*Tropical Ecology* **56**(2): 219-231, 2015 ISSN 0564-3295

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# Simulation of vegetation dynamics in Himalaya using dynamic global vegetation model

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**Abstract:** In order to understand the possible vegetation dynamics in the event of climate change for the Himachal Pradesh part of Western Himalaya, vegetation and its LAI and biomass were simulated using Spatially Explicit Individual based Dynamic Global Vegetation Model (SEIB DGVM). The study used climate data (global reanalysis by the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) to generate mean annual climate trends to synthesize expected vegetation. The vegetation transects selected in Himachal Pradesh represent a biogeographic transition covering temperate-subtropical regime. In the present study, an attempt was made to simulate vegetation in two configurations across the study area as follows: (i) contiguous sites (40 grids of 10 km × 10 km) at alpine and temperate transitions, and (ii) discrete sites randomly selected (22 grids of 10 km x 10 km) covering a range of vegetation types. Simulations were carried out for 70 years time period (based on annual mean climate data for 100 years). In comparison to the earlier predictions made by several vegetation models, the SEIB model produced biomes which are in agreement with overall existing patterns available in the region. The SEIB model also produced leaf area index and biomass for each plant functional type and biome for each grid in the study area.

**Resumen:** Con el fin de comprender la posible dinámica de la vegetación en caso de cambio climático para la parte de Himachal Pradesh de los Himalaya Occidentales, la vegetación junto con su Índice de Área Foliar (LAI, siglas en inglés) y su biomasa fueron simulados mediante el uso de un Modelo Dinámico de Vegetación Global Espacialmente Explícito basado en Individuos (SEIB DGVM, siglas en inglés). El estudio utilizó datos climáticos (re-análisis mundial por los Centros Nacionales de Predicción Ambiental y el Centro Nacional de Investigación Atmosférica) para generar tendencias medias anuales del clima para sintetizar la vegetación natural. Los transectos de vegetación seleccionados en Himachal Pradesh representan una transición biogeográfica que abarca un régimen templado-subtropical. En el presente estudio se intentó simular la vegetación en dos configuraciones en toda el área de estudio, de la siguiente manera: (i) sitios contiguos (40 retículas de 10 km × 10 km) en transiciones alpinas y templadas, y (ii) sitios discretos seleccionados al azar que cubren unagamade tipos de vegetación (22 retículas de 10 km × 10 km). Las simulaciones se llevaron a cabo para un período de 70 años (con base en datos climáticos anuales promedio para 100 años).En comparación con predicciones anteriores hechas a partir de varios modelos de vegetación, el modelo SEIB arrojó biomas que son consistentes con los patrones existentes disponibles en la región. El modelo SEIB también produjo un índice de área foliar y la biomasa para cada tipo vegetal funcional y bioma de cada retículaen el área de estudio.

**Resumo:** A fim de entender as dinâmica possíveis da vegetação em caso de mudanças

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climáticas para a Himachal Pradeshpartedos de Himalaias Ocidentais, a vegetação, o seu IAF e a biomassa foram simulados utilizando a Configuração Espacial Individual Explícita baseada no Modelo Dinâmico Vegetação Global (SEIB DGVM). O estudo utilizou dados climáticos - reanálise global pelos Centros Nacionais de Previsão Ambiental e do Centro Nacional de Pesquisa Atmosférica (NCAR) - para gerar tendências médias climáticas anuais para sintetizar a vegetação expectável. Os transeptos selecionados de vegetação em Himachal Pradesh (HP) representam uma transição biogeográfica cobrindo o regime temperado-subtropical.Neste estudo, foi feita uma tentativa de simular a vegetação,em toda a área de estudo,para duas configurações da seguinte forma: (i) locais contíguos (40 grelhas de 10 km x 10 km) em transições alpinas e temperadas, e (ii) locais discretos escolhidos ao acaso (22 grelhas de 10 km x 10 km), abrangendo uma gama de tipos de vegetação. As simulações foram realizadas para período de 70 anos (com base em dados climáticos médios anuais de 100 anos). Em comparação com as previsões anteriores feitas por vários modelos de vegetação, os biomas gerados peloSEIB estão de acordo com os padrões gerais disponíveis na região. O modelo SEIB também gerou índices de área foliar e biomassa para cada tipo funcional de planta e bioma para cada grelha na área em estudo..

**Key words:** Biome, DGVM, Himalayan vegetation dynamics, PFTs.

## Introduction

Understanding vegetation responses to changing climate is critical for developing adaptation mechanisms (Jones *et al*. 2009; Negi *et al*. 2012), especially in variable rainfall regime in the Indian tropics (Gautam *et al*. 2013). As vegetation often responds slowly to changes in environmental conditions, a time lag between change in climate and shift in vegetation can result in altered biome composition, before any irreversible damage manifests itself at the ecosystem scale (Gonzalez *et al*. 2010; Jones *et al*. 2009; Quillet *et al*. 2010; Rosenzweig *et al*. 2007). Vegetation interacts with the atmosphere in many ways for several functions *e.g.,* photosynthesis, evapotranspiration, productivity, competition, disturbance (Denman *et al*. 2007; LeQuer´e *et al*. 2009). This is due to the fact that biophysical, ecological and physiological processes of vegetation as well as soils have strong influences on the atmosphere in terms of thermal and chemical composition leading to alteration in climate (Quillet *et al*. 2010). The biological processes, depending on the local climate, determine the type of the vegetation that grows in a region and thus may change the vegetation structure and its attributes including albedo, roughness length and leaf area index (LAI) (Pitman 2003).

