Forest Ecosystem Modeling for Policy Planning: A Review

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Abstract

Vegetation modeling is an advanced tool that helps to understand the current forest ecosystem dynamics and provides a peek into future possibilities. In the era of climate change, projecting and monitoring different ecosystem elements and biodiversity are critical in supporting the management and conservation of forest ecosystems. Quantitative models are often used to understand and project the "impact of climate change" and the associated disturbances in forest ecology. Here we present a review of different ecosystem modeling approaches, exploring their potential applications to understand changing forest dynamics and climate change adaptation options in forest ecosystems. This comprehensive and comparative study helps us to get insights into the advantages and limitations of the various modeling-based approaches, providing a guideline for systematic execution of policy assessment according to a defined criteria (e.g., uncertainty management, data required, spatial and temporal dynamics, adaptation measures integration, and level of complexity). Further, we present an overview of ecosystem modeling and its usability for global policy planning in the forest sector. Finally, we suggest ways to use these advanced tools to help policy planning for conservation, restoration, and climate change adaptation in forest ecosystems.

Keywords

Vegetation modeling · Forest · Policy

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24.1 Introduction

Greenhouse gas build-up in the atmosphere and rising temperatures have already caused widespread losses and damages to nature, ecosystems, and people (IPCC 2022). Observed climate change has caused substantial damages, and irreversible losses, to many of the terrestrial ecosystems across the world including the forest ecosystems. These changes include increase in burned area by wildfires, shifting of species poleward and to higher elevations, among other examples. Global temperatures have so far risen by only 1.1 °C, even this small change in global temperatures has already caused irreversible losses and damages in forest ecosystems across the world. Under different climate change scenarios, global temperatures are expected to rise to 2.5–4 °C range (IPCC 2021), even in India. Chaturvedi et al. (2012) suggest that under business-as-usual scenario, the temperatures are likely to rise to 3.3–4.8 °C by 2080s. It is important to understand as to how the projected climate change may affect forest ecosystems in different future warning scenarios. IPCC AR4, WG2 report concluded that one of the most advanced tools to assess the impact of climate change on vegetation dynamics/ terrestrial ecosystems is dynamic global vegetation models (DGVMs) (Fischlin et al. 2007). Vegetation modeling, an emerging sophisticated tool, is being developed to understand ecosystem dynamics and predict future scenarios. The ecosystem model is defined as "a model that explains the interconnection between at least two ecosystem components, where the interactions are true ecological processes" (Tylianakis et al. 2008). Recently, unregulated anthropogenic emissions of warming gases and consequent climate change have been posing severe threats to the protected areas of the environment (IPCC 2022). Moreover, the rising population and demand for resources amplify agricultural expansion and extensive land-use changes, thereby destroying habitats and leading to species extinction (Newbold et al. 2014). Vegetation modeling will help the scientific community to monitor and understand complex environmental dynamics and develop long-term policy measures for effective management (Pasetto et al. 2018). Moreover, modeling biodiversity and ecology would further support the implementation of sustainable development whereby an understanding of resource utilization is obtained through this process (Niesenbaum 2019).

The concept of ecological modeling and its evolution began a century ago (Lotka 1925; Volterra 1926), but technological advancement, as seen within the past decade, has brought significant development in using these models (Chatzinikolaou 2013). The forest ecosystem is also uncertain due to the potential impacts of the changing climate (Keenan 2015; Nunes et al. 2021). Several forest simulation models predict that the forest composition and comprehensive coverage will cease in the future due to unpredictable consequences of climate change (Kirilenko and Sedjo 2007; d'Annunzio et al. 2015). Forest vegetation models have been coded to perform on various scales such as the leaf, stand, ecosystem, and regional and global levels incorporating various processes (such as photosynthesis, stomatal exchange, and evapotranspiration) (Hui et al. 2017). Farquhar's photosynthesis model estimates carbon budget and plant growth at leaf and canopy level, approximating the plant canopy to be a big leaf (Chen et al. 1999; Wang et al. 2017). On the regional and global scale, various ecosystem models have evolved; for instance, Schaefer et al. (2008) applied the Carnegie-Ames-Stanford Approach (CASA) model to estimate terrestrial biomass and carbon fluxes. They created a hybrid model by integrating the Simple Biosphere (SiB 2.5) model that provides biophysical and photosynthesis with the CASA model, which was able to project long-term carbon sources and singles that the individual models could not have. The terrestrial ecosystem carbon model (TECM) is another process-based model that explains the carbon dynamics of soils and plants within the terrestrial ecosystem (Wang et al. 2011). TECM mainly utilizes information on spatially explicit parameters in terrestrial ecosystems to calculate the estimates of carbon pool sizes and carbon fluxes. Schaphoff et al. (2018) provide an extensive overview of the latest version of LPJmL4, a process-based dynamic global vegetation model (DGVM) project, which is the consequence of climate and land use changes on the agriculture, terrestrial biosphere, and hydrological and carbon cycle. Joint U.K. Land Environment Simulator (JULES) is an improved model based on MOSES and TRIFFID DGVM, which includes a multitude of options for photosynthesis scaling from leaf to canopy, with the utmost intricate modeling of light interception profile through the vegetation (Clark et al. 2011).

