Understanding the linkages between climate change and forest

Rinku Moni Devi[1], Maneesh Kumar Patasaraiya[1,*], Bhaskar Sinha[2], Sameer Saran[3], A. P. Dimri[4] and Rajeev Jaiswal[5]

[1]Indian Institute of Forest Management, Bhopal 462 003, India
[2]Centre for Climate Change Studies, Indian Institute of Forest Management, Bhopal 462 003, India
[3]Indian Institute of Remote Sensing, Dehradun 248 001, India
[4]School of Environmental Sciences, Jawaharlal Nehru University, New Delhi 110 067, India
[5]Indian Space Research Organisation, Bengaluru 560 094, India

The present study reviews the application of various regional climate models and remote sensing techniques to understand and define impacts of climate change on the forest resources with specific reference to India. It illustrates the potentials and limitations of regional climate models, vegetation models and remote sensing techniques like normalized difference vegetation index time-series analysis, change detection method and phenological attributes in assessing and monitoring the impacts of climate change on vegetation. The study recommends that regional climate models and remote sensing techniques need to be integrated in tandem for understanding the present and future impacts of climate change on forest ecosystems. This could help to improve the accuracy and prediction, which can contribute to planning effective adaptation strategies in the forestry sector.

Keywords: Climate change, forest, regional climate models, remote sensing.

THE severity and uncertainty related to projected impacts of climate change have compelled the global community to include 'Climate Action' as one of the 17 Sustainable Development Goals (SDGs) declared by the United Nations. Climate change is disrupting national economies, affecting lives, costing people, communities and countries[1]. Numerous studies have been carried out to assess the impact of climate change on various natural resources like agriculture, water and forest. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)[2] has concluded that forest ecosystems could be seriously impacted even by moderate global warming of 1–2°C (ref. 2). Thus forest ecosystems, which provide a variety of ecosystem services vital for humanity, will be adversely impacted. Additionally, forests have the potential in slowing down the current trend of global warming by sequestering CO_2 from the atmosphere. It is estimated that in the last few decades, the world's forests have absorbed as much as 30% (2 Pg C $year^{-1}$) of annual global anthropogenic CO_2 emissions, which is the same amount as absorbed by oceans[3]. Thus, scientific management of forest resources is one of the priority sectors not only for achieving SDGs through ecosystem services, but also as contributing measures of adaptation and mitigation to climate change.

It has been estimated that the composition of one-third of the world's forests could be altered due to climate change[4]. Many studies have also predicted a regional shift of species and forests[5–7] and cause changes in biomes due to change in climate variables[8,9]. Moreover, tropical forests are more vulnerable to climate change and therefore threaten their structure, function and services[10]. A number of studies have been carried out to understand how forest and climate interact with each other. Forests of different climatic zones[11], different types[12,13], different regions[14,15] and different succession stages[16] react to climate change divergently due to their dissimilar sensitivities and resilience to disturbance.

Indian context

According to the IPCC Fifth Assessment report, net annual temperatures of India in the 2030s, with respect to 1970s, will increase by 1.7–2.2°C (ref. 2). Extreme temperatures are expected to increase by 1–4°C, with a maximum increase in coastal regions. One-third of forest areas in India is projected to change by 2100, with deciduous forests changing into evergreen due to increased precipitation[2]. India has 21% of the geographical area under forest cover, which supports the livelihood of nearly 88 million tribal and indigenous people residing in 173,000 villages[17]. The value of forest services such as freshwater, soil nutrients and non-timber forest products is estimated to be 7% of national GDP; however, it amounts to 57% of the income of India's rural poor[18]. This means that any change in structure and function of the forest will have substantial consequences to the already forest-dependent vulnerable communities. Studies from India on climate change and forest have revealed that forest resources might be greatly affected due to changes in temperature

---

*For correspondence. (e-mail: mpatsariya@gmail.com)

and precipitation[19]. Climate modelling-based study predicted a significant decrease in the area for tropical deserts, tropical desert scrubs, tropical moist forests and tropical wet forests and increase in the area for tropical dry forests and tropical very dry forests, especially in central and southern India[20]. In the context of the Himalayan region, an upward shift of timberline vegetation by 300 m and a considerable reduction of snow cover in the Nanda Devi Biosphere Reserve (NDBR), Uttarakhand since 1960 is reported[21]. Further, projected impacts for India indicate that 40–70% of the forested grids[22] in different states are likely to experience shift under a changing climate, resulting in forest die back and loss of biodiversity, which are irreversible[6]. All these changes/shifts in the forest ecosystems will have major implications on the livelihoods of millions of people that are directly linked to the forest resources for a variety of services.

It is therefore important to predict the likely impacts of climate change on forests so that climate-resilient development and conservation strategies can be formulated. However, accurate projections of climate change impact on forest ecosystems at a scale which could be useful for planning any development, livelihood and conservation strategies are lacking, specifically in the Indian context. Application of modern tools and techniques in an integrated research may help generate information that could be mainstreamed with other existing policies and programmes linked to promote forest-based livelihood.

The present study reviews different approaches, tools and techniques adopted across the globe, including India related to the impact of climate change on forest resources. The primary objective of the study is to understand the potential applications as well as limitations of different climate models and remote sensing techniques.

Application of climate modelling in understanding climate change

Climate models are numeric representations of the Earth's natural systems and are used to study how climate responds to changes in natural and human-induced perturbations[23]. The projections derived from climate models are based on physical understanding of the climate system and are generally represented at a higher spatial and temporal scale.

Global climate model and regional climate model

Global climate models (GCMs) are mainly used for simulating global climate system for providing estimates of climate variables[24]. The accuracy of GCMs normally decreases for a smaller area due to its coarse resolution and lack of capturing fine features. In order to overcome these limitations of GCMs, dynamical downscaling using high-resolution regional climate models (RCMs) is performed. RCMs lead to better estimations of climate conditions since their horizontal resolutions are much finer than the GCMs[25]. Downscaling and nesting are done for obtaining high-resolution climate or climate change information from relatively coarse-resolution GCMs. It has been observed that over a period of time, there is a shift from GCM to RCM for better representation of climate change and its associated impacts. A review of progress in the last 25 years of IPCC[2] revealed the development and evolution of different climate models within different scenarios with significantly improved resolution, i.e. from 500 km to ~40 km (ref. 26). The model outputs along with observations derived from other sources may help in projecting the likely impacts of global warming with higher confidence.

