Pt. Govind Ballabh Pant

Memorial Lecture : XXIV

Prof. P. S. Roy

September 10, 2018
at
Kosi-Katarmal, Almora

G.B. Pant National Institute of Himalayan Environment and Sustainable Development
(An Autonomous Institute of Ministry of Environment, Forest and Climate Change, Govt. of India)
Kosi-Katarmal, Almora, 263643, Uttarakhand

Prof. (Dr.) Parth Sarathi Roy

- **NASI Seniour Scientist Platinum Jubilee Fellow**
  Centre for Earth, Ocean and Atmospheric Sciences University of Hyderabad, Hyderabad
- **Former Director & Outstanding Scientist**
  ISRO-Indian Institute of Remote Sensing, Dehra Dun
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Notable Professional Achievements:

- ·International Expert and Team Leader (2015-2018) Government of Bangladesh
- Invited Speaker (2014) Swiss Federal Office for the Environment (FOEN) and Swiss Academy of Sciences. Vienna, Austria
- Invited Speaker (2014) Brazilian Space Agency (INPE), Curitiba, Paraná, Brazil
- Visiting Professor (2014) University of Illinois, Urbana-Champaign, USA
- Erasmus Mundus Visiting Scholar (2013) University of Twente, The Netherlands
- Visitor (2013) University of Freiburg, Germany
- Global Expert Team (1997) European Space Agency, ISPRA (Italy)
- Chairman (2005-2010) ISRO-NNRMS Geospatial Data Standards Committee
- Evolving Geospatial Education Strategy Group (2012-2013) MHRD, Govt. of India
- High level Working Group on Western Ghats (2012-2013) MoEF, Govt. of India
- Procedure for National 10K Cartographic Maps (2011-2012) MST, Govt. of India
- Project Director (2004-2010) National Natural Resource Census, NNRMS

Fellow of Academies:

- Fellow of National Academy of Sciences (FNASc)
- Fellow of National Academy of Agriculture Sciences (FNAAS)
- Fellow of Indian Society of Remote Sensing
- Fellow of National Institute of Ecology (FNIE)
- Fellow of Indian Geophysical Union (FIGU)
- Fellow of Telangana Academy of Sciences

Awards & Recognitions:

- *B.P. Pal National Environmental Fellow Award*, MoEFCC, GoI, Delhi
- *Dr. Boon Indrambarya Gold Medal*, ACRS, Beijing (China)
- *NASI Platinum Jubilee Senior Scientist Fellow Award*
- *Sri Hari Om Ashram Vikram Sarabhai Award*, PRL, Ahmedabad
- *ISRO Performance Excellence Award* (2015)
- ISRO *Merit Award* for Space Science and Applications
- *ISRO-ASI Award*, Astronautical Society of India
- *Young Scientist Award* (1991) Indian Remote Sensing Society
- Life Time Achievement *Bhaskara Award*, Indian Society of Remote Sensing
- *Life Time Achievement Award*, Emergency Management Research Institute, Hyderabad
- *"Maharana Udai Singh Award"* for distinguished service, Mewar Foundation, Jaipur
- *India Geospatial Leadership Award* for 'Capacity Building and Professional Development'
- ISRO Team Excellence award for Rajiv Gandhi National Drinking Water Mission
- ISRO Team Excellence award for ISRO Disaster Management Support Programme
- Team Excellence Award for Assessment of Irrigation Potential projects in India

Summary of Research Contribution:

- ·Pioneering contribution of Forest cover assessment of India using two-time period satellite data sets (i.e. 1972-75 & 1980-82) for forest mapping and monitoring in 1980. Prof. Roy developed methodology for restoration ecology for wasteland development planning and actual site identification using geospatial technique.
- Prof Roy made outstanding research contribution in conservation ecology by characterizing biodiversity at landscape level by integrating satellite remote sensing, landscape ecology and field sampling. He has been Project Director of the national program of "Biodiversity Characterisation at Landscape level". It became first

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Earth Observation and Sustainable Development of the Himalayas

Parth Sarathi Roy
National Academy of Sciences, India – Senior Scientist
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University of Hyderabad, Hyderabad, India

It is my privilege and honour to deliver the 24th Pandit Govind Ballabh Pant Memorial Lecture on the annual day of G.B. Pant National Institute of Himalayan Environment and Sustainable Development and the birth anniversary of Pt. Govind Ballabh Pant. I am thankful to the authorities for acknowledging my research contributions and for providing the opportunity to deliver the memorial lecture. G.B. Pant institute, an institute of national importance, has been carrying out yeoman service for the nation with particular reference to the Himalayas. I congratulate the Director and his team of scientists and employees on this occasion of the institute.