Predicting the potential effects of future climatic change and human disturbances on natural vegetation dynamics requires large-scale bio-geographical models (Allen 2003; Kriticos *et al*. 2003; MacDonald *et al*. 2008; Root *et al*. 2005; Smith *et al*. 1992a, b). Earlier efforts of modeling vegetation dynamics employed biogeography models (Cox *et al*. 2000; Prentice *et al*. 1992), terrestrial biogeochemistry models (Parton *et al*. 1987) and forest gap models (Solomon *et al*. 1980). Terrestrial biogeochemistry models mostly focused on the simulation of biogeochemical cycles through plant physiological processes whereas forest gap models relied on simulation of ecological succession at the species level (Levis *et al*. 2004). Application of gap models at global scale requires a very large amount of computing power (Pitelka *et al*. 2001).

Thus DGVM was evolved as an integrating framework in order to bring synergy from the advantages of terrestrial biogeochemistry models, biogeography models, forest-gap models (Cox 2001; Foley *et al*. 1996; Friend *et al*. 1997; Sitch *et al*. 2003; Woodward *et al*. 1998). DGVMs simulate the changes in vegetation dynamics and carbon fluxes of terrestrial ecosystems used for testing hypothesis (Costanza *et al*. 1997; Cramer *et al*. 2001) and predicting the future responses of ecosystem structure and functioning in relation to long term environmental changes (Quillet *et al*. 2010; Sitch *et al*. 2008).

There are two basic approaches to modeling vegetation response to changing climates: static (time-independent) and dynamic (time-dependent) bio-geographical models. Static models attempt to predict the distribution of the potential vegetation by relating two entities, *viz.,* geographic distribution of climate parameters and vegetation, with an assumption of equilibrium conditions for both climate and terrestrial vegetation, whereas dynamic processes prevalent in reality are actually ignored (Peng 2000). The dynamic models include the dynamic modules- establishment, competition, mortality and disturbance which are not considered by the static models (Cramer *et al*. 2001).

Dynamic Global Vegetation models (DGVMs) consist of simple biogeography rules that deal with the presence of vegetation types according to climate coupled with carbon and nitrogen cycle modules to track the biogeochemistry addressing the plant growth and decay (Bachelet *et al*. 2001). To generalize plant function to the global scale, DGVMs represent vegetation as plant functional types (PFTs) instead of individual species (as employed in forest gap models). Plant functional types are classes of plant species with presumably similar roles in an ecosystem, responding in a comparable manner to environmental conditions like water and nutrient availability (Lavorel *et al*. 1997). Characterization of PFTs is achieved by describing the combination of physical, phylogenetic and phenological attributes. Physical attributes can be plant growth form, bioclimatic tolerance and phenology *e.g.,* evergreen, raingreen or summergreen. The environmental condition ranges for defining the synthesized PFTs in the SEIB model for the present study are given in Annexure I. In the present study, the terminology used for PFTs and biomes are on the lines of the definitions given in the SEIB-DGVM (Sato *et al*. 2007). Similar terminologies have also been used by several DGVMs (Cox 2001; Haxeltine & Prentice 1996; Pavlick *et al*. 2012; Sitch *et al*. 2003). The definitions and characterization of the PFTs and biomes in the DGVMs as mentioned above are exclusively based on the climatic and environmental parameters (*e.g*., Annexure I & Annexure II). It is important to note that while the distributions of ecosystems are always locale specific, the PFT/biome is independent of specific geographical location. However, as the present study has been exclusively carried out for the Himachal Pradesh in the Himalaya, the PFT/biome terminology has been modified to suit the Himalayan context and "Boreal" term has been replaced by "Himalayan". The environmental conditions for the boreal vegetation PFTs/biomes conceived in the SEIB model is the same as in the Himalayan vegetation categories. Also, the "boreal" term is mostly associated with Arctic Circle and thus may not justify its place in the Himalaya and thus the change in the global terminology in the present study is justified and ecologically acceptable.

Representation of biosphere-atmosphere interactions in climate models is yet to represent reality at its best and to overcome such gaps, climate models are coupled with DGVMs. This coupling has two major advantages: first, the representation of feedbacks between vegetation and climate is much improved, and second, DGVMs can also be applied in transient situations when vegetation is not in equilibrium with climate (Kleinen *et al*. 2011). DGVMs have commonly been developed, operated and validated at a higher spatial resolution than is usually the case for General Climate Models (GCMs) (Alessandri *et al*. 2007; Liu *et al*. 2006).

Land Surface Model (LSM) coupled with DGVM simulating dynamics of boreal, temperate, tropical rain forest and savanna ecosystems, involve a validated mechanism of leaf area index (LAI). The model updates daily to a maximum value set by annual vegetation dynamics as well as average net primary production (Bonan *et al*. 2002). JeDi (Jena Diversity) DGVM model is based on plant functional trade-off approach combined with simple mass-based aggregation mechanism (Pavlick *et al*. 2012). It is able to capture the broad patterns of terrestrial biogeochemical fluxes. Additionally, this model represents how mechanistically it can reproduce the global-scale biogeographical patterns of plant species richness and community evenness (Pavlick *et al*. 2012). Spatially Explicit Individual Based (SEIB) DGVM is the first biogeochemical model with 3-D representation of the forest structure, where individual trees compete for light and space (Sato *et al*. 2007). It has 3-D light interception among individual trees and thus improves radiation through the canopy. Recent adaptation of SEIB DGVM applied to the African continent for the 21st century climate scenario (Sato *et al*. 2007) show the slow increment in the trend of net primary productivity, biomass and soil carbon. The study indicates that the vegetation dynamics and invasive tree recruitment modifies the transient change in distribution and function in vegetation patterns under changing environment. The model improves upon the previous versions in terms of tree mortality, fire incidence based on field observation spread across African vegetation (Sato & Takeshi 2012). Simulations using BIOME4 vegetation model showed changes in NPP from (-5) to 40 % by 2030 across different agro-ecological zones (AEZ) under A2 scenario (Ravindranath *et al*. 2011).