Applications of RCM in natural resources management

One of the important applications of a climate model is to predict the likely impacts of climate change on natural resources. It is only recently that scenarios developed using these techniques have been actually applied to a variety of impact assessments such as of temperature extremes[27], water resources[28], agriculture[29], forest fires[30], etc. A brief and critical analysis of the literature representing the application potential of RCMs in different natural resources is made. Arnell *et al.*[31] studied climate change scenarios from a regional model estimating changes in run-off in southern Africa. Jacob *et al.*[32] studied the inter-comparison of RCMs for Europe and identified how systematic biases vary across different models. Lucas-Picher *et al.*[33] verified the ability of four RCMs (CLM, HadRM3, HIRHAM5 and REMO) to represent the Indian monsoon characteristics for the period 1981–2000. Mathison *et al.*[34] completed four simulations for the HighNoon project covering India and the Himalaya focusing on the catchment areas using PRECIS model at 25 km resolution.

The projections by RCM mostly depend on climate data, scenarios used and assumptions made, which can be further applied to a wider set of scenarios along with other socio-economic factors. There are some limitations while using model results as they have varying degrees of uncertainty in the projections. Nevertheless, it does suggest a robust way of decision-making in different sectors. Many pilot studies have been conducted for determining the uncertainty aspects – whether the high-resolution scenarios actually lead to significantly different calculations of impacts compared to the coarser-resolution GCM from which the high-resolution scenarios are partially derived. Giorgi *et al.*[35] found a significant difference in simulated crop yields over the central plains of the United States when the results of high-resolution

RCM scenarios were compared with a coarser-resolution GCM scenario. Mearns *et al.*[36] concluded a statistically significant decrease in corn yield in Iowa, USA using the large-scale (GCM) scenario, whereas an insignificant increase was observed while using the high-resolution scenario. Stone *et al.*[37] found significant differences in changes in water yield when used under finer and coarser climatic scenarios for the Missouri River Basin, USA. Impact assessment of climate change on crop productivity in the tropics by Zacharias *et al.*[38], showed model biases. Hay[39] and Hertzler[40] suggested robust ways of applying uncertain climate information to agricultural decision-making (e.g. hedging, foreclosing options, creating new options and diversification), which are critical in planning resilient future land/water management options for agriculture. Results of the projected climate change over the Cauvery basin of Tamil Nadu, India for A1B scenario using RCMs showed an increasing trend for temperature (maximum and minimum) and rainfall with their influence on the yield and suggested adaptation strategies, including system of rice intensification, using temperature-tolerant cultivars and green manures/biofertilizers for economizing water and increasing rice productivity under warmer climate[41]. From the above review of the results of different models under different scenarios, one may infer that results of different RCMs and other models can be compared to enhance further the suitability and applicability of the models for planning adaptation strategies in the agriculture sector.

In the forestry sector, Ravindranath *et al.*[6] made an assessment of the impact of projected climate change on forest ecosystems in India based on climate projections of RCM of the Hadley Centre (HadRM3) using the A2 (740 ppm CO_2) and B2 (575 ppm CO_2) scenarios. The study further used the BIOME4 vegetation response model, which concluded shift in forest types under A2 and B2 scenarios. Chaturvedi *et al.*[42] also reported a shift in vegetation type in India using IBIS, a vegetation dynamic model for A2 and B2 scenarios based on climate projection using HadRM3. Iverson and Prasad[43] studied the tree species richness and forest type community for Eastern United States using the DISTRIB model along with climate scenarios created by GCM. The DISTRIB empirical model was used to generate suitable habitat and potential future distributions of common tree species for each scenario[44]. Patch models have been used to study forest response to past climate[45], direct effects of CO_2 (ref. 46) and possible future climate changes[47]. Fischlin and Gyalistras[48] assessed the impact of climate change on forests in the Alps at high temporal, spatial and qualitative resolution using climate model CCC-GCMII and forest patch model FORCLIM to simulate forest responses to the obtained climate scenarios. Lindner *et al.*[49] reviewed the existing knowledge about observed and projected impacts of climate change in different European forest regions. Further, study analysed its vulnerability, adaptive capacity focusing more in future research regarding quantification of impacts of climate change on European forests.

The Indian network for climate change assessment (INCCA) report provides comprehensive information on the impact of climate change for different sectors in different regions across the country[17]. This information is especially useful for planning future adaptation strategies in agriculture, water, human health and other important sectors. The State Action Plan of Madhya Pradesh (MP) provides details of climate change vulnerability assessment in the context of MP and climate projections for the 2030s (2021–50) and 2080s (2071–98)[50]. Vulnerability assessment related to the forestry sector has been done using vulnerability index for India, which is based on the observed datasets of forest density, forest biodiversity as well as the model-projected vegetation-type shift estimates for forested grids.

Limitations of climate models

Most of the climate model-based studies in the Indian forestry sector have been done using 50 × 50 km resolution. However, the climate variables at this resolution may not be adequate for proper planning at the local or regional level. Moreover, India Meteorological Department (IMD) local *in situ* weather observations may not be reliable for understanding the changes in micro-level studies. Additionally, the number of weather stations is inadequate and not uniformly distributed in India. Thus, the corresponding gridded data may also at times not be of much input for micro-level studies.

Many studies clearly depict the possible limitations of climate models along with vegetation models in understanding/projecting the impacts of climate change on forests. Iverson and Prasad[43] suggested that there may be errors in the input layers of potential species drivers or tree species sampling that can create uncertainty and therefore, these assumptions must be acknowledged while interpreting the results. Second, potential climate scenarios created by the various GCMs can make a large difference in the model output. Third, most models assume that tree species occur in all environments, except outside the range and equilibrium with the climate, but for many species the opposite is true[51]. Fourth, statistical models cannot account for changes in physiological and effect of species interaction in the model output. Therefore, the model can neither assess the changes due to competition among species, nor can it account for changes due to water efficiency or temperature acclimation of species[52]. There is also a limitation in simulating the vegetation component in RCMs as coupling will not provide comprehensive land-use processes and limits the presentations of various interactive surface fluxes with the adjacent atmosphere. RCMs are not used for vegetation dynamics studies but for climate projections; but RCM data can be used as input to vegetation models. Thus to study vegetation dynamics along with climate projections, RCMs need to be coupled with suitable land use/vegetation components, viz. JULES, dynamic global vegetation model (DGVM), etc. DGVM coupled with GCM is suitable for use in global climate change studies, but has certain limitations in their representation of physical and biogeochemical mechanisms, such as photosynthesis and respiration as well as in the representation of regional properties of vegetation[53]. The next generation model – earth system model (ESM), e.g. JULES is a community land surface model that has evolved from the met office surface exchange scheme (MOSES). It is used as a standalone model and also as the land surface component in the met office unified model. It is generally used for operational weather forecasting and leading climate change simulations.