Modeling helps policymakers anticipate the impacts of ecosystem degradation on human actions and projects future scenarios based on direct and indirect factors. Simulation of interaction between humans and the environment is essential for summiting the pathways to Sustainable Development Goals 2030. Despite all advancements in Vegetation modeling, it is evident that the research community has used a few models for management and decision-making processes, given the complexity of understanding mathematical models (DeAngelis et al. 2021). In this study, we attempt to review different Vegetation modeling approaches and explore their potential to understand forest dynamics and their applications in climate change adaptations.

24.2 Vegetation Modelling: From Correlative to Process-Based Approaches

Models are valuable tools for summarizing, arranging, and combining information or data into formats that enable the creation of probabilistic, quantitative, or Bayesian statements regarding the potential or future condition of the modeled entity (Duarte et al. 2003). Based on the complexity and degree of formalization, the Vegetation modeling can be sub-segmented into correlative, process-based, and expert-based models (Ferrier et al. 2016). Traditionally, the most common method of management was based on information provided by experts (Sutherland 2006). The term “expert” can be defined as one who attained a highly precise skill set in a specific field through learning experience (Kuhnert et al. 2010). An expert-based method generally comprises the following steps as described: deciding on how the information is to be used, what to bring out from it, designing the elicitation process, actual conducting the elicitation, and finally converting the output into quantitative statements that can be applied to a modeling approach (Martin et al. 2012). This approach has a time advantage over other models when the final decision is to be made exceptionally quickly with minimal data.

Correlative models use statistical techniques to develop the direct connection between biodiversity data (species abundance, richness, distribution) and environmental variables (Morin and Lechowicz 2008; Li et al. 2020). Based on actual observation data, correlative models generate information on biodiversity trends and their responses to the controlling factors, but they do not make an attempt to describe the mechanisms behind such patterns and reactions. They are usually used to forecast the future impact of environmental changes, the effects on biodiversity by human intervention, to help human production activities (increasing agricultural production), and to understand the ecological requirements for different species (Rahbek et al. 2007; Elith and Franklin 2013; Cobos et al. 2019). Since these models are designed based on data from the past state of the system, rapid decisions based on statistical relationship is feasible (Cuddington et al. 2013). However, under the current climate change conditions, models based on the previous data of a system are not suitable for future simulations (Williams et al. 2007). For example, many studies have predicted changes in species range based on climatic conditions in India. Models such as MaxEnt and SMCE use climatic data and species occurrence data of a particular location to develop a correlation and predict the future species range under climate change (Nimasow et al. 2016; Yadav et al. 2022). However, they deny including relevant ecological processes such as interspecific interactions and demographic relationships, which can also limit the species range, and their effect may not be included in future predictions.

Process-based models that work based on understanding critical ecological processes from a theoretical perspective give a suitable framework for including specific responses to changing environmental conditions (Cuddington et al. 2013). These are often more challenging to design than correlative models, because they need considerable information on factors that drive biodiversity patterns (Ferrier et al. 2016). There are many types of process models, for example, gap models, biogeochemical models, and DGVMs. Gap models are applied to investigate changes in vegetation and species interactions at significantly higher spatial resolution (plots the size of a single canopy gap or individual trees) across daily to yearly time steps. However, simulation of dynamics over several stands and cells is achievable. Biogeochemical models project carbon, water, and mineral (nutrient) cycles in terrestrial ecosystems such as forests. In climate change research, these models are widely applied to predict ecosystem net primary production, carbon flow, and storage. DGVMs project changes in vegetation attributes (such as leaf area and phenology) across annual to decadal time steps at vast geographical scales (Kerns and Peterson 2014) (more details on DGVMs are available in Sect. 24.3.2). However, Hybrid models are a combination of empirical and mechanistic components. There are two kinds of hybrid models: the first one integrates process-based empirical models by creating signal-transfer environment productivity functions, and the second one includes a causal structure with both empirical and mechanistic components (Luxmoore et al. 2002; Pretzsch 2009).