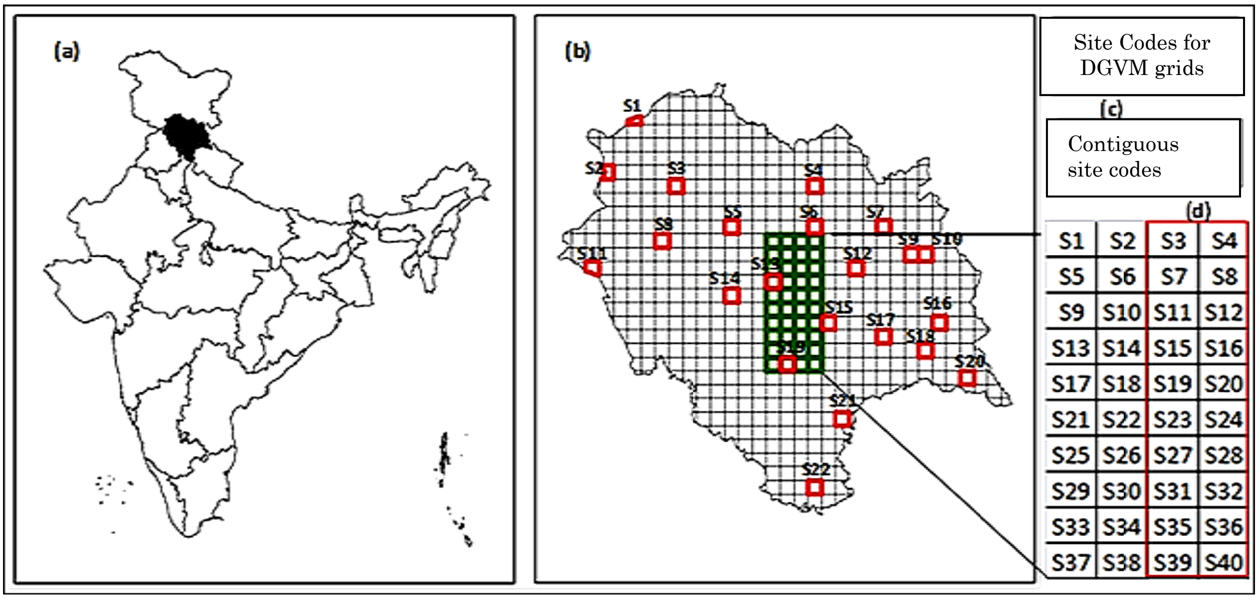



**Fig. 1**. Study area, Himachal Pradesh, India (a) divided into 10 km × 10 km grid, (b) model simulations in two configurations - discrete in red color and contiguous sites in green color, (c) assigned grid codes, (d) grids with biome transition in red square.

Recently, few research initiatives have focused on simulation of potential vegetation in India to the future climate change scenarios (Gopalakrishnan *et al.* 2011 & Ravindranath *et al.* 2011) and further research is needed for holistic understanding. These studies have mostly employed the models with very coarse resolution inputs and hence a need was felt to take up a study using a model that has a better resolution so as to account for the local variability in the global context (Singh *et al.* 2013).

The objective of the current study is to simulate the vegetation pattern using a fine resolution DGVM in terms of the synthesis of PFTs and biomes and their key functional response in terms of LAI and biomass to the environmental parameters.

## Materials and methods

### *Study area*

The study area, Himachal Pradesh (HP), India is shown in Fig. 1. The altitude ranges from 350 m to 6,975 m above the mean sea level. It is located between latitude 30° 22' 40'' N to 33° 12' 20'' N and longitude 75° 45' 55'' E to 79° 04' 20'' E (Ramachandra *et al.* 2012). The region has a deeply dissected topography, complex geological structure and rich temperate flora in the sub-tropical latitudes (Murthy *et al.* 2012). Physiographically the state of HP can be divided into five zones- *viz.,* (1) wet sub-temperate zone, (2) humid sub-temperate zone, (3) dry temperate-alpine high lands, (4) humid sub - tropical zone and (5) sub-humid sub-tropical zone (Chandrashekhar *et al.* 2003). The average annual rainfall is about 1600 mm. The climate varies between hot and humid in the valley areas to freezing cold in the areas of perpetual snow northwards. The soils of Himachal Pradesh can be divided into nine groups as: (i) alluvial soils, (ii) brown hill soil, (iii) brown earth, (iv) brown forest soils, (v) grey wooded or podzolic soils, (vi) grey brown podzolic soils, (vii) planosolic soils, (viii) humus and iron podzols (ix) alpine humus mountain skeletal soils (GSI 2012) on the basis of their development and physico-chemical properties. The forest area of Himachal Pradesh state is 55,673 sq km, which constitutes 66.52 % of the total geographical area of the region (FSI 2011). The major forest types are moist Siwalik and moist Bhabar Sal (3C/C2 (a,b), dry mixed deciduous forest (5B/C2), Himalayan sub-tropical scrub (9/C1/DS1), Chir Pine (9/C1 (a,b)), Oak scrub (12/C1/DS1), Himalayan temperate secondary scrub (12/C1/DS2), Cypress forest (12/E1), dry broad leaved and coniferous forest (13/C1), dry temperate conifer forest (13/C2 (a,b)) sub alpine pasture (14/DS1), dry alpine scrub (16/C1) and dwarf Juniper scrub (16/E1) (Champion & Seth 1968).