There are many studies where climate and vegetation models have been coupled. For example, Atkin *et al.*[54] studied the temperature-dependent changes in leaf scaling relationships to quantitatively account for thermal acclimation of respiration in a coupled global climate–vegetation model. DGVM was used by Sitch *et al.*[55] for the evaluation of terrestrial carbon, future plant geography and climate carbon cycle feedback. Large uncertainties were associated with the response of tropical vegetation to drought and the boreal ecosystem to elevated temperature and changes in soil moisture. There are also studies showing the association between gross photosynthetic activity and climate across the boreal forest and tundra of Canada[56], and change in vegetation density using a coupled biosphere atmosphere model[57]. These vegetation model integrations either in RCM or GCM will help in assessing species distribution. There are studies with the species distribution model integrated with the climate projections[58]. Table 1 provides a comparison of some critical aspects of different vegetation models. To overcome the limitations of models, intersectoral impact model inter-comparison project (ISI-MIP) offers a framework to compare climate impact projections in different sectors (water availability, river flooding, coastal flooding, agriculture, ecosystems and energy demands) at different scales. ISI-MIP is a community-driven initiative for modelling the impact of climate change aimed at contributing to a quantitative, cross-sectoral and cross-scale modelling for the synthesis of differential impacts of climate change, including the associated uncertainties. The key goal of ISI-MIP is to contribute to the comprehensive understanding of the impacts of politically and scientifically relevant climate change scenarios[59]. The present review highlights the integration of climate models with vegetation models, in particular for impact of future projections based on climate models on vegetation. However, there exists a gap in terms of projections related to climate variables and associated impacts on vegetation. However, the remote sensing data of past vegetation could be a potential input to different vegetation models that may help understand the impact of climate change on vegetation.

Application of remote sensing in understanding climate change

The need to detect and project changes in the forest ecosystems has never been greater. However, traditional methods of collecting ecological data do not translate readily to regional or global extent. Therefore, ecologists and conservation biologists are applying the rapidly developing discipline of remote sensing to provide techniques and data sources necessary to prepare scientific responses to environmental change. Ecological monitoring of vegetation and wildlife, assessment of biomass, etc. require data from broad spatial limits that cannot be collected using field-based methods. Thus, satellite-based earth observations are being used in ecological and forestry research. Furthermore, the synoptic and repetitive data acquisition capabilities of satellite-based sensors have the potential to detect, identify and map canopy changes that are important to the forest ecosystem managers for planning and monitoring. Application of remote sensing techniques includes identifying and detailing the biophysical characteristics of species (plant and animal), habitats, predicting the distribution of species, spatial variability in species richness, and detecting natural and human-induced change ranging from regional to global scale of forest.

Remote sensing in assessing the impact of climate change on forests

There are many studies related to assessment on forest types[60], biodiversity[61], biomass[62], net primary productivity[63], deforestation and land-use change[64] using remote sensing techniques. Remote sensing data have shown evidence that climate has been changing rapidly[65]. In addition, high spatial and temporal resolution together with accuracy of remotely sensed data can provide technical support for monitoring vegetation dynamics at large scales. Time series of advanced very high resolution radiometer (AVHRR) data and normalized difference vegetation index (NDVI) trends have shown alteration to vegetation structure, primary productivity, biomass accumulation and growing season length[66]. Moreover, direct impact of climate change on vegetation productivity, biomass and phenological patterns of vegetation has been reported using NDVI for many ecosystems[67]. Similarly, the impact of vegetation on local climate has also been reported[68].

Studies related to understanding the relationship between climate change and forest using remote sensing techniques can be broadly categorized into time-series analysis, change detection and phenological observation.

Table 1. Comparison of some critical aspects of different models

						Disturbances			
DGVM	Bioclimatic constraints	Number of plant functional types (PFTs)	Nitrogen	Soil carbon	Competition	Nitrogen deposition and (or) nutrient stress	Fire/disease/grazing	Land-use and land-use change	Implicit*
CLM–DGVM[93]	Direct and indirect	10	Based on LPJ[60]		Light, water, space among PFTs	No	Fire	Three land-use classes	n/a
IBIS 2.6 (ref. 94)	Direct and indirect	12 on two canopy levels	Constant C : N ratios	5 pools	Light, water among PFTs	No	Fire	No	No
LPJ–DGVM[95]	Direct and indirect	10	Implicit	2 pools	Light, water among PFTs	No	Fire	No	No
JULES[96]	Direct and indirect	5	Constant N	4 Pools	Lotka–Volterra adapted to PFTs[#][97,98]	No	Fire	No	Fraction of the PFT reduces the area

n/a, Not available. *Some disturbances are implicitly included in the calculation of the models (e.g. a fractional loss representing undifferentiated disturbances). [#]Horizontal competition (herbs replace grasses and trees have the advantage on herbs) and carbon density competition.

Studies based on time-series analysis

Studies based on time-series analysis are applied in assessing the impact of climate change using time series of different vegetation indices like NDVI, enhanced vegetation index (EVI), etc. Many of these studies also cover other climatic products like MODIS-LST (moderate-resolution imaging spectroradiometer-land surface temperature) to assess the possible impact of climatic and atmospheric variables on forests. These studies are mostly correlation or regression-based analysis of time series of NDVI or EVI with local climatic variables like temperature and precipitation. Such correlation studies help in assessing the impact of climatic variability over a period of time on forest growth, health, physiology and other factors. In addition, these studies also help in identifying the dominant climate factor responsible for influencing the growth of a particular forest or species.

Therefore, time series of NDVI and EVI is regarded as the appropriate and best spectral indicator of vegetation activity and phenological characteristics, and also as a powerful method to carry out different studies to correlate climate change impact on regional and global scales[69]. NDVI has also been used in a range of applications, including the study of vegetation–climate interactions[70], detection of long-term vegetation changes[71], assessment of vegetation functional characteristics[72] and modelling of the global carbon balance[73]. Consistent NDVI time series is widely applied to monitor forest health[74] and to investigate the interactions between climate and forest ecosystems[75].

Limitations of time series NDVI data are mainly due to uncorrected effects of cloud, water, snow and shadow, and less frequently from the effects that increase NDVI, including high solar and scan angles. Even after corrections, some noise remains in the NDVI datasets, mainly arising from effects that tend to decrease NDVI. Table 2 summarizes some of the studies related to climate change impact on forests with the help of time-series NDVI.