Tribute to Pandit Govind Ballabh Pant

Pandit ***Govind Ballabh Pant****, born on 10 September 1887, in Khoont village, on the slopes of the Shyahi Devi hill, near Almora, was an Indian freedom fighter and one of the architects of modern India. Today, as a mark of tribute, several scientific institutions, including hospitals, educational institutions and foundations, bear his name. He was one of the most respected leaders of our freedom movement. In honour of his exemplary services to the nation, Pantji received India's highest civilian honour, the Bharat Ratna, in 1957, and he continued to be Chief Minister of free India. Among his many achievements as a statesman was the abolition of the zamindari system. His judicious reforms and stable governance in Uttar Pradesh stabilized the economic condition of the most populous state of India.*

1. Introduction

The Himalayas hold the most fragile ecosystems on Earth. Hitherto the ecosystem services provided by the Himalayas have sustained a vast human population and high levels of biodiversity. Environmental, biological, socio-cultural and economic variations across the Himalayas have led to the evolution of diverse and unique traditional agroecosystems, crop species and livestock, which help traditional mountain farming societies to sustain themselves. The survival of the Himalayan ecosystems and wildlife is now threatened by human activities like timber harvesting, livestock grazing, agricultural expansion and climate change. Highly sensitive to climate change, these ecosystems are being affected at a faster rate than the other terrestrial ecosystems. The region also experiences many disasters like, earthquake, landslides, cloud burst, flash-floods and forest fire causing major damage to life and infrastructure. The climate of the Himalayas is not uniform and is strongly influenced by the South Asian monsoon and the mid-latitude westerlies. Projecting the impacts of climate change in the Himalayas is challenging because of the complex interactions between global, regional and local forces and responses. The historical climate data relating to the region are sparse, but scientists are fairly confident about projections of future temperature increases. Climate change is predicted to be greater in the Eastern Himalayan region compared with the IPCC's projections for the Asian region. The altitudinal shift in vegetation belts is expected to be around 80 – 200 m per decade, with greater shifts at the higher altitudes. Glaciers, snowfields and high-altitude ecosystems, with the biodiversity therein, will be the most impacted by climate change. There is more uncertainty in the projections of the amounts and timing of precipitation (Fig 1 and 2) [1]. Knowledge of human adaptation in the Himalayas has developed more slowly compared to other world mountain systems. However, the impact is going to be severe as the people have limited adaptive capacity considering the economic, socio-political and technological shortcomings in the region.

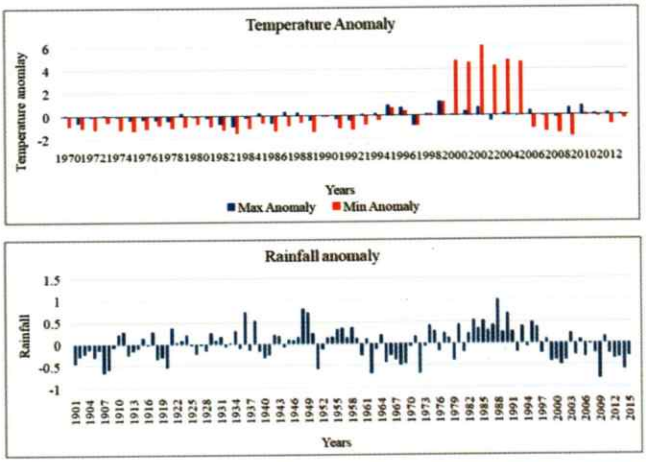

Figure 1: Temperature and rainfall anomaly over the Northern Himalayas (*Source: Roy et al., 2018*) [1].