### *Methodology*

In the present study, an attempt was made to simulate vegetation in two spatial patterns across Himachal Pradesh: (i) contiguous sites at alpine and temperate transitions (ii) discrete sites covering varied vegetation types (Fig. 1). The sample grid design was aimed to include variability of model outputs with respect to the transition zone of changing vegetation types. This sample design also helps to identify each grid with reference to the land cover observed from satellite remotely sensed derived maps. Contiguous sites are preferred for validation of all kinds of fluxes in relation to the existing maps, whereas discrete sites help to assess the overall distribution of spatial pattern in the region. Simulation for the synthesis of PFT/biome and their LAI and biomass was carried out over a 70 year time period (based on annual mean climate data of 100 years) using a frame work of grid resolution of 10 km × 10 km. Study results were analyzed for 62 vegetation grids which included 40 contiguous and 22 discrete sites.

SEIB-DGVM generates daily climate of specified location based on NCEP/NCAR reanalysis of daily climatic dataset. The resultant climate data contain the following items: air temperature, soil temperatures at 0 - 10 cm depth, soil temperatures at 10 - 200 cm depth, soil temperatures at 300 cm depth, precipitation, total cloudiness, wind velocity, specific humidity, and daily air temperature range. The NCEP/NCAR reanalyzed climate data was interpolated from the available online generator. SEIB DGVM uses canopy level light interception in 3-D, which has advantage over the models using 2-D radiative transfer mechanisms in terms of absorption of photosynthetically active radiations by sub-canopy components such as herbaceous strata. SEIB operates on an average annual pattern of climate to grow vegetation digitally from bare ground in terms of various plant functional types constituting different biomes and synthesizing plant functional types (PFTs) as depicted in Annexure I and biomes in Annexure II.

Model operates by synthesizing a virtual forest in a window of 30 m × 30 m in which woody components and grasses establish, photosynthesize, respire, regenerate, compete and meet mortality, in a digital sense. In the current simulation experiment the model outcome was depicted as 10 km × 10 km grid cell. The SEIB-DGVM utilizes three computational time steps: a daily time step for all physical and physiological processes, a monthly time step for soil decomposition and tree growth, and an annual time step for vegetation dynamics and disturbance. SEIB induces the disturbance also at an appropriate stage as a mortality strategy.

## Results

### *Climate patterns*

Climate patterns for selected sites show a century wide trend of temperature (NCEP/NCAR) followed by temperature and precipitation trends for a typical year. This annual pattern is used iteratively for entire cycle of simulation to derive trends in PFTs and biomes. Precipitation range showed similarity across all the sites probably indicating homogeneity over the contiguous sites. Maximum air temperature at site 8(c), being located in deep valley region, showed very little variations in comparison to other two sites (19 & 25) for 100 years (Fig. 2).

DGVM outputs include various plant and ecosystem function parameters which can be used towards evaluating basic plant biophysical traits such as leaf area index and biomass to facilitate spatial representation and comparison with satellite-derived parameters/datasets.

### *Biome patterns and plant functional types*

In the contiguous sites out of the 40 locations studied, two biomes were simulated by DGVM including temperate deciduous (20 sites) and Himalayan evergreen forest (20 sites) over a period of 70 years of simulation. The model has depicted five plant functional types (temperate broad-leaved summer green (TeBS), Himalayan needle-leaved evergreen (HiNE), Himalayan broad-leaved summer green (HiBS), temperate herbaceous (Te-H), tropical herbaceous (TrH)) (Annexure I). With regard to herbaceous PFTs, model has synthesized temperate herbaceous ($C_3$) at 36 sites and only at 4 locations the tropical herbaceous ($C_4$). However, amongst the woody PFTs, TeBS was synthesized at 31 sites followed by HiBS at 21 sites and HiNE at 21 sites (Table 1).

In the discrete sites (Fig. 1), model has depicted five woody plant functional types (temperate broad-leaved summer, Himalayan needle-leaved evergreen, Himalayan broad-leaved summer green, temperate herbaceous, tropical herbaceous).

### *Functional parameters (LAI and Biomass)*

Patterns of PFT functioning over a period of 70 simulated years has been analyzed for conti-

**Table 1**. Plant functional types simulated over 70 years in contiguous sites (refer to Fig. 1(c).

| | | | |
|---|---|---|---|
| HiNE, HiBS, Te-H | HiNE, HiBS, Te-H | HiNE, HiBS, Te-H | HiNE, HiBS, Te-H |
| TeBS, HiNE, HiBS, Te-H | HiNE, HiBS, Te-H | HiNE, HiBS, Te-H | HiNE, HiBS, Te-H |
| TeBS, HiNE, HiBS, Te-H | TeBS, HiNE, HiBS, Te-H | TeBS, HiNE, HiBS, Te-H | HiNE, HiBS, Te-H |
| TeBS, HiNE, HiBS, Te-H | TeBS, HiNE, HiBS, Te-H | TeBS, HiNE, HiBS, Te-H | HiNE, HiBS, Te-H |
| TeBS, Te-H | TeBS, Te-H | TeBS, HiNE, HiBS, Te-H | TeBS, HiNE, HiBS, Te-H |
| TeBS, Te-H | TeBS, Te-H | TeBS, HiNE, HiBS, Te-H | TeBS, HiNE, HiBS, Te-H |
| TeBS, Te-H | TeBS, Te-H | TeBS, Te-H | TeBS, HiNE, HiBS, Te-H |
| TeBS, Tr-H | TeBS, Te-H | TeBS, Te-H | TeBS, Te-H |
| TeBS, Tr-H | TeBS, Te-H | TeBS, Te-H | TeBS, Te-H |
| TeBS, Tr-H | TeBS, Tr-H | TeBS, Te-H | TeBS, Te-H |