24.3 Vegetation Modeling at Leaf, Individual, Plot, Regional, and Global Levels

Vegetation models are designed at various scales, ranging from the leaf to the plant canopy and at the plot, regional, and global levels. These models mainly project phenomena such as photosynthesis and respiration, carbon distribution between plant organs, nitrogen uptake and mineralization, litter production, and Soil Organic Carbon (SOC), and these processes are used to understand the carbon fluxes between the atmosphere, soil, and plants (Hanson et al. 2004).

24.3.1 Leaf and Stand Models

At the leaf level, *Farquhar, von Caemmerer, and Berry* (FvCB) is the most commonly used model for projecting photosynthesis and leaf-level carbon and water fluxes (Rogers et al. 2017). The photosynthesis module predicts leaf-level carbon uptake based on biochemical or physiological characteristics, as well as the abiotic environment (intercellular CO_2 concentration and temperature). Similarly, stomatal modules connect the intercellular leaf space to the canopy air space and biophysically constrain carbon and water fluxes from the perspective of gas diffusion (Xu and Trugman 2021). Individual tree growth models such as *BWIN*, *Prognaus*, *Silva*, and *Moses* are widely used for predicting the influence of climate change on tree development, yield predictions, and ecosystem fluxes (Vospernik 2017). Most growth models are designed based on the mass balance method and consider organic matter decomposition, ecosystem fluxes (forest), and water balance. Hence, these models can evaluate above- and below-ground biomass production and assess carbon dynamics for a particular location (Hui et al. 2017). Table 24.1 represents some of the widely used individual and strand-level models (the table is classified based on type, spatial structure, and temporal structure).

Climate change affects specific physiological processes in plant species, such as photosynthesis, respiration, and growth, and can be investigated by different models. While certain models focus on the impact of elevated CO_2 concentration on the ecosystem, others, especially biogeochemical models, simulate the consequences of various climatic factors on the forest ecosystem carbon cycle. The physiological principles predicting growth (3-PG) model was developed to connect the traditional, mensuration-based growth and yield with process-based carbon balance models. Gross primary production (GPP) in forest ecosystems is mostly estimated using 3-PG process-based model at the stand level. By combining remote sensing and GIS techniques, the upgraded version of 3-PGS (physiological principles in predicting growth with satellite) estimates biophysical variables, including LAI (leaf area index), CWC (canopy water content), and FAPAR (fraction of absorbed

Table 24.1 The leaf and stand-level Vegetation models and classification based on temporal and spatial structure

Sl. no.	Model name	Type	Spatial structure	Temporal structure	Reference
1	3-PG	Process-based	Stand or cohort	Monthly	Almeida et al. (2004)
2	PNET (-C.N., -DAY)	Process-based	Stand	Monthly/ daily	Aber et al. (1997)
3	BWIN PRO	Empirical model	Individual	5 year	Albrecht et al. (2011)
4	SIMWAL	Process-based	Individual	Hour	Balandier et al. (2000)
5	EMILIION	Process-based	Individual	1/50 day	Bosc (2000)
6	Hybrid	Process-based	Individual	Daily	Friend et al. (1997)
7	BALANCE	Process-based	Individual	Daily	Rötzer et al. (2010)
8	FORECAST	Hybrid model	Individual	Yearly	Kimmins et al. (1990)
9	TREE-BGC	Process-based	Individual	Daily	Korol et al. (1995)
10	FORGEM	Process-based	Individual	Daily	Kramer et al. (2008)
11	TREEMIG	Process-based	Cohort	Yearly	Lischke et al. (2006)
12	CO2FIX V.2	Empirical model	Cohort	Yearly	Masera et al. (2003)
13	WOODPAM	Process-based	Stand	Monthly	Peringer et al. (2013)
14	BIOME-BGC	Process-based	Stand	Daily	Pietsch et al. (2003)
15	SILVA	Hybrid model	Individual	5 year	Pretzsch et al. (2002)
16	YIELD-SAFE	Process-based	Individual	Daily	Van der Werf et al. (2007)

photosynthetically active radiation), which can be used to simulate forest biomass and productivity at regional level (Gupta and Sharma 2019).