In India, there is a lack of studies focusing on climate change impact on forests due to non-availability of various long-term accurate and consistent data on vegetation and climate variables. These gaps in data limit the application of NDVI and other remote sensing techniques in understanding the impact of climate change on forests. To minimize this gap, there are various climate models which provide a large amount of different types of meteorological data for a long period with accuracy and consistency, e.g. WorldClim. However, there is no scientific study related to the possible change in species behaviour using NDVI or EVI time series, which could be attributed to climate change. An understanding of the species-level sensitivity to climate change using time-series analysis can assist in designing and strategizing the future silvilcultural practice, as an adaptation measure to climate change.

Studies based on change detection

Change detection involves superimposing two classified maps of different periods to find the change in land use, including changes in vegetation[76]. Moreover, the process of change detection is based on the ability to measure

Table 2. Studies using time-series vegetation indices for climate change assessment

Time series						
Time-period	Vegetation index	Sensor	Climatic variables	Techniques/methodology	Inference	References
2001–11	NDVI	MODIS	Rainfall, temperature	Trend series analysis, regression, correlation	Detected land-cover changes due to changed climatic conditions	99
1998–12	NDVI	SPOT-4 VGT	Rainfall, temperature	Correlation, sensitive variable analysis	Rainfall change is a more sensitive variable for forest growth	100
1982–99	NDVI	NOAA	Rainfall, temperature	Multivariate analysis	Inter-annual NDVI variation exhibits a strong relationship with El Niño (ENSO)	101
2001–12	EVI	MODIS	Rainfall, temperature	Trend series analysis, regression, correlation	EVI change positively correlated with average temperature and precipitation	102
1982–2010	Maximum NDVI	AVHRR SPOT-VGT	Rainfall, temperature	Trend series analysis, regression, correlation	Positive linear correlation between NDVI and temperature and a negative correlation between NDVI and mean wind speed	103

temporal impacts. According to Macleod and Congalton[77], in general, remote sensing considers the following four aspects of change detection: (a) detect changes, (b) identify the nature of change, (c) measure the aerial extent of change, and (d) assess the spatial pattern of change. There are many studies based on satellite data, which attribute land degradation, deforestation and change in canopy to climate change. Rahman[78] concluded a significant change in vegetation cover using NDVI values of 2001 and 2010 in Patuakhali coastal area of Bangladesh. In the Indian context, there are many studies based on change detection techniques, which assess the possible change in forest degradation or land use due to climate change. Amin and Singh[79] carried out a study on land-use/land-cover mapping of Srinagar city in Kashmir Valley and observed that the Srinagar city had experienced significant changes from 1999 to 2007. The analysis also showed that changes in the land-use pattern have resulted in the loss of forest area, open spaces, etc. The spatial distribution of tropical forests in Sonitpur district, Assam, showed a progressive decline from 1994 to 2001, using remote sensing techniques and intensive ground truthing[80]. The study further revealed that the loss of forest cover was more pronounced between 1999 and 2001 than between 1994 and 1999, due to deforestation and encroachment in the moist deciduous and other forest areas.

Detection does not imply attribution of the change to the particular assumed cause. 'Attribution' of causes to climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence. A number of studies have assessed the change in land-use pattern, rate of deforestation and loss of forest cover with the help of change detection techniques; however, these changes cannot be directly attributed to climate change even though all studies indicate that changed climatic variables are indirectly attributed to the observed changes.

There are few limitations in change detection studies, since the process for change detection involves a number of methodological considerations such as proper orthorectification of remotely sensed data, minimizing errors on account of varying phenophases which influence reflectance/radiometry, and availability of snow/cloud-free images[81]. The uncertainty related to establishing a causal relationship between climate change and vegetation response could be reduced using advanced vegetation observation technologies and enhanced change detection methods.

Phenological observation-based studies

Plants are finely tuned to the seasonality of their environment, and shifts in phenology provide some of the most compelling evidence that species and ecosystems are being influenced by global environmental change. Researchers across disciplines have observed shifting phenology at multiple scales, including earlier spring flowering in individual plants and an earlier spring green-up of the land surface as revealed in satellite images. Experimental and modelling approaches have sought to identify the mechanisms causing these shifts, as well as to make projections regarding the consequences. Climatic condition determines the reproductive behaviour of any individual species and studies indicate that the flowering and fruiting dates of some tree species show significant variation (advanced or delayed) as a result of climate change[82]. The change in the phenological pattern of some of the tree species can be regarded as an indicator of climate change as some plants are highly sensitive to even a slight change in their normal climate pattern, especially with respect to temperature and precipitation. Hence, phenological variation in plants may act as a tool for predicting the impacts of climate change on plants. The extreme sensitivity of life-cycle events to inter-annual variations in meteorological conditions makes phenological studies important and relevant in addressing critical questions related to monitoring of species in response to climate change[83]. More recently, the utility of phenology for analysing climatic and ecological changes has prompted substantial new scientific interest in seasonal-to-decadal-scale dynamics in vegetation[84]. Field observations of species-level pheno-phases have been successfully associated with local and regional climatic variations occurring over several decades[85]. Furthermore, long-term records of budburst and flowering dates show strong associations with inter-annual variation in air temperature. Warmer spring temperatures have advanced flowering dates by about 4 days/1°C (ref. 86) and leaf unfolding by about 3.2–3.6 days/1°C in Europe (ref. 87). On an average, springtime phenological events have changed by 2.3 days/decade globally[87]. Phenological differences due to annual variation in snowfall and exposition may lead to erroneous conclusions, unless sufficient ground information is used for interpretation of images.

Tree phenological observations in India have proved to be the most effective impact indicators of climate change as many species are highly sensitive even to the smallest change in the long prevailing climate of any ecosystem[83]. It is evident that climate change will occur during the long lifespan of tree species and changes in phenology may be the major visible short-term response. Lal *et al.*[88] have reported that date of onset of summer monsoon over India could become more variable in future owing to climate change. Ovaskainen *et al.*[89] have concluded that long-established phenologies can be disrupted by climate change. Therefore, long-term observation of phenology of these species could be a potential source of information about climate change impact in the Indian subcontinent. As reported in the above-mentioned studies, phenological changes in tree species could be the most effective indicator of climate change; therefore, the need for establishing phenological stations around forest areas assumes significance. Studies involving remote sensing and phenology in understanding the impact of climate change are constrained by the lack of long-term recorded data on different phenological stages like flowering and budding of different species. There is a need to integrate remote sensing technology and ground observed data to establish a link between possible impacts of climate change on forest species.