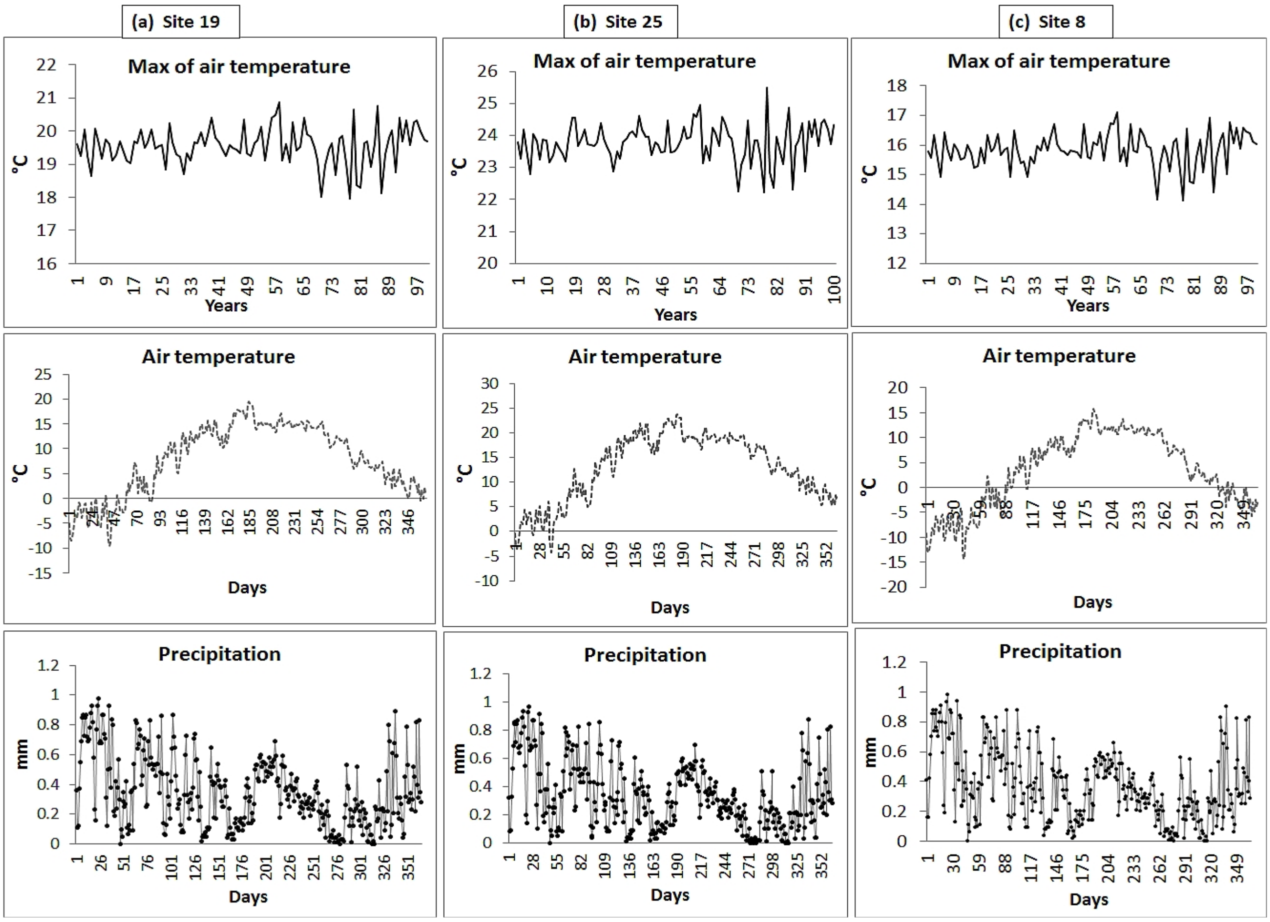



**Fig. 2**. Maximum air temperature, annual variation in air temperature and precipitation over selected sites 19 (a), site 25 (b) and site 8 (c).

guous and discrete sites with respect to leaf area index (Fig. 3) using the Jenks algorithm from Arc GIS software suite. Major PFTs *viz*., TeBS, HiNE, HiBS and Te-H were analyzed for comparison in terms of the maximum LAI synthesized. In contiguous sites, TeBS PFT was initially synthesized in the southern most cells and its LAI in TeBS PFT was 2.75 in the 70th year (Fig. 3). In discrete sites, TeBS synthesized LAI ranging from 0.26 to 2.41 from 1st year to 70th year. In contiguous grids, HiNE and HiBS are synthesized in the northern most cells only. In discrete sites, HiNE occurred at four grid sites in the beginning of simulation with LAI ranging from 1.82 to 4.33. Whereas in the continuous sites HiNE showed large increment in LAI pattern across 70 years of simulation and ranged from 3.51 to 6.79. HiBS initially synthesized high LAI of 4.39 and gradually decreased to 1.47 at 70th year. Te-H LAI value ranged from 1.79 to 3.92 in the initial years of simulation and decreased to 2.50 (Fig. 3) in the 70th year.