Similarly, Yan et al. (2011) applied the PnET-CN model to describe the carbon sequestration potential using biogeochemical cycles of carbon (C) and nitrogen (N); they also validated the output using the data from coniferous forests in south China. EMILION model can be used to project the carbon budget of current branches based on their age and position within the crown, considering parameters such as distribution of light and interception, respiration, photosynthesis, transpiration, stomatal conductance, phenology, water transfer, and intra-annual growth by utilizing an object-oriented approach (Bosc 2000). FORECAST Climate model operates through a hybrid simulation approach, representing moisture and temperature availability on tree growth and survival and nutrient cycling, litter decomposition, and also representing the impact of growing CO_2 on water use efficiency (Seely et al. 2015).

24.3.2 Regional and Global Ecosystem Models

Understanding the ecosystem response to climate change on a global scale is essential both as a scientific question and for making policy decisions. The accuracy of regional models depends on how effectively the field data used for model development represents the region of interest (ROI), how accurate the environmental model driving variables (vegetation type, climate) represent the ROI, and the accuracy of the model prediction and observe data for the region (Olson et al. 2001). In this section, we will explain different DGVMs, which are mainly used globally and in India.

DGVM is a computational-based model that simulates terrestrial vegetation and the phenomenon and processes related to it; broadly speaking, the biogeochemical or hydrological cycles and the influence climatic parameters have on them. It is powerful enough to capture the transition in the forest ecosystem due to the influence of one or more input parameters from climatic variables to soil parameters (Kumar et al. 2018). Fischlin et al. (2007) suggested that one of the most advanced tools to assess the impact of climate change on vegetation dynamics/terrestrial ecosystems is dynamic global vegetation models (DGVMs). Prentice (1989) put forward the first outline for DGVMs (Fig. 24.1). In DGVMs, time series datasets are fed to replicate the ecological processes and the way they influence the establishment of dominant forest vegetation. DGVMs were needed because static vegetation was incapable of including the plant life cycle, and various cyclic processes such as carbon cycle and nitrogen cycle were not integrated, nor were considered the various anthropogenic and natural disturbances and climatic extremes (Quillet et al. 2010). The important processes represented in DGVMS are (1) terrestrial or surface processes, including energy flow and water budget; (2) carbon flux and plant growth as part of the carbon cycle; (3) plant establishment, completion, and mortality as vegetation dynamics; and (4) natural and anthropogenic disturbances such as a forest fire, overgrazing, land-use change, and storms (Korappath and Bilyaminu 2022). Table 24.2 represents a few DGVMs and required input parameters and outputs.

Although a PFT (plant functional types)-based approach is employed in most of the DGVMs rather than an individual species-based approach, much information about species type is suppressed on the regional scale rather than on the global scale, to the point where the dominant species may be excluded. The necessity to input high-resolution land use datasets for accurate energy and water cycle measures in coupled model systems such as RCM-DGVM improved model performance and accurate projections. It also requires modifying the parameters for their applicability at a regional scale (Myoung et al. 2011). In India, several studies are available where DGVMs have been applied to assess the impact of climate change on forest