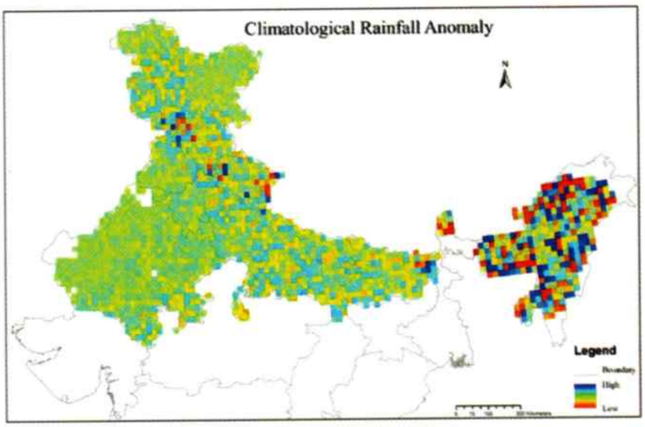

Figure 2: Gridded long-term climatological rainfall anomaly over the Himalayas *(Source: Roy, et al., 2018)*[1].

2. Unique Himalayan Mountains

The Hindu Kush–Himalayas (HKH) is a dynamic landscape with a rich biodiversity. The region is endowed with a rich variety of gene pools and species. The region hosts parts of four Global Biodiversity Hotspots, namely the Himalayan Hotspot, the Indo-Burma Hotspot, the Mountains of South-West China Hotspot and the Mountains of

[1] Roy et al. (2018): Climate anomaly of Himalaya, India using gridded climate data of India Meteorological Department: Climate and Ecology.

Central Asia Hotspot. It is well known for its soil formations, vegetation types and climatic conditions and for its unique flora and fauna, with high levels of endemism. There are numerous critical ecoregions of global importance. Approximately 39% of the HKH is grassland, 20% forest, 15% shrub land, and 5% agricultural land. The remaining 21% is barren land, rocky outcrops, built-up areas, snow cover and water bodies. The elevation ranges from < 500m to > 6000m. The landscapes and communities in the HKH region are being simultaneously affected by rapid environmental and socioeconomic changes. Identifying and understanding the key ecological and socio-economic parameters of the mountain ecosystems have become crucial for planning and policy making for environmental management and sustainable development of the region. The welfare of some 1.3 billion people downstream is also linked to the state of the natural resources of the HKH region.

3. Sustainable Development in the Himalayas

The 2030 Agenda marks a milestone in the evolution of society's efforts to define and manage progress towards sustainable development in all its facets: social inclusion, economic growth and environmental sustainability. The Sustainable Development Goals (SDGs) and the associated Global Indicator Framework represent the first truly data-driven framework in which countries can engage with the aim of evidence-based decision-making. The Agenda recognizes that ***'if you can't measure it, you can't manage it'*** and that data are the enabler of implementation. The 2030 Agenda aims to be relevant to all countries, rich and poor, leaving no one behind. The scope and scale of it is such that effective monitoring of progress towards achieving the hundreds of targets and reporting on the associated indicators by countries will require substantial modernization of many national statistical and geospatial systems, as well as the integration and exploitation of many new data sets.

The scale and scope of the indicator framework are daunting even to the most developed countries, and there is broad recognition that there will be substantial requirements of the supporting data involved in the measurement and monitoring of a great number indicators at different scales. Measurement of some of the indicators is entirely achievable for many countries today, whilst tracking others will require improvements and robust methodologies for which consistent and comparable information needs to be developed. The design of the 2030 Agenda is driven by the recognition that future sustainable development strategies must be evidence-based and data-driven. Satellite data have a role to play in relation to most of the 17 goals and around a quarter of the targets.

3.1 Data-Driven Development

Significant investments have already been made by national governments in space-based infrastructure that is providing free, open, continuous and consistent earth observation (EO) satellite data streams. Value of the data has been proven in many sectors: these data support the science that underpins strategies for global decision-making and for monitoring our progress at all geographical scales as we explore new development paths aimed at sustainable management of the planet. The indicator framework of the 2030 Agenda is predicated on the emergence of a data revolution, including within the National Statistical Organisations (NSOs) that will be required to routinely report the progress of countries towards the targets. NSOs have long used a diversity of data sources and techniques to produce official statistics, such as censuses and household surveys, as well as administrative data. Further, in today's technologically driven society, citizens are exposed daily to geospatial datasets through mobile phone technology, GPS and Internet mapping applications. With the importance of high-quality, timely and accessible data in informing the SDGs, there is recognition that the full realization of the 2030 Agenda at all levels (from local to global scales) will require the use of multiple types and new sources of data, including geospatial information and EO satellite data. Advanced data processing and big data analytical techniques will be needed to extract the necessary information from all these data sets.