Recently, a number of other approaches have been developed in understanding the relationship between forest and climate variables, and these are constantly evolving. The Holdridge life zone classification system is used in determining the life zones objectively from frequently available climate variables. This system is applied globally to assess the sensitivity of global vegetation distribution to climate change[90]. Thuiller[91] estimated shifts in the ecological zones of the earth by about 160 km in a north–south direction with each temperature change of 1°C. The concept of plant functional types (PFTs) is also used for understanding the impact of climate change on species. PFTs are defined as non-phylogenetic groupings of species, which perform similar functions in an ecosystem. They can be defined in relation to either the contribution of species to ecosystem processes (such as carbon or water cycling), or the response of species to changes in environmental variables (such as climatic variables or disturbance). Changed PFTs in different climate change scenarios is also an important tool to link climate change impact on vegetation type[92]. A reliable database of remote sensing of the longer period will improve basic data for climate change impact assessments. Climate variables are often the mean values of assessment studies, which do not fully express the actual situation, given other factors also influence the results. The available multi-source ground and spatial data along with climate variables should be analysed together so that data fusion aspects of forest ecosystems at different temporal and spatial resolutions can be explored.

Review on the application of different remote sensing techniques as discussed above reveals that they hold significant potential in understanding the past trend/response of vegetation. However, there is a lack of studies that directly attribute the change in vegetation to climate change.

Conclusion

This review clearly indicates that forest ecosystems and forest-based livelihoods are likely to be adversely impacted due to climate change, and therefore require immediate preparedness for developing adaptation strategies for forest-dependent communities to cope with climate change. This can happen only when there are accurate and reliable data related to projected change in forest structure and function due to climate change. Studies related to likely impact of climate change on forests are limited in the Indian context, which hinders in developing adaptation policies and programmes in response to climate change.

With the advancement of new tools and techniques like remote sensing and climate models, it is imperative to apply these techniques in an integrated way to enhance understanding of the impact of climate change on forests. The use of remote sensing data and technique is most effective in monitoring the changing pattern of forest cover. It provides some of the most accurate means of measuring the extent and pattern of changes in forest cover and density over a period of time. The changes in past climate variables generated from climate models along with observations made through remote sensing can provide more insights in understanding the impact of climate change on forests.

Studies reviewed related to different climate models suggest that the projections vary from model to model, and thus increase the inaccuracy and uncertainty in the overall assessment. In this context, RCMs and vegetation response models are being continuously modified to improve the reliability of projections related to understanding the change in forest landscape due to climate change. Therefore, the current knowledge of the impact of climate change may not be adequate for micro-level decision-making due to related uncertainties and errors of different climate and vegetation models. These uncertainties can be reduced using satellite data as input to vegetation models. This will help bridge the gap in understanding the impact of climate change on forest ecosystems and services, besides generating reliable information towards the formulation of effective policies and strategies related to adaptation and mitigation of climate change. This will not only help reduce the vulnerability of forest-dependent communities to climate change, but also enable in prioritizing districts/states/regions in terms of future vulnerability.

