbances, and management activities contributes to assess forests long-term sustainability and biodiversity^[20].

Integration of different disturbances modules such as forest fires and insect infestations, FSM can assist build adaptive management strategies that respond to changing environmental conditions at landscape levels^[19]. These interventions will allow the forest stakeholders or managers to explore the opportunities and challenges of novel management and silviculture operations are developed.

In total, integrating diversified appropriate modelling modules like, fire, carbon, growth, succession, *etc.* into decision-support systems is warranted by the unprecedented environmental changing scenarios. This integration can improve the evaluation of the sustainability of forest ecosystems in a changing environment, offering useful insights for forest managers and policymakers^[18]. Thereby FSM has a greater relevance in long

term sustainability and biodiversity conservation.

2.2 Historical development of simulation models

Models are very old to the field of forestry, it all started in the late 18th century when the German foresters have developed yield models for many of the temperate species to estimate yield and prepared prediction tables for different diameter and height classes^[21]. Until, second half of the 20th century growth and yield models developed based on extensive data collection and estimations of timber were useful tools for forest management^[18]. Later in the late 1960s, an attempt has been made to develop process-based models by International Biodiversity Program (IBP). IBP conducted research on several biomes, including forest biome focusing on biomass, nutrient, and water flow dynamics. Computer models were developed to mimic environmental mechanism. Although the models accurately represented ecosystems, they fell short of their full potential. According to Kwa^[22], these models were mathematically complex and impossible with those existing computing methods and gadgets while, it was remaining biologically basic. Despite its drawbacks, a part of the models *i.e.*, compartment models, called biogeochemical models are nevertheless widely utilized to represent the terrestrial carbon cycle in earth system models. CENTURY models used for predicting carbon changes in agroforestry areas, grasslands; FOREST-BGC used in foreseeing the forests belowground carbon; Carnegie Ames Stanford Approach (CASA) for forest productivity and carbon^[23] are the derived examples from the sub models of IBP models.

Forest gap model, which was first developed in 1969 as a subset

of individual-tree models, have gained popularity among forest ecologists for answering a wide range of applied research questions, including long-term dynamics of structure, biomass, and composition of forest [24]. One of the successful forest gap model, JABOWA was developed in 1972 [25]. Its acronyms stands for the last names of the developers i.e., Janak, Botkin, Wallis. This model was widely used in successional studies for a smaller geographical area assuming the similar environmental conditions for future.

Later for large spatial scale modelling, the development of Digital Global Vegetation Model (DGVM) was started in mid of 1990's. These DGVM are integrated approach which include five broad groups of processes, like plant physiology, plant geography, vegetation dynamics, biogeochemistry, and biophysics. Probably the first of its kind was IBIS [26]. These models cannot distinguish between different species, instead uses plant functional types. Moreover, DGVM's simulate for cohorts of similar size distribution instead individual plants [27]. Forest simulation boundaries were extended again in 1993 after successful development of 3-PG (Physiological Principles in

Predicting Growth) model, a process-based model developed by Landsberg and Waring [15] in Australia for eucalyptus plantations. Contemporarily, in Germany for predicting long-term behaviour of forests under changing environmental conditions, model 4C was developed [28]. It was process-based model deals at both tree and stand level. Model relays on eco-physiological tests, long-term observations, and physiological modelling at an intermediate degree of complexity.

In the beginning of the 21st century terrestrial biosphere models were developed. Terrestrial biosphere models reflect the junction of the atmosphere, hydrosphere, geosphere, and biosphere. Very recently, in 2020's Earth System Prediction and Management Models were developed. These are very comprehensive Complex models in which chemistry, biology and physical processes were interrelated to understand the planet [27].

3. Development of simulation models

Fundamental steps in simulation models generally consists of two steps i.e., model initialization and model prediction (Fig. 3).