3.2 Role of Earth Observation

The science of satellite remote sensing integrates the understanding, interpretation and establishment of relations between natural phenomena and measurements of the electromagnetic energy that is either emitted or reflected from the Earth's surface or its atmosphere. These measurements are made for a large number of locations on the Earth's surface by sensors onboard space-borne satellites, and the output is in the form of imagery. The last 50 years since the first satellite was launched have seen space-borne remote-sensing advance from small-scale production of low-resolution images for a select few, motivated primarily by military requirements in the Cold War era, to daily acquisition of over 10 terabytes of information, increasingly available to all, motivated largely by the needs of Earth-observation science. More than 150 Earth-observation satellites are currently in orbit, carrying sensors that measure different sections of the visible, infrared and microwave regions of the electromagnetic spectrum. The majority of Earth-observation satellites carry "passive" sensors. Newer satellites also employ "active" sensors that emit energy and record the reflected or backscattered response, from which information about the Earth can be inferred. Features of the instruments depend on the purpose for which each was designed. In simple terms, these are (1) the minimum size of objects distinguishable on the Earth's surface (spatial resolution), (2) the width of the region of electromagnetic spectrum sensed (spectral extent), (3) the number of digital levels used to express data collected (radiometric resolution) and (4) the intervals between imagery acquisition (temporal resolution). Moreover, the number of regions of spectrum for which data are collected, the time taken to revisit the same area of Earth, the spatial extent of images produced, and whether the satellite's orbit follows the Sun-illuminated section of the Earth (Sun synchronous) or remains over a fixed point on the Earth (geostationary) all vary between satellites and their sensors. There are various satellite systems that provide bio-physical, ecological and climate variables for studies in the Himalayas. The development of satellites has been in step with increasing computing capabilities. As the data storage capacities and processing speeds increased, simultaneous enhancement in the ability of Earth-observation satellites to capture, process and return information is noted. Fifty years of Earth-observation satellite development has provided a wealth of memorable images and has driven forward our understanding of Earth-system processes.

Today satellite observations are significant data sources for monitoring, measuring and understanding the Earth's terrestrial, aquatic and climatic environments, as well as used to assess how do the terrestrial, aquatic and climatic environments are changing and how does each component react to human influence. Some of the most revolutionary advances brought about by satellite observations are building spatial repository of natural resources, improving and updating maps. Satellite remote sensing has thus proved invaluable in studying natural or human disturbed ecosystems or fragile and extreme environments.

Recent years have seen the application of data from Earth-observation satellites extend into new research fields. Urban and regional planners require nearly continuous acquisition of data to formulate policies and programs, and new satellites with increased spatial and spectral resolution provide data to meet these requirements. From rainfall monitoring, flood-risk modeling, subsidence detection and forest species, density and degradation monitoring to archaeological surveying, melting glaciers and crime-risk mapping from nighttime imagery, satellite imagery is now widely used for societal applications. The 46 years' archive of Landsat imagery provides data for land-use and urban-growth modeling, whereas nighttime imagery of electrified urban areas is facilitating the construction of global human-population spatial databases, which are finding applications in disease-burden estimation and epidemic modeling. Globally consistent satellite data now exist on a range of climatic variables, including temperature, rainfall and vegetation area. These data are beginning to find significant applications across the low-income regions of the world in exploring food security and resource accessibility and construction of early-warning systems in planning for the effects of crop failure and disease outbreaks. The resultant maps are improving decision making and efficient resource allocation. Moreover, with the climatic and environmental preferences and tolerances of numerous species quantified, the same global imagery is helping to infer present and future distributions for improved conservation planning. From the availability of habitats for giant Pandas to the distributions of malarial mosquitoes, satellite imagery has become an important asset for ecologists and epidemiologists alike.

The increasing number of Earth observation satellites and the availability of imagery are driving down data costs. Free online databases and open distribution of processed imagery are making many types of data available to all. Although this is a welcome trend, even unprocessed data from numerous satellites are not readily available and many operators still charging high fees for imagery. Software packages for handling and processing satellite imagery were previously rare, as well as complex and expensive, but they are becoming widespread and more user friendly. Basic software is now, in many cases, cheap or even free, but the most powerful and advanced programs still require costly licenses. Training in the use of satellite imagery has also grown as such data have become central to numerous disciplines, but the costs of courses of cutting-edge computing, imagery and software often remain prohibitively high for institutions in low-income countries.