---

1. Stern, N., *The Economics of Climate Change: The Stern Review*, Cambridge University Press, Cambridge, UK, 2007.
2. Edenhofer, O. *et al.*, Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment, Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom, 2014.
3. Bellassen, V. and Luyssaert, S., Carbon sequestration: managing forests in uncertain times. *Nature*, 2014, **506**(7487), 153–155.
4. Shriner, D. S. and Street, R. B., *The Regional Impacts of Climate Change*, Cambridge University Press, New York, 1998, pp. 253–330.
5. Hansen, A. J., Neilson, R. P., Dale, V. H., Flather, C. H., Iverson, L. R., Currie, D. J. and Bartlein, P. J., Global change in forests: responses of species, communities, and biomes interactions between climate change and land use are projected to cause large shifts in biodiversity. *BioScience*, 2001, **51**(9), 765–779.
6. Ravindranath, N. H., Joshi, N. V., Sukumar, R. and Saxena, A., Impact of climate change on forests in India. *Curr. Sci.*, 2006, **90**(3), 354–361.
7. Chen, I. C., Hill, J. K., Ohlemüller, R., Roy, D. B. and Thomas, C. D., Rapid range shifts of species associated with high levels of climate warming. *Science*, 2011, **333**(6045), 1024–1026.
8. Dale, V. H., Tharp, M. L., Lannom, K. O. and Hodges, D. G., Modelling transient response of forests to climate change. *Sci. Total Environ.*, 2010, **408**(8), 1888–1901.
9. Hanewinkel, M., Hummel, S. and Cullmann, D. A., Modelling and economic evaluation of forest biome shifts under climate change in Southwest Germany. *For. Ecol. Manage.*, 2010, **259**(4), 710–719.
10. Betts, R. A., Malhi, Y. and Roberts, J. T., The future of the Amazon: new perspectives from climate, ecosystem and social sciences. *Philos. T. R. Soc. London, Ser. B*, 2008, **363**(1498), 1729–1735.
11. Bonan, G. B., Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science*, 2008, **320**(5882), 1444–1449.
12. Goldstein, A. H., Hultman, N. E., Fracheboud, J. M., Bauer, M. R., Panek, J. A., Xu, M. and Baugh, W., Effects of climate variability on the carbon dioxide, water, and sensible heat fluxes above a ponderosa pine plantation in the Sierra Nevada (CA). *Agric. For. Meteorol.*, 2000, **101**(2), 113–129.
13. Hänninen, H., Climate warming and the risk of frost damage to boreal forest trees: identification of critical eco-physiological traits. *Tree Physiol.*, 2006, **26**(7), 889–898.
14. Fearnside, P. M.. Plantation forestry in Brazil: the potential impacts of climatic change. *Biomass Bioenerg.*, 1999, **16**(2), 91–102.
15. Canadell, J. G. and Raupach, M. R., Managing forests for climate change mitigation. *Science*, 2008, **320**(5882), 1456–1457.
16. Sykes, M. T., Prentice, I. C. and Cramer, W., A bioclimatic model for the potential distributions of north European tree species under present and future climates. *J. Biogeogr.*, 1996, **23**, 203–233.
17. INCCA, Indian Network for Climate Change Assessment. Report 2. Climate Change and India: a 4 × 4 Assessment – a sectoral and regional analysis for 2030s. Ministry of Environment and Forests, Government of India. November, 2010.
18. Sukhdev, P., Costing the earth. *Nature*, 2009, **462**(7271), 277.
19. Joshi, P. K., Rawat, A., Narula, S. and Sinha, V., Assessing impact of climate change on forest cover type shifts in Western Himalayan eco-region. *J. For. Res.*, 2012, **23**(1), 75–80.
20. Chakraborty, A., Joshi, P. K., Ghosh, A. and Areendran, G., Assessing biome boundary shifts under climate change scenarios in India. *Ecol. Indic.*, 2013, **34**, 536–547.
21. Panigrahy, S., Anitha, D., Kimothi, M. M. and Singh, S. P., Timberline change detection using topographic map and satellite imagery. *Trop. Ecol.*, 2010, **51**(1), 87–91.
22. Gopalakrishnan, R., Jayaraman, M., Bala, G. and Ravindranath, N. H., Climate change and Indian forests. *Curr. Sci.*, 2011, **101**(3), 348–355.
23. Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P. and Meehl, G. A., The next generation of scenarios for climate change research and assessment. *Nature*, 2010, **463**(7282), 747–756.
24. Ghosh, S. and Mujumdar, P. P., Future rainfall scenario over Orissa with GCM projections by statistical downscaling. *Curr. Sci.*, 2006, **90**(3), 396–404.
25. Parry, M. L. (ed.), *Climate Change 2007 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Fourth Assessment Report of the IPCC*, Cambridge University Press, Vol. 4, 2007.
26. Jones, N., Climate assessments: 25 years of the IPCC. *Nature*, 2013, **501**, 298–299.
27. Hennessey, K. J., Whetton, P. H., Katzfey, J. J., McGregor, J. L., Jones, R. N., Page, C. M. and Nguyen, K. C., Fine resolution climate change scenarios for new South Wales. Annual Report. CSIRO, Australia, 1998, p. 48.
28. Hay, L. E., Wilby, R. L. and Leavesley, G. H., A comparison of delta changes and downscaled GCM scenarios for three mountainous basins in the United States. *J. Am. Water Resour. Assoc.*, 2000, **36**, 387–397.
29. Thomson, A. M., Brown, R. A., Ghan, S. J., Izaurralde, R. C., Rosenberg, N. J. and Leung, L. R.., Elevation dependence of winter wheat production in eastern Washington State with climate change: a methodological study. *Climate Change*, 2002, **54**(1–2), 141–164.
30. Wotton, B. M., Stocks, B. J., Flannigan, M. D., Laprise, R. and Blanchet, J. P., Estimating future 2 × CO_2 fire climates in the boreal forest of Canada using a regional climate model. In proceedings of Third International Conference on Forest Fire Research and the 14th Conference in Fire and Forest Meteorology, University of Coimbra, Portugal, 1998, pp. 1207–1221.
31. Arnell, N. W., Hudson, D. A. and Jones, R. G., Climate change scenarios from a regional climate model: estimating change in runoff in southern Africa. *J. Geophys. Res: Atmos.*, 2003, **108**(D16), 4519–4528.
32. Jacob, D., Bärring, L., Christensen, O. B., Christensen, J. H., de Castro, M., Deque, M. and van den Hurk, B., An intercomparison of regional climate models for Europe: model performance in present-day climate. *Climate Change*, 2007, **81**(1), 31–52.
33. Lucas-Picher, P., Christensen, J. H., Saeed, F., Kumar, P., Asharaf, S., Ahrens, B. and Hagemann, S., Can regional climate models represent the Indian monsoon? *J. Hydrometeorol.*, 2011, **12**(5), 849–868.