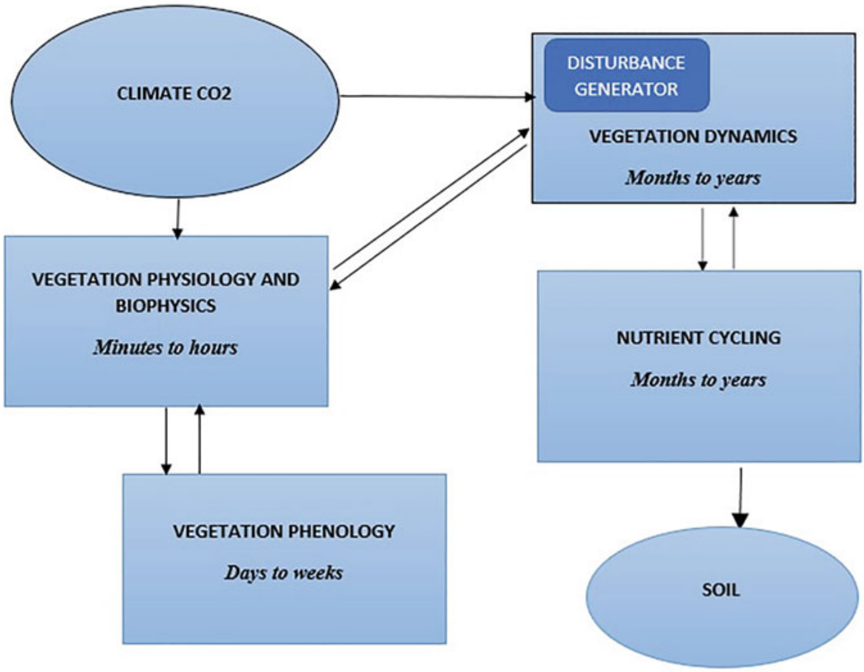

Fig. 24.1 The general framework and mechanisms of a DGVM and its time scale (adapted from Cramer et al. 2001)

ecosystems (Chaturvedi et al. 2011, 2012; Gopalakrishnan et al. 2011; Kumar et al. 2018).

24.4 Modeling and Policy-Making

The first National Forest Policy in India lead back to 1894, the British era. The policy was formulated to benefit the British Empire, restricting local people from utilizing forest resources and large-scale commercial deforestation by the East India Company. After independence, the National Forest Policy, 1952 was India's first forest policy; it was formulated with the concern about the need for efficient forest management and to prevent forest exploitation after the havoc of mindless deforestation during the colonial era. It incorporated every aspect that the world is concerned about today, such as protection measures, community interactions and administrative measures by the government, the scope for research, and annual budget allotment, which are mentioned and have evolved. It is also argued that to increase the forest cover to about one-third of the total land area today, we need even more robust and reliant policies to not only manage and protect the forest cover today but also the future and revive the already ailing forest regions. Making

Table 24.2 Major DGVMs that are broadly used in India and globally; we also represent the required inputs, outputs, and plant functional type (adapted from Aaheim et al. 2011, Kumar et al. 2018)

Model	Required input	PFTs	Output	Description
IBIS	1. Longitude and latitude (m) 2. Monthly mean temp. (°C) 3. Monthly mean temp. range (°C) 4. Minimum temp. ever recorded minus avg. temp. of the coldest month (°C) at that location 5. Mean "wet" days per month (days) 6. Monthly mean precipitation rate (mm/day) 7. Monthly mean relative humidity (%) 8. Monthly mean cloudiness (%) 9. Percentage of sand (%) 10. Percentage of clay (%)	Temperate broad-leaf evergreen Tropical broad-leaf evergreen Tropical broad-leaf drought-deciduous Temperate broad-leaf cold-deciduous Boreal conifer evergreen Boreal broad-leaf cold-deciduous Temperate conifer evergreen Boreal conifer evergreen Boreal broad-leaf cold-deciduous Boreal conifer cold-deciduous Evergreen shrub Cold-deciduous shrub	Average evapotranspiration Soil temperature Fractional cover of canopies Height of vegetation canopies Leaf area index NPP Total soil carbon and nitrogen Average sensible heat flux Vegetation types (IBIS classification) Total carbon from the exchange of CO_2	IBIS is recognized as the first model of its kind. It guides the researchers to develop improved global dynamic models with a better understanding to simulate the impacts of climate change on forests and their ecological processes. IBIS is a framework that combines land surface, vegetation dynamics, biogeochemical cycles, and hydrological processes. IBIS allows for the simulation of both short-term physiological processes and long-term ecosystem dynamics, which can be effectively included in atmospheric models. (Foley et al. 1996; Kucharik et al. 2000)
JULES	1. Longitude of the region 2. Temperature (°C) 3. Daily mean precipitation 4. Frequency of wet days 5. Incoming short- and long-wave	Broad-leaf trees Needle leaf trees C3 (temperate) grasses C4 (tropical)	Soil temperature Soil moisture Surface runoff Plant respiration Soil evaporation Gross primary productivity NPP Soil respiration	The Hadley Centre climate model includes the Joint U.K. Land Environment Simulator (JULES) to represent the land surface. It parameterizes the