Increasingly, limitations of satellite data applications have shifted from the technology of acquiring the data to the techniques required on the ground to exploit information within remotely sensed data optimally. The conventional trade-offs in spectral, spatial and temporal characteristics, which must now be solved by choosing imagery from different satellite sensors, are gradually being made unnecessary by new technology. Forthcoming launches and plans should herald the first images with a spatial resolution under 0.5 m, high spatial resolution SAR imagery, laser imaging and detailed nighttime data. Improvements in data processing and fusion could help eliminate cloud-obscured and nighttime data loss and provide multi-image virtual databases for modeling of environmental and social processes. Finally, the declassification of military space technology may well provide valuable new data in the future, just as it has done in the past. There can be no doubt that satellite remote sensing is likely to continue to grow as an operational tool for mapping, monitoring and managing the Earth, as a profit-making entity and as a primary data source for Earth-system science.

The existing trends in satellite design are likely to continue, and new ones will emerge, driven by both operational need and profits. Although global issues such as climate change and its effects will continue to provide justification for large multi-sensor satellites, the design directions in which smaller commercial satellites will head is less clear. The potential for real-time imagery has just begun to be realized, and personalized imagery beamed to handheld devices will soon show users their positions in traffic or the current weather at their destinations. To speculate further, the online availability of such imagery could facilitate a real-time or "live" Google Earth. Google Earth Engine allows us to process huge quantities of satellite data for various environmental analyses online. Such a resource potentially enables revolutionary studies involving the global tracking of terrestrial and oceanic life, which could help create, for instance, real-time disease epidemic models, dynamic traffic control and reactive conservation - but it also raises significant security and privacy concerns.

3.2.1 How can satellite data help?

Satellite Earth observation data offer benefits for the SDGs and for the NSOs reporting against the indicators:

- ❖ Satellite Earth observation data make the prospect of a Global Indicator Framework for the SDGs viable. For many indicators, the coverage and frequency of measurements from which the indicators are derived would simply not be feasible, technically or financially, if satellite observations were not used.
- ❖ They will potentially allow more timely statistical outputs, reduce the frequency of surveys, reduce the respondent burden and other costs and provide data at a more disaggregated level for informed decision making.
- ❖ They will improve the accuracy in reporting by ensuring that data are more spatially-explicit and directly contribute to informing the targets and indicators, helping to augment statistical data, validating national statistics and providing disaggregation and granularity of the indicators. Satellite data can support the evolution from traditional statistical approaches to more measurement-based solutions as some challenges, including some in relation to the environment and human populations, become more pressing, and the need for more accurate, spatially explicit and frequently updated evidence grows.

Satellite EO data presents unique opportunities for countries to engage in the SDGs. But there are some significant technical challenges, such as the volume of data and our capacity to integrate different data streams, including the combination of geospatial data with traditional national statistical data. Space data providers of all kinds, including public-good agencies and commercial data and value-added information providers, are exploring new strategies for managing the enormous data volumes and for extracting the underlying information so that users of all types and sizes can access and analyze satellite data. Online virtual laboratories such as Google Earth Engine, the Copernicus Data and Information Access Service, ESA's Thematic Exploitation

Platforms, NASA's Earth Exchange and Descartes Labs are changing user expectations and stimulating moves towards 'bringing users to the data' and providing simpler formats and means of analysis.