34. Mathison, C., Wiltshire, A., Dimri, A. P., Falloon, P., Jacob, D., Kumar, P. and Yasunari, T., Regional projections of North Indian climate for adaptation studies. *Sci. Total Environ*., 2013, **468**, S4–S17.
35. Giorgi, F., Mearns, L. O., Shields, C. and McDaniel, L., Regional nested model simulations of present day and 2 × CO_2 climate over the central plains of the US. *Climate Change*, 1998, **40**(3–4), 457–493.
36. Mearns, L. O., Giorgi, F., Whetton, P., Pabon, D., Hulme, M. and Lal, M., Guidelines for use of climate scenarios developed from regional climate model experiments, IPCC Guideline Paper, 2003.
37. Stone, M. C., Hotchkiss, R. H. and Mearns, L. O., Water yield responses to high and low spatial resolution climate change scenarios in the Missouri River Basin. *Geophys. Res. Lett.*, 2003, **30**(4).
38. Zacharias, M., Kumar, S. N., Singh, S. D., Rani, D. S. and Aggarwal, P. K., Evaluation of a regional climate model for impact assessment of climate change on crop productivity in the tropics. *Curr. Sci.*, 2015, **108**(6), 1119.
39. Hay, J., Extreme weather and climate events, and farming risks. In *Managing Weather and Climate Risks in Agriculture* (eds Sivakumar, M. V. K. and Motha, R. P.), Springer, Berlin, 2007, pp. 1–19.
40. Hertzler, G., Adapting to climate change and managing climate risks by using real options. *Crop Pasture Sci.*, 2007, **58**(10), 985–992.
41. Geethalakshmi, V., Lakshmanan, A., Rajalakshm, D., Jagannathan, R., Sridhar, G., Ramaraj, A. P. and Anbhazhagan, R., Climate change impact assessment and adaptation strategies to sustain rice production in Cauvery basin of Tamil Nadu. *Curr. Sci*., 2011, **101**(3), 342–347.
42. Chaturvedi, R. K., Gopalakrishnan, R., Jayaraman, M., Bala, G., Joshi, N. V., Sukumar, R. and Ravindranath, N. H., Impact of climate change on Indian forests: a dynamic vegetation modelling approach. *Mitig. Adapt. Strat. Global Change*, 2011, **16**(2), 119–142.
43. Iverson Louis, R. and Prasad, A. M., Potential changes in tree species richness and forest community types following climate change. *Ecosystems*, 2001, **4**(3), 186–199.
44. Solomon, A. M., West, D. C. and Solomon, J. A., Simulating the role of climate change and species immigration in forest succession. In *Forest Succession: Concepts and Application* (eds West, D. C. Shugart, H. H. and Botkin, D. B.), Springer, New York, 1981, pp. 154–177.
45. Solomon, A. M. and Bartlein, P. J., Past and future climate change: response by mixed deciduous–coniferous forest ecosystems in northern Michigan. *Can. J. For. Res*., 1992, **22**, 1727–173.
46. Solomon, A. M., Transient response of forests to CO_2 induced climate change: simulation modelling experiments in eastern North America. *Oecologia*, 1986, **68**, 567–579.
47. Smith, T. M., Smith, J. B. and Shugart, H. H., Modelling the response of terrestrial vegetation to climate change in the tropics. In *Tropical Forests in Transition-Ecology of Natural and Anthropogenic Disturbance Processes* (ed. Goldammer, J. G.), Birkhauser Verlag, Basel-Boston, 1992, pp. 253–268.
48. Fischlin, A. and Gyalistras, D., Assessing impacts of climatic change on forests in the Alps. *Global. Ecol. Biogeogr*., 1997, **6**, 19–37.
49. Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J. and Lexer, M. J., Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *For. Ecol. Manage*., 2010, **259**(4), 698–709.
50. Madhya Pradesh (MP) State Action Plan on Climate Change – Integrating Concern – Converging Possibilities, State Knowledge Management Centre on Climate Change, Environmental Protection and Coordination Organization, Housing and Environment Department, Government of MP, 2014.
51. Loehle, C. and LeBlanc, D., Model-based assessments of climate change effects on forests: a critical review. *Ecol. Model*., 1996, **90**(1), 1–31.
52. Neilson, R. P. and Marks, D., A global perspective of regional vegetation and hydrologic sensitivities from climatic change. *J. Veg. Sci*., 1996, **5**(5), 715–730.
53. Quillet, A., Peng, C. and Garneau, M., Toward dynamic global vegetation models for simulating vegetation–climate interactions and feedbacks: recent developments, limitations, and future challenges. *Environ. Rev*., 2010, **18**(NA), 333–353.
54. Atkin, O. K., Atkinson, L. J., Fisher, R. A., Campbell, C. D., Zaragoza-Castells, J. O., Pitchford, J. W. and Hurry, V., Using temperature-dependent changes in leaf scaling relationships to quantitatively account for thermal acclimation of respiration in a coupled global climate–vegetation model. *Global Change Biol*., 2008, **14**(11), 2709–2726.
55. Sitch, S., Huntingford, C., Gedney, N., Levy, P. E., Lomas, M., Piao, S. L. and Jones, C. D., Evaluation of the terrestrial carbon cycle, future plant geography and climate–carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs). *Global. Change Biol*., 2008, **14**(9), 2015–2039.
56. Bunn, A. G., Goetz, S. J. and Fiske, G. J., Observed and predicted responses of plant growth to climate across Canada. *Geophys. Res. Lett*., 2005, **32**(16), 1–4.
57. Bounoua, L., Collatz, G. J., Los, S. O., Sellers, P. J., Dazlich, D. A., Tucker, C. J. and Randall, D. A., Sensitivity of climate to changes in NDVI. *J. Climate*, 2000, **13**(13), 2277–2292.
58. González-Orozco, C. E., Pollock, L. J., Thornhill, A. H., Mishler, B. D., B. Knerr, N., Laffan, S.W. and Kujala, H., Phylogenetic approaches reveal biodiversity threats under climate change. *Nature Climate Change*, 2016, **6**(12), 1110–1114.
59. Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O. and Schewe, J., The Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP): project framework. *Proc. Natl. Acad. Sci. USA*, 2014, **111**(9), 3228–3232.
60. Reed, B. C., Brown, J. F., Vander Zee, D., Loveland, T. R., Merchant, J. W. and Ohlen, D. O., Measuring phenological variability from satellite imagery. *J. Veg. Sci*., 1994, **5**(5), 703–714.
61. Bawa, K., Rose, J., Ganeshaiah, K. N., Barve, N., Kiran, M. C. and Umashaanker, R., Assessing biodiversity from space: an example from the Western Ghats, India. *Conserv. Ecol*., 2002, **6**(2), 7.
62. Salunkhe, O., Khare, P. K., Sahu, T. R. and Singh, S., Above ground biomass and carbon stocking in tropical deciduous forests of state of Madhya Pradesh, India. *Taiwania*, 2014, **59**(4), 353–359.
63. Turner, D. P., Ritts, W. D., Cohen, W. B., Gower, S. T., Running, S. W., Zhao, M. and Ahl, D. E., Evaluation of MODIS NPP and GPP products across multiple biomes. *Remote Sensing Environ*., 2006, **102**(3), 282–292.
64. Thiam, A. K., The causes and spatial pattern of land degradation risk in southern Mauritania using multi temporal AVHRR-NDVI imagery and field data. *Land Degrad. Dev*., 2003, **14**(1), 133–142.
65. Lucht, W. *et al.*, Climatic control of the high-latitude vegetation greening trend and Pinatubo effect. *Science*, 2002, **296**, 1687–1689.
66. Myneni, R. B., Dong, J., Tucker, C. J., Kaufmann, R. K., Kauppi, P. E., Liski, J. and Hughes, M. K., A large carbon sink in the woody biomass of northern forests. *Proc. Natl. Acad. Sci*., 2001, **98**(26), 14784–14789.
67. Nemani, R. R., Keeling, C. D., Hashimoto, H., Jolly, W. M., Piper, S. C., Tucker, C. J. and Running, S. W., Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science*, 2003, **300**(5625), 1560–1563.
68. Zhang, J., Dong, W., Congbin, F. and Lingyun, W., The influence of vegetation covers on summer precipitation in China: a statistical analysis of NDVI and climate data. *Adv. Atmos. Sci*., 2003, **20**(6), 1002–1006.