(continued)

Table 24.2 (continued)

Model	Required input	PFTs	Output	Description
	radiation (W m^{-2}) 6. Diurnal temp. range (K) 7. Specific humidity 8. Wind speed	grasses Shrubs	Surface fluxes of heat Surface fluxes of carbon	hourly flows of energy, water, and CO_2 from the ground to the atmosphere. By developing seasonal stores of energy, water, and carbon budget, it can simulate changes in vegetation from decade to century (https://jules.jchmr.org/)
Biome-BGC	1. Altitude 2. Mean monthly values of precipitation (mm) 3. Temperature (°C) 4. Cloud cover (%) 5. Available water capacity of the topsoil 6. AWC of the subsoil	Tropical evergreen Temperate broad-leaved evergreen Summer green Tropical rain green Temperate evergreen conifer Boreal evergreen Temperate boreal deciduous Temperate grass Tropical/ warm-temperate grass	1. Annual total precipitation (mm/yr) 2. Annual average air temperature (°C) 3. The annual maximum value of the projected leaf area index 4. Annual total evapotranspiration (mm/yr) 5. Annual total outflow (mm/yr) 6. Annual total NPP 7. Annual total net biome production	Biome-BGC is a model that estimates the fluxes and storage of energy, water, carbon, and nitrogen for the plant and soil components of terrestrial ecosystems. Because its algorithms depict physical and biological processes that influence energy and mass flows, it is a process model
LPJ	1. Daily air temperature (°C) 2. Precipitation (mm) 3. Solar radiation (W m^{-2}) 4. CO_2 concentration (ppm) 5. Soil texture (%) 6. Temperature (°C) 7. Soil water content	Tropical broad-leaved rain green Temperature needle-leaved evergreen Tropical broad-leaved evergreen Temperate broad-leaved evergreen Temperate	Vegetation structure PFTs Biomass carbon	Lund-Potsdam-Jena (LPJ) is a powerful model for studying the impacts of climate change on global vegetation (Sitch et al. 2003)

(continued)

Table 24.2 (continued)

Model	Required input	PFTs	Output	Description
		broad-leaved summer green Boreal needle-leaved evergreen Boreal needle-leaved summer green		
LPJmL	1. Temperature (°C) 2. Precipitation (mm) 3. Rainy days 4. Cloud cover (%) 5. Atmospheric CO_2 6. Soil texture (%) 7. Potential evapotranspiration 8. Soil temperature PFTs	Temperate needle-leaved evergreen Temperate broad-leaved evergreen Tropical broad-leaved evergreen Temperate broad-leaved summer green Tropical broad-leaved rain green Boreal summer green Boreal needle-leaved evergreen C3 herbaceous C4 herbaceous	GPP NPP Net ecosystem exchange (NEE) Autotrophic and heterotrophic respiration Vegetation carbon Soil carbon	LPJmL is a dynamic global vegetation, hydrology, and crop model that incorporates the carbon, water, and nitrogen cycles at the plant and soil levels. It is based on an extended Farquhar photosynthesis scheme, stomatal conductance mechanics, and functional and allometric principles, and it can represent managed and natural ecosystems and the biogeochemical fluxes between them

decisions that will have its impact, even after centuries, is not easy and needs scientific insights to formulate, thus compelling us to use the Vegetation model to get insights into the future.