4. Examples

4.1 *Topography and Altitudinal Mapping in the Himalayas: Prospects from Space*

Topographic variations and altitude determine the environmental, biological, socio-cultural and economic variations in the Himalayas. They also manifest in diverse and unique traditional agroecosystems, crop species, and livestock among the traditional mountain farming societies to sustain themselves. Digital satellite imagery provides substantial high-quality data for mapping, inventorying, monitoring and surveying. In the last decade, high-resolution satellite imagery from satellites such as IKONOS, SPOT5 and Quickbird has opened a new era of remote sensing and photogrammetry as their 1-m resolution imagery will display sufficient metric quality to support geo-positioning with meter-level accuracy and topographic mapping at scales of 1:10,000 and larger. Recently, the use of high-resolution satellite imagery in digital mapping has increased significantly and has become a reliable substitute for aerial photography in many applications. HRSI also offers the capability for rapid data acquisition in large areas. In the last decade, several mathematical models for satellite sensor orientation and 3D geo-positioning have been investigated. These models can be categorized into two groups: (1) rigorous mathematical models that can present accurately satellite sensor motion in space and the relationship between the satellite image space and the ground space and (2) non-rigorous mathematical models (known as empirical models) that can approximate the relationship between the image and the object spaces with the aid of the control points. The empirical mathematical models do not need any information about the sensor motion in space or the satellite ephemeris data. They rely solely on the use of the control points to construct the relationship between the image and object spaces. Generally, the rigorous mathematical models are more accurate than the empirical mathematical models. However, because of the restricted satellite sensor information of some of the new high-resolution satellites, the need to change the mathematical model for different satellite sensors and the need for specialized software, the use of empirical mathematical models has been increasing. The great benefit of using empirical mathematical models is that one set of equations can be used directly and can be applied to different images from different sensors. Recently, the 3D affine model has gained considerable interest due to its simplicity and accurate results. The model is linear in its unknowns, does not require any further information about the satellite sensor and is a straightforward model that requires a minimum of four ground control points. The model was tested for IKONOS and Quickbird satellite images, and the results revealed that the 3D affine model is a practical model that can be used for modeling high-resolution satellite sensors. In remote sensing, black-and-white or gray-scale imagery is called panchromatic, and color imagery is called multispectral. Panchromatic satellite-imagery resolution varies from 60 cm, for the Quickbird satellite, to 1 m for the IKONOS satellite, 5 m for the Indian Remote Sensing series, 10 m for the French SPOT satellite series and 15 m for the Landsat 8 satellite. It has the potential to provide topographic details in the form of digital elevation models or terrain models. The 3D affine model and different forms of the 3D Polynomial model were utilized to calculate the IKONOS/Quickbird, IKONOS/SPOT5, Quickbird/SPOT5 image transformation parameters and study the potential of use of these models for topographic mapping. Several factors were examined, including the number and accuracy of the GCPs, the base-to-height ratio of the stereo images and the image viewing angles. The effects of the Earth's curvature and the reference coordinate system used were assumed to be minimal because of the small size of the area covered by the stereo images and the use of the local grid coordinate system.

4.2 Vegetation Phenology

Lieth defined phenology as '*the study of the timing of recurring biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species*'. Phenological observations of vegetation are among the most important data in identifying how a plant species responds to regional climatic conditions and its changes because the phenology of a plant depends on seasonally varying environmental conditions such as day length, air temperature and water availability. These factors influence plants during different development stages, viz., germination, flowering and senescence. Shifts in the phenology of plants provide evidence that species and ecosystems are being influenced by global environmental change. Understanding these phenological responses are critical requirements for projecting future ecosystem dynamics in response to climate changes. In mid-latitudes, budding, leafing and flowering of plants depend highly on the air temperature. So, with increasing temperatures, the plant development that takes place in spring starts earlier within a year. The relationship between vegetation phenology and climate is crucial in the context of global change research as it indicates the dynamic responses of terrestrial ecosystems to climate changes. Variability in vegetation phenology has been widely documented at regional and global scales. However, the magnitudes of these changes vary with location, species and investigation period. Phenological patterns in the Himalayas are poorly understood because of the region's richness in species and lack of historical ground-based observations. Field-based observations on rhododendrons in the Himalayas show that flowering has started taking place a month earlier than in the past in some species. The Alpine plant diversity of the Himalayas is greater than the global average, and there is significantly higher plant diversity and richness at the elevations between 4200 m and 4500 m compared to similar elevations of any other mountain range. Studies show that warming will cause significant decline in biodiversity across a wide variety of alpine habitats in the Himalayas, including the Tundra and rangelands. With their limited geographic range, endemic species are particularly susceptible to climate change. The flowering of most alpine species is significantly influenced by the pace of snow melt. This will affect the alpine vegetation and flower-dependent animals due to disruptions in the vegetation - pollinator relationships. Species found at lower elevations can migrate to higher elevations. Alpine ecosystems are particularly vulnerable to warming as species occurring near the mountain tops will have no space for their upward march.