Model provided outputs with respect to root, leaf and trunk biomass for the respective simulation years indicating the accumulation pattern in PFTs. The biomass accumulation patterns from the model outputs in different sites across contiguous transects *viz.,* 5, 19, 22 & 37 are shown in Fig. 4. Sites 22 and 37 are represented by two PFTs whereas other grids have more number of PFTs. TeBS showed a higher biomass accumulation of 140 Mg C ha$^{-1}$ at site 22 whereas at site 37 it showed a lesser biomass level of 40 Mg C ha$^{-1}$. Site 5, which showed very high biomass of HiNE (160 Mg C ha$^{-1}$) while in the same grid HiBS synthesized very low biomass (~30 Mg C ha$^{-1}$). As expected, herbaceous PFT showed lower level biomass compared to the woody PFTs. At site 19, three woody PFTs - HiNE, TeBS and HiBS were synthesized and they accumulated biomass of 124, 43, 32 Mg C ha$^{-1}$ respectively (Fig. 4).

Biomass pattern in discrete sites has been represented as two examples - site 6 having more number of PFTs and site 11 having less number of PFTs. Site 6 belonging to subtropical zone, has generated three woody PFTs HiNE, TeBS and HiBS and they accumulated biomass of 120, 52, 22 Mg C ha$^{-1}$ respectively. At Site 11, TeBS was the only woody PFT synthesized which showed higher biomass (180 Mg C ha$^{-1}$) at 30$^{th}$ year and decreased to 105 Mg C ha$^{-1}$ at 70$^{th}$ year due to distrubance factor such as mortality and fire (Fig. 5).

### *Biomass distribution in PFTs, Biomes and validation*

A SEIB-DGVM simulation of 70 years has provided the grid wise biomass accumulation pattern across the contiguous grids as well as the discrete grids for the synthesized PFTs and biomes (Figs. 4 & 5). Amongst the contiguous sites, HiNE has the highest biomass of 165 Mg C ha$^{-1}$ and 124 Mg C ha$^{-1}$ at sites 5 and 19 respectively, whereas, TeBS PFT biomass was recorded as 140 Mg C ha$^{-1}$ at site 22.

Highest biomass of 227.2 Mg C ha$^{-1}$ (Table 3) was simulated in Himalayan evergreen biome observed across the study area. In contiguous sites, the Himalayan evergreen biome showed biomass ranging from 115.6 to 210.7 Mg C ha$^{-1}$. Temeprate deciduous biome synthesized 142.7 Mg C ha$^{-1}$ biomass in contiguous category whereas in discrete sites temperate deciduous accumulated 111.6 Mg C ha$^{-1}$. The herbaceous biomes in discrete sites *viz.,* moist savanna accumulated 74.6 Mg C ha$^{-1}$ indicating prevalence of woody elements. The alpine biome recorded lower biomass levels 4.1 Mg C ha$^{-1}$ typical of the alpine systems.

Himalayan evergreen forest/woodland biome biomass ranged from 60 to 230 Mg C ha$^{-1}$ and the temperate deciduous forest synthesized 20 to 145 Mg C ha$^{-1}$ of biomass which is similar to the range of biomass reported by FSI (2011) (Table 4). As discussed above, true validation of the model outcome with the ground inventory of biomass may pose difficulties due to several assumptions and generalizations made for defining a PFTs in the model, however, it can be seen that the biomass simulations are very much matching with the reported biomass levels (Table 4) .

## Discussion

### *Biome and plant functional types*

The SEIB simulations have synthesized the PFTs for the 70 years of simulations. It can be seen that depending on the various climatic controls, different grids have different distribution of PFTs. In contiguous sites, out of 40 sites, 12 showed maximum number of PFTs (TeBS, HiBS, HiNE and Te-H) as compared to the rest which showed less than three PFTs (Table 1).

Most of the DGVMs simulations are carried out in order to understand the long term vegetation-climate interactions in dynamic sense rather than predicting an accurate PFT or biome at a particular location. Moreover, the DGVMs mostly use a coarse resolution climate data and the potential vegetation and also include several theoretical considerations that make the one to one comparison of the DGVM outcome with the ground observations a bit difficult (Quillet *et al.* 2010 & Verheijen *et al.* 2013). In the present study, biomes simulated over the contiguous sites in 10 km x 10 km grids were compared with available vegetation map based on remote sensing data (IIRS 2002) (Table 2). The PFTs and biomes simulated by the DGVM were compared with its constituent vegetation types from the available vegetation map. The major vegetation cover types are mixed conifers followed by Deodar, dry deciduous, Chir pine, moist deciduous, Oak, *Betula*/*Rhododendron* and temperate broad leaf (Table 2). Simulated