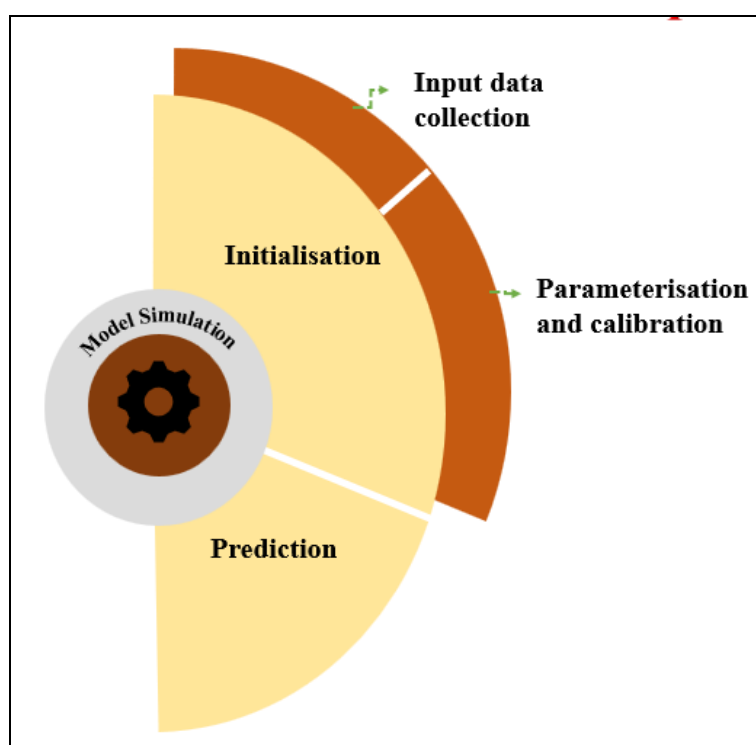


Fig 3: Fundamental steps in forest simulation modelling

3.1 Model initialization

Initialisation of model refers to the establishment of initial existing condition of the area in the model. Further, it again be classified into two different steps.

1. **Input data collection:** In this step, several variables required for mathematically defining the existing conditions are collected. Input data for the models requires five different components to define existing conditions, which comprises state variables, external variables, mathematical equations, parameters, and universal constants [29]. State variables includes the details related to existing forest species, their age, growth and conditions along with the soil conditions. The external variables comprise the varying climatic factors (Sunshine, temperature, windspeed, rainfall, etc.), management factors (thinning, fertilisation, irrigation, pruning, etc.) and forest fire. Well-defined mathematical

equation based on the theoretical concept suitable for the local condition and species including universal constants and different parameters should be selected or developed or modified.

2. **Parameterization and calibration:** Parameterization is the process of adjusting the sensitive parameter value in order to control the behaviour of the simulation models. Models may have several sub models and different mathematical equations to define physiological process [27]. In all the equations consists variables and parameters to predict outcome. Parameters in the equations must be adjusted in order to obtain accepted outcome from the models. These parameter values are adjusted based on species, geographical area, plant functional types. Equations may contain several parameters, of which important parameter is selected based on sensitivity analysis. The selected crucial

parameter is called as sensitive parameter and which is used in calibrating the equation for the specific purpose.

3.2 Model prediction

In this stage once the model is developed in order to predict for the future, the future climatic conditions or the managerial changes which will be brought in the future are subjected to initial existing conditions and the future will be foreseen.

4. Approaches in Forest Simulation Model

There are basically three approaches for simulating the forest dynamics.

1. Empirical based modelling.
2. Process based modelling.
3. Gap modelling.

4.1 Empirical based modelling

It is developed, implied in the initial model developmental era and still being used for yield estimation and prediction. It is very simple and deterministic approach. It uses linear or non-linear relationship between the outcome and the growth determined variable to describe the relationship^[18]. It employs mathematical functions or graph curves to describe the relationship. This kind of empirical based modelling is an appropriate method for predicting the short-term forest growth and yield. This method is very useful in forecasting near future without any uncertainties^[30]. Major limitation associated with this approach includes negligence of uncertainties taking place in the ecosystem, inability of the models to predict for the variables that fall outside the range of values used during the model's development^[31].

- **Examples:** Yield tables, Density management diagrams (DMD), PROGNUM model and MaxENT models.

4.2 Process based modelling

Process based modelling approach uses the physiological processes and biophysical parameters of forest ecosystems. These models mimic most of the physiological functions of a plant, including photosynthesis, respiration, mortality, transpiration, allocation, translocation, and nutrient intake, as well as the interaction with the soil and atmosphere. Because of this, PMs can mimic how forests would react to alterations in their surroundings, such as potential climate change^[32].

This approach uses allometric equations for defining physiological process and explain the cause effect relationship. These models take account of many environmental observations like temperature, solar radiation, wind speed and direction, rainfall, vapour pressure deficit, carbon content in the atmosphere while, soil moisture, texture, pH and other physical and chemical contents at finer resolutions^[32]. Though most of the process-based models are simulating at finer resolution, few

models like 3PG, TRAGIC process at course resolution^[33, 34]. This kind of approach is a complex method, may contain various sub models upto hundreds and thousands of parameters^[27]. Large number data and preliminary studies on physiological studies are dire necessity for its implementation. Once it is developed it can be applicable across the different range of environments and to derive various outputs^[35, 36].

There are broad range of process-based models available nowadays starting from a simple 3 PG model to very complex models like ANAFORE, FORCLIM, etc.^[24, 15, 37]. Based on the applicability of the model again it ranged from individual tree models like BALANCE to a biome scale models, Biome-BGC^[38].