4.2.1 Monitoring phenology changes through remote sensing

Due to the terrain characteristics, conventional data collection methods such as ground-based surveys and inventories are complex and time and labour intensive to implement in the remote areas of mountains. Even station-based records relating to species composition and phenology may introduce uncertainties due to the limited nature of in-situ observations, human bias and local perspectives at the species level. Species occurrence and distribution data are therefore relatively coarse and not well recorded in most of the world mountains, particularly in the Himalayan region. The use of remotely sensed data provides a great deal of information and improves our ability to monitor mountain ecosystems even in highly undulating terrains. Now a day's satellite data and field-based surveys are the two main approaches used to study phenology changes, particularly in mountain regions. The time-series data derived from satellite images have been widely used to study vegetation phenology at the landscape, regional and global scales. The start, end and length of the growing season are the key phenological variables that are often estimated through satellite remote sensing. These variables are derived using algorithms that are based on threshold values, inflection points in time-series greenness curves, rates of changes of vegetation index values and so forth. The Normalized Difference Vegetation Index (NDVI) is the most common vegetation index used for estimating the dynamics of vegetation due to climate change. NDVI is the normalized difference in the bi-directional reflectance's in the red and near-infrared (NIR) portions of the spectrum and is based on the contrast in the spectral reflectance of photosynthetically active vegetation, which characteristically has a low reflectance in the red portion of the spectrum and a high reflectance in the near-infrared. Positive values of this index indicate increasingly green vegetation and negative values indicate non-vegetated areas such as water, barren land or snow. The combination of NDVI data derived from different sensors is very well suited for deriving broad-scale phenological metrics from satellite images. NDVI data have been shown to represent real responses of vegetation to climate variability, suggesting the potential of long-term monitoring of vegetation phenology. Algorithms developed to track vegetation phenology based on the time series data collected by satellite sensors include the Advanced Very High-Resolution Radiometer (AVHRR), SPOT Vegetation and Moderate Resolution Imaging Spectroradiometer (MODIS). Applications of Landsat data paved the way for remote sensing of phenology, but Landsat data are not suitable for phenology studies, which require more frequent repeat cycles. Landsat cannot meet this requirement even though it has a fairly high resolution (30 m). Landsat works well for species composition and habitat studies. The longest-running series of high repeat-frequency sensors like the National Oceanic and Atmospheric Administration's AVHRR, SPOT Vegetation and NASA's MODIS (on board Aqua and Terra) has a near-daily repeat cycle of the Earth, with a 1-km spatial resolution. The temporal resolution and moderate spatial resolution of the data together make these sensors well suited for studying large-area phenology. AVHRR vegetation index data are available from a consistently processed database. SPOT Vegetation, Envisat MERIS, MODIS and ISRO's Oceansat-2, on board OCM are leading satellites because of their much better calibrated moderate resolution sensors, with proper instrumentation for studying vegetation greenness compared to AVHRR. MODIS is frequently used for phenology studies because of its improved geometry and radiometry, overall data quality and free-of-charge data policy. Shrestha et al. (2012)[2] documented large-scale climatic and phenological changes at the landscape level in the Himalayas for the first time using temperature and rainfall data along with NDVI values obtained from remotely sensed imagery. They analyzed 1982 to 2006 data and reported that during the period temperature increased by 1.5°C and the average annual precipitation increased by 163 mm. Also, these authors reported finding considerable changes in phenological parameters. Researchers used satellite-derived NDVI data to analyze climate-induced phenological changes in the Himalayan region. Recently new

2 Shrestha et al. (2012): Widespread climate change in the Himalayas and associated changes in local ecosystems. PLoS One: 7(5):e36741.

vegetation type map of India has been prepared using seasonal satellite data, filed sample points, bioclimatic regions, topography and soil maps (Fig 3).

(a)

(b)