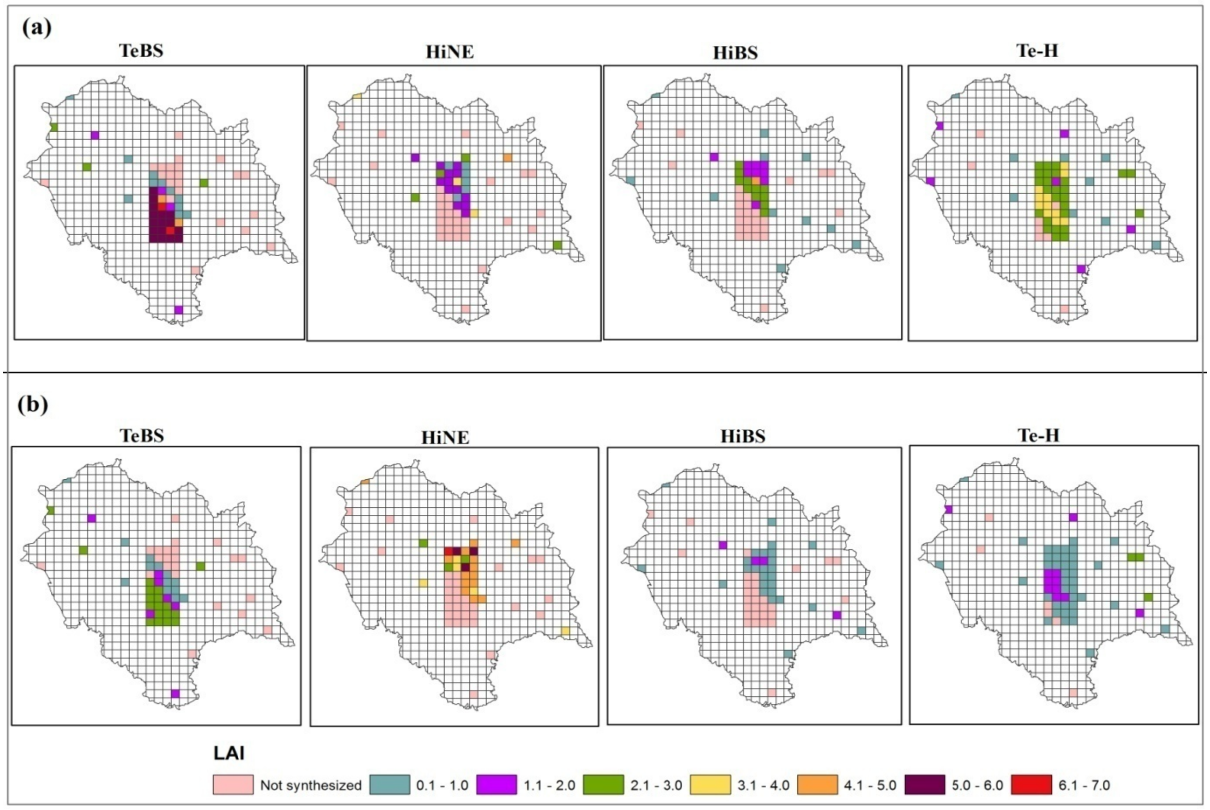



**Fig. 3**. Maximum LAI of four different PFTs (TeBS, HiNE, HiBS and Te-H) simulated by the SEIB model in 1st year (a) also in 70th year (b).

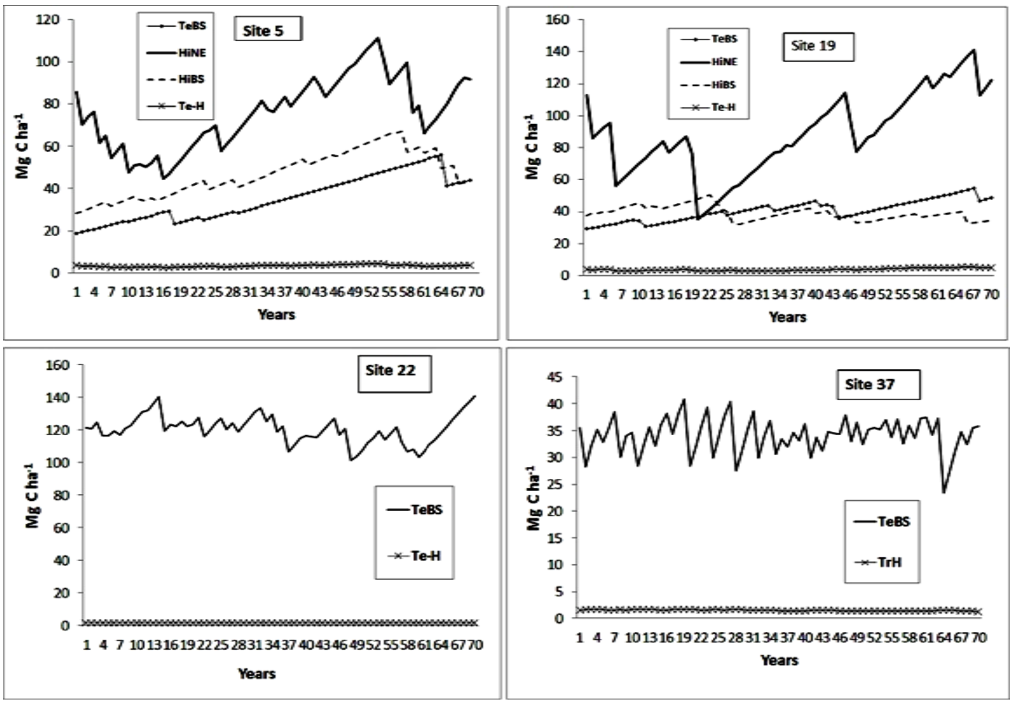
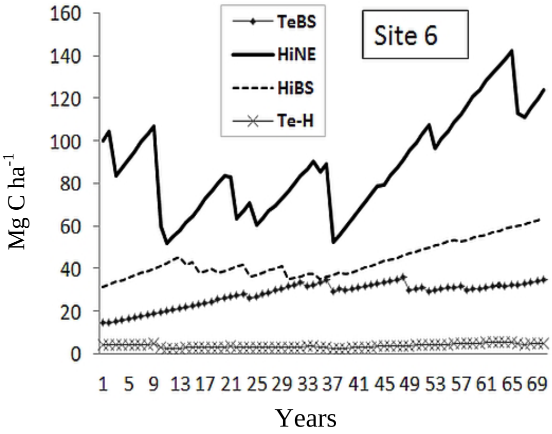



**Fig. 4**. Total biomass patterns in site 5 (a), site 19 (b), site 22 (c) and site 37 (d) at contiguous sites over 70 year period for different plant functional types synthesized by the model.