4.2.1 3-PG (Physiological principles in Predicting Growth) model

3-PG, a process-based model which was developed in Australia for biomass prediction in eucalyptus plantations^[15]. Now, it has been widespread through the globe and made some modifications for its application in multiple regions and stand types^[39, 40, 41, 42]. It is simple, easy to use, free available model, projecting growth in monthly time step at landscape level. Simplicity of this model attributed to the consideration of only few physiological processes to predict the total stand biomass in this model. As mentioned by Gupta and Sharma^[43], it can be used in simulations of effects of various factors like, climatic changes, forest management practices, site attributes impact on stand growth, species interactions, biomass dynamics and hydrological impacts on forest growth and development. This model integrates physiological processes with empirical relations into the C balance model through field calculations and experimental data sets. As a result, it simplifies and lowers the amount of data as well as the intricacy of the steps involved in calculation^[44]. It can be coupled with other models and remote sensing and GIS^[39, 45, 46]. These connections can be useful for large scale ecological investigation^[47, 48, 49].

Structurally 3 PG is a simple model consists of five different sub models namely, Biomass production sub-model, Assimilation and allocation sub-model, Mortality and thinning sub-model, Soil water balance sub-model and Management and outputs sub-model^[43]. Each sub models were interconnected and helps in predicting the total stand biomass. Initial stand data, climatic data, environmental factors, growth modifiers and satellite data on Absorbed Photosynthetically Active Radiations (APAR) are the necessary input for 3 PG model. Growth or production of biomass in the plant by the conversion of PAR received from sun into biomass is the key concept in this model. The quantity of growth was determined or expressed as the function of growth modifiers (Temperature (fT), Vapor Pressure Deficit (fVPD), Frost (fF), Available Soil Water (fASW), and Soil FR (fFR)) as explained in the Fig. 4.

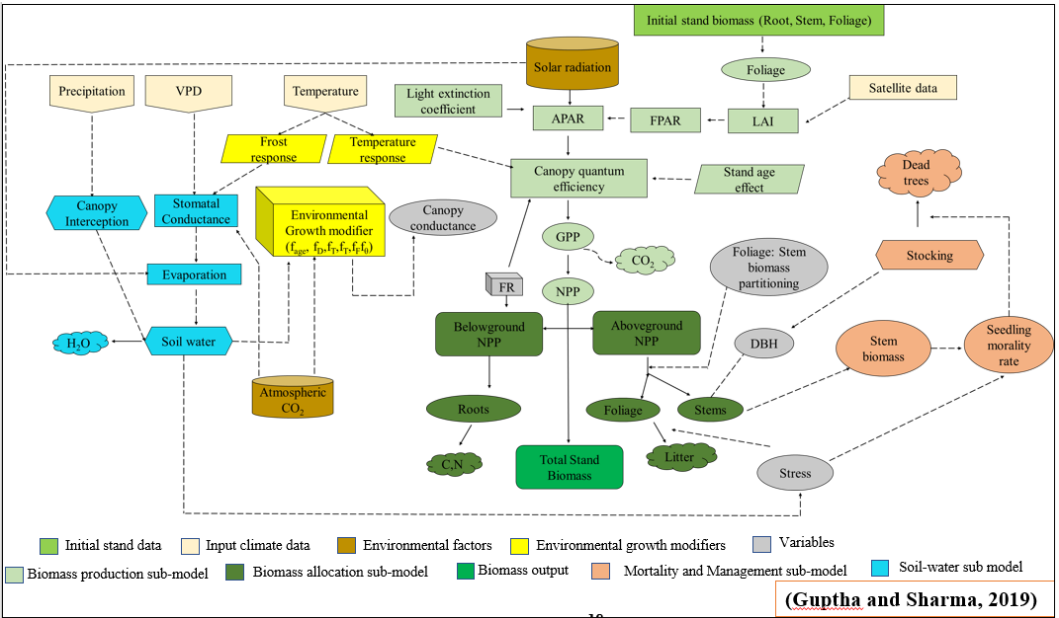


Fig 4: Workflow of 3-PG (Physiological Principles in Predicting Growth) model (adopted from Guptha and Sharma [43])

In the Indian context, there is no complex process-based modelling approach has been done but some partial remote sensing-based process-based models have been used for estimation of carbon pools in forest ecosystems [50]. For instance, Carnegie-Ames Stanford Approach (CASA) model multi-source data driven model which is greatly used forest simulation model for vegetation net primary productivity (NPP) estimation and prediction at regional scales [51]. This model describes the carbon

exchange processes between atmosphere and terrestrial biosphere [52]. Total solar radiation (SOL), fraction of absorbed photosynthetically active radiation (FPAR), water stress coefficient (WSC), temperature stress factors $T_{\epsilon 1}$ and $T_{\epsilon 2}$, and the maximum achievable efficiency (ϵ_{max}) are the parameters used in CASA model [51].