Over the years, Vegetation models have become increasingly dynamic and are increasingly accepted to support computer-based forest policy-making by creating scenarios and projections representing the future of plant growth, forest productivity, carbon sink estimation, and other parameters. Ecology-based models are necessary for environmental arbitrament support and pro-environment policy formulation because they allow the effects of alternative management to be explored spatiotemporally and empirically. However, because environmental issues are so important, further evaluation of the model quality and applicability is essential, particularly if vegetation models are used to support decisions that impact the real world for the sustainability of the ecosystem. Modeling and policy-making interact in specific policy processes, but the relationship is less explored (Rykiel Jr 1996). We will try to discuss how Vegetation models support or might support the process of political decision-making processes. First, we go through the model evaluation process, which includes six steps, as identified by Jacqueline Augusiak and the team in 2014. The primary six elements of the evaluation process are (1) "data evaluation," scrutinizing the data used for model formulation and testing; (2) "conceptual model evaluation," understanding model complexity, design, and assumptions; (3) "implementation validation," testing the execution of equations used and the computer programs run; (4) "model output validation," comparisons of model output with the patterns that shape the model built and the calibrations made; (5) "model analysis" estimating model's sensitivity to parameter alteration; and (6) "model output corroboration," comparability of the model output with other datasets or different model output for the developmental purpose (Thacker et al. 2004). The multidimensional complexity of environmental concerns is addressed with the help of mathematical and statistical concepts and computer-based models; we need systematic checking of various building blocks of a model throughout its lifecycle and evolution to a guaranteed reduction in uncertainties and easy to use so that meaningful insights can be drawn, which will act as a basis for policy developmental plans.

The policy cycle can be summed up in four steps (Fig. 24.2): (1) "agenda or target setting," for achieving ecological sustainability; (2) "policy formulation and adaptation," by the governing bodies, guided by forest ecology experts; (3) "policy implementation," with the help of experts and computer-based modeling for predicting the future impacts of the agendas; and (4) "policy evaluation," analysis of the implemented policy and expanding the scope (Jordan 2001). The models act as an input for policymakers, or the policymakers' decision has to impact the modelers and sips into the models. For example, the t33% of forest cover India had been presenting as a goal to be met is a decision made by policymakers in 1952 and is still practically the basis of target fixing for all modelers working over the Indian region, thus influencing the model as well. So, it is essential to understand and realize how and when Vegetation models influence policy-making and how and when policymakers influence a model's built or structural design. The basic interaction between policy-making, society, forest ecosystem, and modeling is briefly described in Fig. 24.3.

24.4.1 Policy-Making: Ecological Sustainability and Conservation

The government of India has used outcomes of static and dynamic vegetation models to report to UNFCCC (United Nations Framework Convention on Climate Change) about the vulnerability of its forest ecosystem, as part of its various national

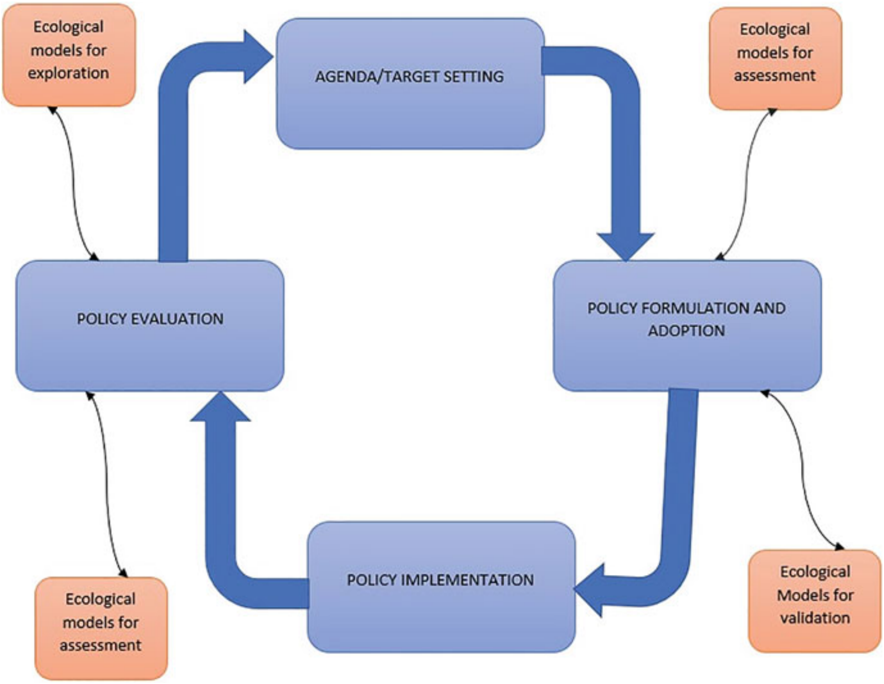

Fig. 24.2 The policy cycle and the possible use of models at various stages (adapted from Süsser et al. 2020)