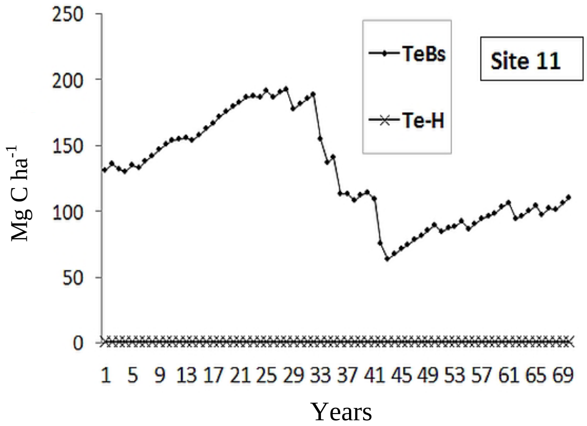




**Fig. 5.** Temporal biomass trends in selected grids from discrete sites.

**Table 2**. Contingency matrix of simulated biome in the grids from SEIB model with vegetation map (the numbers in the cells are the number of grid for the particular pair of observation).

| Simulated | Observed | | | | | | |
|---|---|---|---|---|---|---|---|
| | Cropped | Alpine Grassland | Deodar Gregarious | Plantation | Snow | Temperate Conifer | Total |
| Himalayan Evergreen | 1 | 2 | 6 | 2 | | 4 | 15 |
| Himalayan Evergreen/ Deciduous | | 1 | | 1 | | 1 | 3 |
| Moist savannah, Himalayan deciduous/Evergreen | | | 1 | | | 1 | |
| Temperate Deciduous | 2 | 2 | 6 | 1 | 4 | 5 | 20 |
| Total | 3 | 5 | 13 | 4 | 4 | 11 | 40 |

**Table 3**. Maximum and minimum biomass of synthesized biomes in contiguous and discrete sites.

| Sites | Biome | Biomass (Mg C ha$^{-1}$) | |
|---|---|---|---|
| Contiguous Sites | | Minimum | Maximum |
| C3 | Himalayan Evergreen | 115.6 | 210.7 |
| C27 | Temperate Deciduous | 41.6 | 142.7 |
| Discrete Sites | | | |
| D2 | Temperate Deciduous | 20.1 | 111.6 |
| D6 | Himalayan Evergreen | 63.9 | 227.2 |
| D14 | Alpine/Arctic | 4.1 | 4.1 |
| D18 | Moist savanna | 54.8 | 74.6 |

DGVM biomes (Annexure II) had similar occurrence in terms of biomes at 12 sites mapped as Deodar gregarious from the available map. Temperate forests corresponded to *Betula* or juniper woodlands and match the simulated results. Categories available as cropped or plantations may not be comparable in terms of the potential vegetation of the study area that must have been prevalent should the natural succession proceed.

### *LAI synthesis in PFTs and biomes*

In the contiguous grid sites, TeBS PFT dominated the temperate deciduous biomes in the southern grids which represent the sub-tropical Himalaya and accumulated higher LAI compared to other PFTs in the same biome. HiNE PFT dominated in the Himalayan evergreen biome sho-

**Table 4.** Comparison of the range of biomass (Mg C ha$^{-1}$) for biomes by the model with FSI (2011).

| Biomes | Modeled Output | FSI (2011) |
|---|---|---|
| Himalayan Evergreen Forest | 60-230 | 65-160 |
| Temperate Deciduous forest | 20-145 | 80-180 |

wing higher LAI range whereas, HiBS PFTs had low LAI as expected in the temperate / sub alpine Himalayan region.

The model execution helped to derive the within transect and across region patterns of PFTs with respect to vegetation and biomass for comparing with satellite derived vegetation maps biomass inventory.

## Conclusions

In India, the growing dependence of the millions of inhabitants in the forest and its fringe areas has put enormous pressure on the forest resources. Only scientific and sustainable forest management prescriptions can sustain such an anthropogenic pressure as well as the possible impacts of climate change. The recent DGVMs with better resolution provide holistic and integrated ecological outcomes in terms of structural and functional parameters such as LAI and biomass for various climatic (SRES) scenarios. These dynamic models, if adapted and modified to include better locale specific ecological conditions, will be able to provide key input for robust adaptation and mitigation strategies. The DGVM outcomes may also enable countries for the compliance to international protocols related to climate change and national communication to the UNFCC as well as may address the various requirements of REDD+.

## Acknowledgements

The technical support from the SEIB author, Dr H. Sato was immense. The funding for the project was provided from ISRO-IGBP-NCP. Authors acknowledge the kind suggestions made by Professor J. S. Singh. The authors are thankful to the three reviewers for their extensive comments that have helped in improving the manuscript.

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(Received on 03.10.2013 and accepted after revisions, on 10.12.2013)

**Annexure I.** Plant functional types (*adapted for Himalaya) occurring in study area and their environmental ranges (Sato *et al.* 2007). ($TC_{min}$- minimum coldest-month temperature for survival; $TC_{max}$- maximum coldest-month temperature and $GDD_{min}$- minimum growth-degree-day sum).

| Plant Functional Types | Abbreviation | $TC_{min}$ (°C) | $TC_{max}$ (°C) | $GDD_{min}$ (5 °C base) |
|---|---|---|---|---|
| Temperate broad-leaved summergreen | (TeBS) | -17.0 | 15.5 | 1200 |
| *Himalayan needle-leaved evergreen | (HiNE) | -32.5 | -2.0 | 600 |
| *Himalayan broad-leaved summergreen | (HiBS) | - | -2.0 | 350 |

**Annexure II.** Biome types (*adapted for Himalaya) occurring in study area (Sato *et al.* 2007; Haxeltine & Prentice 1996).

| Biome | Dominant PFT |
|---|---|
| Temperate deciduous forest | TeBS |
| *Himalayan evergreen forest | HiNE |
| *Himalayan deciduous forest | HiNS or HiBS |
| Moist savanna | any |