4.3 Gap modelling

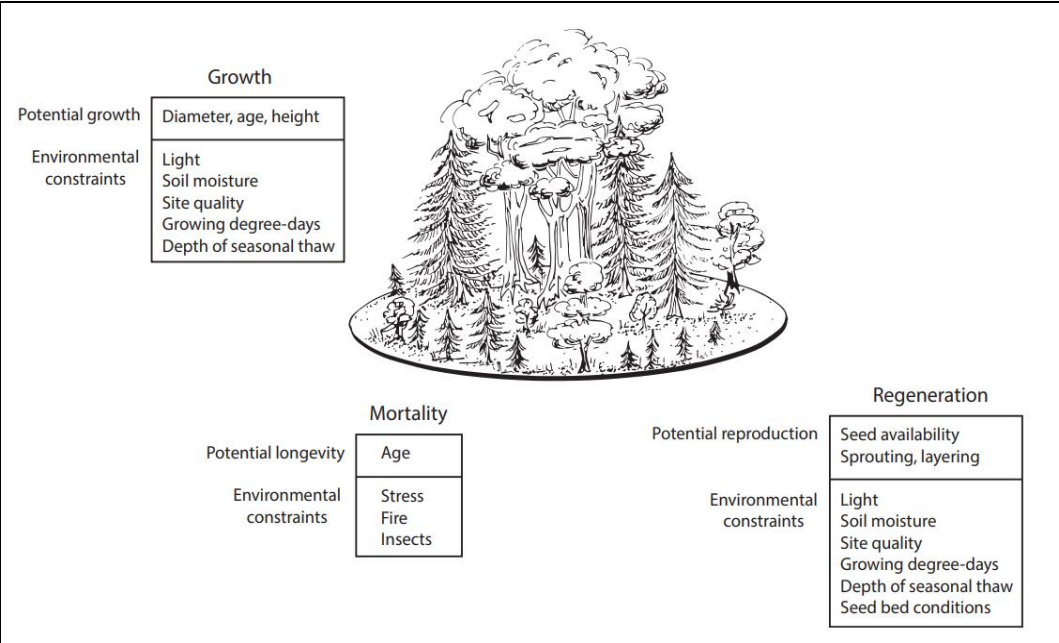


Fig 5: Major process of growth and development considered in forest gap model (Adopted from Bonan [27])

These are individual based simulation models simulates regeneration, growth and survival of the individuals in a small portion of forest area opened due to death of tree or natural calamities called ‘gap’ hence, it was named as Gap models [24]. It is also known as ‘hybrid model’, ‘forest succession model’. This approach is a mixture of stochastic mechanisms like stress-related mortality, disturbances, and successful establishment and deterministic processes like species specific growth rate, optimal increment over time and individual-tree growth response to

environmental variables [53]. Every simulated plot depicts a single, autonomous forest gap which is subjected to gap dynamics and succession over time. Several hundred of these plots are typically run at a single location, or "site," using uniform starting circumstances and site-wide characteristics. Plots differ from variations in mortality and regeneration events due to a combination of stochastic and deterministic mechanisms. Good silvicultural knowledge is dire necessary to employ this simulation model. Averaging of all simulated plots,

each representing a dynamic mosaic of forest gaps with a unique dynamical history in each given year to represent the mean expectation of the characteristics of a wooded landscape of variable size ^[54]. It principally considers three process i.e., regeneration, growth and mortality (Fig. 5). Regeneration prediction based on species-specific seed and seedling banks, which are influenced by each species' abundance on the plot, regeneration strategy, and environmental tolerances ^[55]. For individual growth it considers individual tree size, species, competition and current growth rate and its future dynamics due to changing soil conditions through changes in litter inputs and nutrient requirements ^[56, 55]. While, simulation of survival depends on tolerance to current environmental conditions and prolonged low growth or disturbances.

The basic model of gap modelling has a few limitations, it does not provide any information on the below ground biomass components which forms the significant part of total biomass and carbon. Many basic Gap models like, JABOWA, FORSKA, DIPSIM *etc.* cannot be employed for simulating to the larger areas.

5. Model selection and accuracy enhancement

5.1 Points to ponder while selecting simulation model

There are large number of simulation models available for the forester to predict the future but one has to be very careful with selecting the appropriate simulation models. Hints to select the appropriate models are listed below.