69. Zhang, J., Dong, W., Ye, D. and Fu, C., New evidence for effects of land cover in China on summer climate. *Chin. Sci. Bull.*, 2000, **48**(4), 401–405.
70. Liu, Y., Wang, X., Guo, M., Tani, H., Matsuoka, N. and Matsumura, S., Spatial and temporal relationships among NDVI, climate factors, and land cover changes in Northeast Asia from 1982 to 2009. *GISci. Remote Sensing*, 2011, **48**(3), 371–393.
71. Eklundh, L. and Olsson, L., Vegetation index trends for the African Sahel 1982–1999. *Geophys. Res. Lett.*, 2003, **30**(8), 1430–1433.
72. DeFries, R. S. and Townshend, J. R. G., NDVI-derived landcover classifications at a global-scale. *Int. J. Remote Sensing*, 1994, **15**(17), 3567–3586.
73. Potter, C. S., Terrestrial biomass and the effects of deforestation on the global carbon cycle. *BioScience*, 1999, **49**(10), 769–778.
74. Kasischke, E. S., French, N. H., Harrell, P., Christensen, N. L., Ustin, S. L. and Barry, D., Monitoring of wildfires in boreal forests using large area AVHRR NDVI composite image data. *Remote Sensing Environ.*, 1993, **45**(1), 61–71.
75. Weishou, S., Di, J., Hui, Z., Shouguang, Y., Haidong, L. and Naifeng, L., The response relation between climate change and NDVI over the Qinghai–Tibet plateau. *J. World Acad. Sci., Eng. Technol.*, 2011, **59**, 2216–2222.
76. Jessica, P. K., Porwal, M. C., Roy, P. S. and Sandhya, G., Forest change detection in Kalarani round, Vadodara, Gujarat – a remote sensing and GIS approach. *J. Indian Soc. Remote Sensing*, 2001, **29**, 129–135.
77. Macleod, R. D. and Congalton, R. G. A., Quantitative comparison of change detection algorithms for monitoring Eelgrass from remote sensed data. *Photogramm. Eng. Remote Sensing*, 1998, **64**, 207–216.
78. Rahman, M. M., Temporal change detection of vegetation coverage in Patuakhali coastal area of Bangladesh using GIS and remotely sensed data. *Int. J. Geomat. Geosci.*, 2013, **4**(1), 36.
79. Amin, A. and Singh, S. K., Study of urban land use dynamics in Srinagar city using geospatial approach. *Bull. Environ. Sci. Res.*, 2012, **1**(2), 18–24.
80. Acharjee, S., Changmai, M., Bhattacharjee, S. and Mahanta, J., Forest cover change detection using remote sensing and GIS – a study of Jorhat and Golaghat Districts, Assam. *Int. J. Environ. Resour.*, 2012, **1**(2), 45–49.
81. Roy, D. P., The impact of misregistration upon composited wide field of view satellite data and implications for change detection. *IEEE Trans. Geosci. Remote Sensing*, 2000, **38**(4), 2017–2032.
82. Fitter, A. H. *et al.*, Relationship between first flowering date and temperature in the flora of a locality in central England. *Funct. Ecol.*, 1995, **9**, 55–60.
83. Kushwaha, C. P. and Singh, K. P., India needs phenological stations network. *Curr. Sci.*, 2008, **95**, 832–834.
84. Myneni, R., Keeling, B. C. D., Tucker, C. J., Asrar, G. and Nemani, R. R., Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature*, 1997, **386**(6626), 698–702.
85. Lechowicz, M. J. and Koike, T., Phenology and seasonality of woody plants: an unappreciated element in global change research? *Can. J. Bot.*, 1995, **73**, 175–182.
86. Kramer, K., Phenology and growth of European trees in relation to climate change. Ph D thesis, Landbouw Universiteit, Wageningen, 1996.
87. Parmesan, C. and Yohe, G., A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, 2003, **421**, 37–42.
88. Lal, M., Nozawa, T., Emori, S., Harasawa, H., Takahashi, K., Kimoto, M. and Numaguti, A., Future climate change: implications for Indian summer monsoon and its variability. *Curr. Sci.*, 2001, **81**(9), 1196–1207.
89. Ovaskainen, O., Skorokhodova, S., Yakovleva, M., Sukhov, A., Kutenkov, A., Kutenkova, N. and del Mar Delgado, M., Community-level phenological response to climate change. *Proc. Natl. Acad. Sci.*, 2013, **110**(33), 13434–13439.
90. Emanuel, W. R., Shugart, H. H. and Stevenson, M. P., Climatic change and the broad-scale distribution of terrestrial ecosystem complexes. *Climate Change*, 1985, **7**(1), 29–43.
91. Thuiller, W., Biodiversity: climate change and the ecologist. *Nature*, 2007, **448**(7153), 550–552.
92. Lavorel, S., McIntyre, S., Landsberg, J. and Forbes, T. D. A., Plant functional classifications: from general groups to specific groups based on response to disturbance. *Trends Ecol. Evol.*, 1997, **12**(12), 474–478.
93. Zeng, X., Shaikh, M., Dai, Y., Dickinson, R. E. and Myneni, R., Coupling of the common land model to the NCAR community climate model. *J. Climate*, 2002, **15**(14), 1832–1854.
94. Foley, J. A., Levis, S., Prentice, I. C., Pollard, D. and Thompson, S. L., Coupling dynamic models of climate and vegetation. *Global Change Biol.*, 1998, **4**(5), 561–579.
95. Sitch, S. *et al.*, Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change Biol.*, 2003, **9**(2), 161–185.
96. Clark, D. B. *et al.*, The Joint UK Land Environment Simulator (JULES), model description-part 2: carbon fluxes and vegetation dynamics. *Geosci. Model Dev.*, 2011, **4**(3), 701.
97. Lotka, A. J., *Elements of Physiological Biology*, Dover Publications, New York, 1925.
98. Volterra, V., Fluctuation in the abundance of a species considered mathematically. *Nature*, 1926, **118**(2972), 558–560.
99. Piao, S., Wang, X., Ciais, P., Zhu, B., Wang, T. A. O. and Liu, J. I. E., Changes in satellite-derived vegetation growth trend in temperate and boreal Eurasia from 1982 to 2006. *Global Change Biol.*, 2011, **17**(10), 3228–3239.
100. Eckert, S., Hüsler, F., Liniger, H. and Hodel, E., Trend analysis of MODIS NDVI time series for detecting land degradation and regeneration in Mongolia. *J. Arid Environ.*, 2015, **113**, 16–28.
101. Ning, T., Liu, W., Lin, W. and Song, X., NDVI variation and its responses to climate change on the northern loess plateau of China from 1998 to 2012. *Adv. Meteorol.*, 2015, 1–10.
102. Li, Z., Nadon, S. and Cihlar, J., Satellite-based detection of Canadian boreal forest fires: development and application of the algorithm. *Int. J. Remote Sensing*, 2000, **21**(16), 3057–3069.
103. Guo, Z. X., Wang, Z. M., Song, K. S., Zhang, B., Li, F. and Liu, D. W., Correlations between forest vegetation NDVI and water/thermal condition in Northeast China forest regions in 1982–2003. *Chin. J. Ecol.*, 2007, **26**(12), 1930–1936.

ACKNOWLEDGEMENTS. We thank the Director, Indian Institute of Forest Management, Bhopal for providing the necessary facilities and infrastructure for the study. We also thank our colleagues for their valuable inputs and encouragement.

Received 29 July 2016; revised accepted 7 September 2017

doi: 10.18520/cs/v114/i05/987-996