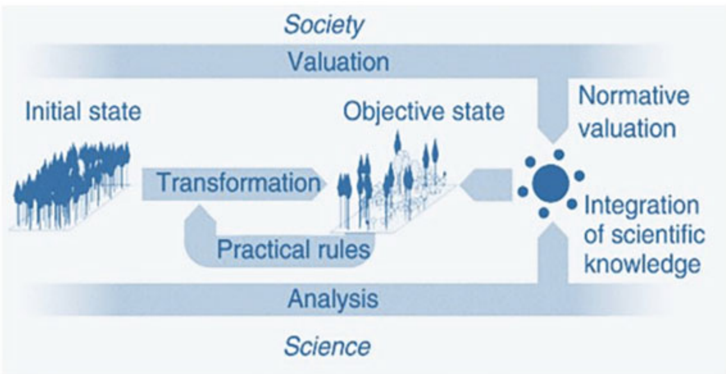

Fig. 24.3 Management concept for forest ecosystems. A system is converted from a starting state to a target state. Society's normative valuation and scientific knowledge contribute to the growth and accomplishment of the desired state (adapted from Süsser et al. 2021)

communications to the global body. For example, India's initial national communication to UNFCCC (MoEF 2004) used BIOME-3 vegetation response model to simulate the impact of climate change on Indian forests and to identify vulnerable grids in Indian forests. This analyses further reported projected shifts in Indian forest boundaries, changes in forest types, shifts in NPP, potential forest die-back, and possible loss or change in biodiversity under changing climate scenarios. Similarly, in 2012, as part of its second national communication, India used a dynamic vegetation model, namely "IBIS" (MoEFCC 2012). Similarly, the latest report to UNFCCC from China shows that according to the results of the multimodel ensemble analyses, the forest area exposed by decreasing NPP will reduce during low greenhouse gas (GHG) concentration scenarios. In contrast, it is also projected that at a high GHG concentration scenario, the forest area affected by decreasing NPP will increase after 2050, from 5.4% (2021–2050) to 27.6% (2071–2099) of the total forest area.

Let us look into some of the adaptive measures by making changes in policies related to ecological sustainability and conservation taken by various countries around the globe. The following discussed statistics of various countries are documented in the report "The Global Forest Goals Report, 2021" published by the Department of Economics and Social Affairs of the UN. Countries such as China and Liberia made clear guidelines to train and support research on tree breeding and seedling production for silviculture and afforestation. A forest carbon offset scheme has been initiated in the Republic of Korea, and New Zealand has further increased economic incentives for afforestation to strengthen its emission trading scheme. Ecuador formulated REDD+ action plans to reduce CO_2 emissions by 20% by 2025 through policy measures to reduce deforestation. Japan reported new financing methods such as forest environment tax, Nigeria launched green bonds, and Suriname raised the concession fee, and many other nations reported similar steps to promote sustainable forest management or forest growth. Canada, China, Serbia, Suriname, Lesotho, the Slovak Republic, and the United States of America have been vocal about the increasing interdependency of the forest ecosystem for employment. In China, the number of persons generating revenue from the forest increased from 52.47 million in 2015 to 60 million in 2020. Aside from providing roughly 196,000 employments in 2017 and 2018, the United States Forestry Service (USFS) employed about 955,400 individuals nationwide in the forest products sector. During 2017–2019, Uzbekistan restored more than 500,000 ha of an area prone to soil and water erosion. Vietnam protected fragile mangrove forests by getting shrimp farmers' help from UN-REDD and formulated an organic farming model. In Mongolia, UN-REDD helped people create a national policy for protecting forests and addressing climate change that focuses on sustainable forest management. India added 20,000 ha of forest and tree cover every year, and India led the world in official employment in the forest industry (6.23 million people employed).

24.5 Conclusion

In this review, we compare the various ecosystem modeling approaches that are being used to predict ecosystem dynamics to understand the forest change dynamics and climate change adaptation in forest ecosystems and assess their application in forest policy and planning. It is evident that different modeling approaches are undergoing fast evolution due to advancements in technology. These models are practical tools to evaluate various hypotheses and future climatic scenarios for effective decision-making and assess how policy decisions may impact the ecosystem. The future projections from these models can be used for formulating policy-making and sustainable environment plans. However, there is no model that can represent all the aspects of the ecosystem. Accepting the fact that “All the models have limitations, but they are useful,” it is a big challenge for policymakers whose decisions may affect people’s lives.

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