- 1. Model assumptions:** Deep knowledge about the model is essential, the model assumption should be in line with the existing condition as much as possible so that we can expect the more reliable outcome from the model. The model should represent the key process driving the changes in the area of interest. For more reliable output, select the tested and validated models in the areas similar to the interested ecosystem type ^[57].
- 2. End use or application:** The model selection should be in such a way that the selected model should be able to deal with the specific research (or management) objectives of interest like, yield estimation, carbon estimation, nutrient dynamics, water balance *etc.* ^[58]. Moreover, models vary greatly with spatial resolution, choose the model with appropriate spatial and temporal resolution fits to the interested area.
- 3. Data availability:** Input data required for initialisation and parameterisation of the models varies. Before choosing the model one has to confirm the availability or possible collection of data to fulfilment of basic necessary requirements to run the model.
- 4. Model flexibility:** Model chosen should be flexible so that it can accommodate the range of stand condition and different management options.
- 5. Less complicated model:** In the race of achieving maximum accuracy or reliability, selection of highly complicated models should be avoided as finer resolution, more accurate models require large input datasets and may confront challenges in data computation. In such cases, expensive high speed computational resources are essential.

5.2 Accuracy enhancement of simulation models

Fine-scale representation of factors such as topography, soil characteristics, and vegetation structure is captured by high-resolution data (images) aids simulation models to accurately depict the intricate relationships and feedbacks in the ecosystems. In case of extremities in variables, high quality

datasets can build or calibrate model better which is important for understanding disturbance and system resilience ^[59]. Moreover, Well-calibrated, high-resolution input datasets aid in limiting the amount of uncertainty in process representations and model parameters. As a result, predictions of factors like forest carbon stocks and sequestration potential become more accurate ^[60, 61]. After selecting the model and collecting inputs, accurate parameterization specific to the location and specific to the type of species or ecosystem is most required to increase the accuracy of the model ^[62]. Moreover, calibration of the model using sensitivity analysis and other calibration techniques in order to adjust model parameters to represent data as of observed data enhances the accuracy of the model. Large variation or limited accuracy resulted in a non-calibrated model.

Simulation models can depict the intricate interactions and feedbacks that drive system behaviour by using feedback loops to simulate the cyclical flows of influence between various system components ^[63]. These feedback loops also allow models to depict complex interactions, dynamic effects propagation, self-regulation, and learning ^[64]. As a result, simulations become more precise and realistic. Rather than using a single model to predict the output, use of a multi models for the same application or predict the same output and averaging the output of from the different models will be a wise method getting an accurate value. Model data fusion using Bayesian interface greatly reduces model biases and enhance the reliability of the models ^[65].

6. Challenges in simulation modelling

There are several challenges accompanied with the use of simulation models for prediction. First, these prediction models are complex the complexity can be very high for some complex models such that a single simulation model encompasses hundreds of sub-models and thousands of parameters to calibrate ^[27]. Foremost requirement for any model development or simulation is the adequate data representing the system. Models may not be able to accurately capture the many feedbacks, interactions, and nonlinearities that define real-world systems in the absence of enough data. Lack of high-quality data even hinders uncertainty estimation, spatial and temporal heterogeneity of the system ^[66].

Sufficient amount of initial data is essential to run model, which will be lacking in most of the regions of the world and for most of the species too. This made the simulation models useless for many of the species ^[20, 67]. Enough data are needed to estimate the parameters that control the inputs of the model. Parameter estimations are quite uncertain when there is little data, which makes simulations unreliable. In many areas still researchers lack data even for parameterization and modelling ^[6]. Fine-scale process simulation of vast landscapes can be computationally demanding -. Hardware and software developments are required to enable such simulations.

7. Conclusion

Many forest ecosystems will probably face challenges in adapting to the anticipated rapid climate change. In order to help forest managers and policymakers in developing long-term strategies, forest growth models represent a promising and available tool for predicting the effects of various climate change and management scenarios on growth of individual trees and forest stands as well as the future distribution of forest tree species under changing conditions. Among the different approaches of modelling process based enhanced hybrid models are the best models for long term predictions but the care must

be taken for selecting the suitable model based on the data availability is highly recommended.

To create more reliable simulations of forest resilience, empirical and experimental work is essential, particularly when it comes to adding additional mechanistic features to models. While process-based models are ideal, adding more process features to models is hampered by data availability. Forest simulation modelling research appears to be a dynamic and demanding field, given the need for better data acquisition, growth forecasting, successional pattern predictions, and forest management linked to ecosystem services. Other challenges include data availability and the compromise between model complexity and inferential potential. One effective method to prevent skewed estimates of single models resulting from the flaws in individual modelling methodologies is to use the multi-model averaging methodology.

There is a need for studying more fundamental physiological processes for an accurate understanding of cause-effect relationship between the different external factors and the processes. Initial data is the basic hindrance to apply simulation models in most of the forests and end applications. There is a need for a robust database collection techniques development which may help in collecting wide range of data. However, processing large quantity of databases for complex models is difficult, there is a large scope for simplification of models. Development of techniques to exchange or combine the information of two or more different models simultaneously will be definitely useful for a multi model approach implication to obtain a more reliable output from the models.

8. Competing interests

Authors have declared no competing financial or non-financial or personal interests that could have appeared to influence the work reported in this paper.

9. Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

10. References

- IUCN. Forests and Climate Change. International Union for Conservation of Nature Gland, Switzerland; c2021.
- Thom D, Seidl R. Accelerating Mountain Forest Dynamics in the Alps. *Ecosys.* 2022; 25(3):603-617.
- Kramer RD, Ishii HR, Carter KR, Miyazaki Y, Cavaleri MA, *et al.* Predicting effects of climate change on productivity and persistence of forest trees. *Ecol. Res.* 2020;35(4): 562-574.
- Renner SS, Zohner CM. Climate change and phenological mismatch in trophic interactions among plants, insects, and vertebrates. *Ann. Rev. Eco. Evol. System.* 2018;49:165-182.
- Feeley KJ, Bravo-Avila C, Fadrique B, Perez TM, Zuleta D. Climate-driven changes in the composition of New World plant communities. *Nat. Clim. Cha.* 2020;10(10): 965-970.
- Hartmann H, Bastos A, Das AJ, Esquivel-Muelbert A, *et al.* Climate Change Risks to Global Forest Health: Emergence of Unexpected Events of Elevated Tree Mortality Worldwide. *Ann. Rev. Pla. Bio.* 2022;73(1):673-702.
- Allen CD, Breshears DD. Drought-induced shift of a forest-woodland ecotone: rapid landscape response to climate variation. *Proc. Nat. Acad. Sci.* 1998;95(25):14839-14842.
- Esquivel-Muelbert A, Baker TR, Dexter KG, Lewis SL, Brien RJW, *et al.* Compositional response of Amazon forests to climate change. *Glob. Change Biol.* 2019;25:139-156.
- Scholes R, Settele J. Terrestrial and Inland Water Systems. Working Group 2 Contribution to the Fifth Assessment Report. IPCC, International Panel on Climate Change, Geneva; c2014.
- Locatelli B, Kanninen M, Brockhaus M, *et al.* Facing an Uncertain Future: How Forest and People Can Adapt to Climate Change. CIFOR, Bogor; c2008.
- Shaw MR, Pendleton L, Cameron DR, *et al.* The impact of climate change on California's ecosystem services. *Clim. Change.* 2011;109:465-484.
- Hurteau MD. The role of forests in the carbon cycle and in climate change. *Clim. Cha.* 2021;561-579.
- Doughty CE, Keany JM, Wiebe BC, *et al.* Tropical forests are approaching critical temperature thresholds. *Nature.* 2023;621:105-111.
- Kimmins JP. Forest Ecology: A Foundation for Sustainable Management, 2nd ed. Englewood Cliffs, Prentice Hall; c1997.
- Landsberg JJ, Waring RH. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *For. Ecol. Manage.* 1997;95:209-228.
- Levina E, Tirpak DENNIS. Adaptation to climate change: key terms. Organization for Economic Co-operation and Development. International Energy Agency; c2006.
- Mäkinen A. Uncertainty in forest simulators and forest planning systems. *Dissertationes Forestales (97)*, University of Helsinki, Sweden; c2010.
- Peng C. Understanding the role of forest simulation models in sustainable forest management. *Environ. Imp. Assess. Rev.* 2000;20(4):481-501.
- Larocque GR. Simulation Models of the Dynamics of Forest Ecosystems. *Forests.* 2022; 13(5):705.
- Peng C, Wen X. Forest simulation models. In: Shao G, Reynolds KM, editors. *Computer Applications in Sustainable Forest Management*, Springer, Dordrecht; c2006.
- Vuokila Y. Functions of variables density yield tables of pine based on temporary sample plots. *Commun. Inst. Forest. Fenn.* 1965;60:1-86.
- Kwa C. Local Ecologies and Global Science: Discourses and Strategies of the International Geosphere-Biosphere Programme. *Soc. Stud. Sci.* 2005;35(6):923-950.
- Potter CS, Randerson JT, Field CB, Matson PA, Vitousek PM, Mooney HA, *et al.* Terrestrial ecosystem production: A process model based on global satellite and surface data. *Glo. Biogeochem. Cycl.* 1993;7(4):811-841.
- Bugmann H. A review of forest gap models. *Climatic Change.* 2001;51:259-305.
- Botkin DB, Janak JF, Wallis JR. Some Ecological Consequences of a Computer Model of Forest Growth. *J. Ecol.* 1972;60:849-872.
- Foley JA, Prentice IC, Ramankutty N, Levis S, Pollard D, Sitch S, *et al.* An integrated biosphere model of land surface processes, terrestrial carbon balance, and vegetation dynamics. *Glo. Biogeochem. Cycl.* 1996;10(4):603-628.
- Bonan G. Climate Change and Terrestrial Ecosystem Modeling. Cambridge University Press; c2019.
- Bugmann H, Grote R, Lasch P, Lindner M, Suckow F. A new forest gap model to study the effects of environmental change on forest structure and functioning. In: Mohren GMJ, Kramer K, Sabaté S, editors. *Global change impacts on tree physiology and forest ecosystems*. Kluwer

- Academic Publishers; c1997.
29. Jorgensen SE, Fath BD. Fundamentals of ecological modelling: Applications in Environmental Management and Research (4th Ed.). Elsevier; c2011.
 30. Bossel H. Modelling forest dynamics: moving from description to explanation. *Forest Ecol. Manage.* 1991;42:129-142.
 31. Kimmins JP. Modeling the sustainability of forest production and yield for a changing and uncertain future. *Forest Chron.* 1990;66:271-280.
 32. Bosela M, Merganičová K, Torresan C, Cherubini P, Fabrika M, *et al.* Modelling future growth of mountain forests under changing environments. In: Tognetti R. editor. *Climate-Smart Forestry in Mountain Regions*; c2022.
 33. Hauhs M, Kastner-Maresch A, Rost-Siebert K. A model relating forest growth to ecosystem-scale budgets of energy and nutrients. *Ecol. Model.* 1995;83:229-243.
 34. Forrester DI, Tang X. Analysing 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.* 2016;319:233-254.
 35. Fontes L, Bontemps JD, Bugmann H, Van Oijen M, Gracia C, *et al.* Models for supporting forest management in a changing environment. *For. Sys.* 2010;19:8-29.
 36. Coops NC, Waring RH. A process-based approach to estimate lodgepole pine (*Pinus contorta* Dougl.) distribution in the Pacific Northwest under climate change. *Clim. Change.* 2011;105:313-328.
 37. Deckmyn G, Verbeeck H, Op de Beeck M, *et al.* ANAFORE: A stand-scale process-based forest model that includes wood tissue development and labile carbon storage in trees. *Ecol. Modell.* 2008;215:345-368.
 38. Thornton PE, Running SW, Hunt ER. Biome-BGC: terrestrial ecosystem process model, Version 4.1. 1. ORNL DAAC; c2005.
 39. Coops NC, Waring RH. Estimating forest productivity in the eastern Siskiyou Mountains of southwestern Oregon using a satellite-driven process model, 3-PGS. *Can. J. For. Res.* 2001;31:143-154.
 40. Esprey LJ, Sands PJ, Smith CW. Understanding 3-PG using a sensitivity analysis. *For. Ecol. Manag.* 2004;193:235-250.
 41. Stape JL, Ryan M, Binkley D. Testing the utility of the 3-PG model for growth of *Eucalyptus grandis* x *europhylla* with natural and manipulated supplies of water and nutrients. *For. Ecol. Manag.* 2004;193:219-234.
 42. Rodríguez-Suárez JA, Soto B, Iglesias ML, Diaz-Fierros F. Application of the 3-PG forest growth model to a *Eucalyptus globulus* plantation in Northwest Spain. *Eur. J. For. Res.* 2010;129:573-583.
 43. Gupta R, Sharma LK. The process-based forest growth model 3-PG for use in forest management: A review. *Ecol. Modell.* 2019;397:55-73.
 44. Silva Da WCM, Ribeiro A, Neves JCL, de Barros NF, Leite FP. Water balance model and eucalyptus growth simulation in the Rio doce basin, Brazil. *Acta Sci.* 2013;35:403-412.
 45. Feikema PM, Morris JD, Beverly CR, Collopy JJ, Baker TG, Lane PNJ, *et al.* Validation of plantation transpiration in south-eastern Australia estimated using the 3-PG+ forest growth model. *For. Ecol. Manag.* 2010;260:663-678.
 46. Waring RH, Coops NC, Running SW. Predicting satellite-derived patterns of large-scale disturbances in forests of the Pacific Northwest Region in response to recent climatic variation. *Remote Sens. Environ.* 2011;115:3554-3566.
 47. Nolé A, Law BE, Magnani F, Matteucci G, Ferrara A, Ripullone F, Borghetti M, *et al.* Application of the 3-PGS model to assess carbon accumulation in forest ecosystems at a regional level. *Can. J. For. Res.* 2009;39:1647-1661.
 48. Adhikari A, White JD. Climate change impacts on regenerating shrub land productivity. *Ecol. Model.* 2016;337:211-220.
 49. Coops NC, Waring RH, Plowright A, Lee J, Dilts TE. Using remotely-sensed land cover and distribution modeling to estimate tree species migration in the Pacific Northwest Region of North America. *Remote Sens.* 2016;8:1-15.
 50. Pal MK, Pradhan PM. Estimation of Net Primary Productivity Using CASA Biosphere Model in Hyderabad and Roorkee Region of India. In: Nanda SJ, Yadav RP, Gandomi AH, Saraswat M, editors. *Data Science and Applications. ICDSA 2023. Lecture Notes in Networks and Systems, Vol 819.* Springer, Singapore; c2024.
 51. Wu C, Chen KEC, You X, He D, Hu L, *et al.* Improved CASA model based on satellite remote sensing data: simulating net primary productivity of Qinghai Lake basin alpine grassland. *Geosci. Model Dev.* 2022;15(17):6919-6933.
 52. Cramer W, Kicklighter DW, Bondeau A, Moore III B, Churkina G, *et al.* The Participants of the Potsdam NPP Model Intercomparison: Comparing global models of terrestrial net primary productivity (NPP): overview and key results. *Global Change Biol.* 1999;5:1-15.
 53. Shugart HH, Foster A, Wang B, *et al.* Gap models across micro- to mega-scales of time and space: Examples of Tansley's ecosystem concept. *For. Ecosyst.* 2020;7:14.
 54. Shugart HH, Seagle SW. Modeling forest landscapes and the role of disturbance in ecosystems and communities. In: Pickett STA, White PS, editors. *The ecology of natural disturbance and patch dynamics.* Academic Press, San Diego; c1985.
 55. Yan X, Shugart HH. FAREAST: A forest gap model to simulate dynamics and patterns of eastern Eurasian forests. *J. Biogeogr.* 2005;32:1641-1658.
 56. Pastor J, Post WM. Development of a linked forest productivity-soil process model. Environmental Sciences Division Publication, USDOE, Oak Ridge National Laboratory; c1985.
 57. Newnham RM. Simulation Models in Forest Management and Harvesting. *For. Chron.*; c1968. p. 7-13.
 58. Shanin VN, Komarov AS, Bykhovets SS. Simulation modelling for sustainable forest management: a case-study. *Proce. Environ. Sci.* 2012;13:535-549.
 59. Yang Q, Meng FR, Bourque CPA, *et al.* Production of high-resolution forest-ecosite maps based on model predictions of soil moisture and nutrient regimes over a large forested area. *Sci. Rep.* 2017;7:10998.
 60. Ma L, Hurr G, Tang H, Lamb R, Campbell E, *et al.* High-resolution forest carbon modelling for climate mitigation planning over the RGGI region, USA. *Environ. Res. Lett.* 2021;16(4):045014.
 61. Malle JT, Mazzotti G, Karger DN, Jonas T. Regionally optimized high resolution input datasets enhance the representation of snow cover and ecophysiological processes in CLM5, EGUspHERE; c2023.
 62. Sun J, Mao F, Du H, Li X, Xu C, Zheng Z, *et al.* Improving the Simulation Accuracy of the Net Ecosystem Productivity of Subtropical Forests in China: Sensitivity Analysis and Parameter Calibration Based on the BIOME-BGC Model. *Forests.* 2024;15(3):552.
 63. Naugle A, Verzi S, Lakkaraju K, Swiler L, *et al.* Feedback

- density and causal complexity of simulation model structure. *J. Simul.* 2021;17(3):229-239.
64. Wynn DC, Maier AM. Feedback systems in the design and development process. *Res. Eng. Design.* 2022;33:273-306.
65. Trotsiuk V, Hartig F, Cailleret M, *et al.* Assessing the response of forest productivity to climate extremes in Switzerland using model-data fusion. *Glob. Chang. Biol.* 2020;26: 2463-2476.
66. Suárez-Muñoz M, Mina M, Salazar PC, Navarro-Cerrillo RM, Quero JL, Bonet-García FJ, *et al.* A Step-by-Step Guide to Initialize and Calibrate Landscape Models: A Case Study in the Mediterranean Mountains. *Front. Ecol. Evol.* 2021;9:653393.
67. Wu M, Feng Q, Wen X, Deo RC, Yin Z, Yang L, *et al.* Random forest predictive model development with uncertainty analysis capability for the estimation of evapotranspiration in an arid oasis region. *Hydro. Res.* 2020;51(4):648-665.
68. He HS, Yang J, Shifley SR, Thompson FR. Challenges of forest landscape modelling- Simulating large landscapes and validating results. *Lands. Urb. Plann.* 2011;100(4):400-402.