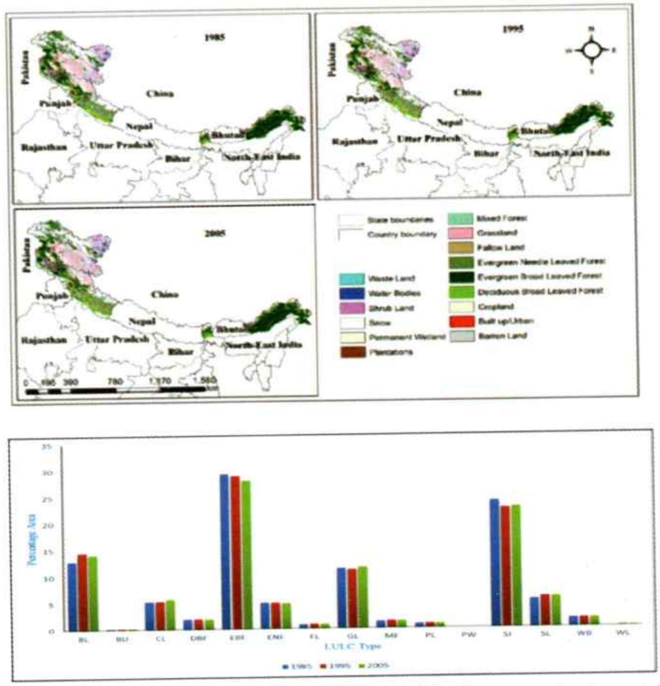

Figure 3: Subplot (a) indicates new vegetation type map of India prepared using satellite remote sensing [3]; and subplot (b) represents LULC change map in Indian Himalaya Hill ranges during 1985, 1995 and 2005 [3].

The multidate satellite images are used to monitor phenology as discriminant for vegetation types (Fig 4).

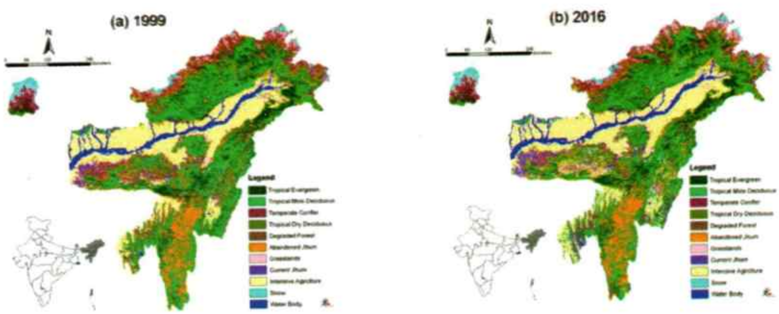

Figure 4: Land use and Land cover of northeastern Indian during (a)1999 and (b)2016 mapped using digital satellite temporal dataset using phenology as discriminant [4].

3 Roy et al. 2015: New Vegetation Type Map of India Prepared Using Satellite Remote Sensing: Comparison with Global Vegetation Maps and Utilities. Int. J. Appl. Earth Obs. Geoinf: 39:142 – 159.

4 Joshi et al. (2009): Report to NATCOM II India, Ministry of Environment, Forest and Climate Change.

4.3 Vegetation Distribution and Climate

The spatial distribution of Himalayan vegetation depends on the altitude, rainfall, soil and temperature. The spatio-temporal variations in these physical factors have resulted in markedly diversified phytogeographic zones in the Himalayas, which are characterized by a high degree of endemism. Hence, climate change is considered one of the key drivers having adverse effects on the biodiversity and ecosystem services of the Himalayas. Mountains are unique areas for detection of climate changes, and Himalayan ecosystems are highly vulnerable to the adverse impacts of climate change. Changes in rainfall and temperature alter the functioning of ecosystems. Rapid melting of glaciers, decreasing snow cover, changes in vegetation cover, species migration and loss, erratic weather patterns, water scarcity and increasing frequency and magnitude of natural disasters are some of the predominant impacts of climate change on Himalayan systems. H.G. Champion was the first to describe and classify the forests of a large portion of the Himalayas. Subsequently, in 1968, Champion and Seth (1968)[5] identified the forest types of India including the Indian Himalayan region. The vegetation types of the Himalayan hill ranges vary from species-rich broadleaf forests in the lower elevations to alpine scrubs at the higher altitudes and the large expanses of grasslands beyond which there exist large glaciers.

4.4 Biodiversity in the Himalayas

It is estimated that 37.48% of the Himalayan region is under natural vegetation including alpine pastures. Most of the area is covered with temperate forests, followed by subtropical broadleaved forests. The other major forest types/natural vegetation in the region include temperate conifer, pine, scrub land, open scrub, deodar, deciduous and evergreen forests. Barren land occupies around 29% of the area, followed by agriculture (16%) and snow cover (5%). Singh & Singh (1987)[6] divided the Indian Himalayan region into three major botanical ecoregions, viz., the western, the central and the eastern Himalayas, including the mountains of north-eastern India and Assam. The eastern Himalayan region supports luxuriant evergreen broadleaf forests in the lower ranges, often referred to as tropical rain forests. Compared to the western region, the conifer forests have a low expression and are generally mixed with broadleaf species. The number of species of Rhododendron and Quercus in this region is many times greater than in either the central region or in the western region. Tree ferns are mostly confined to the eastern region. Epiphytes are in abundance in the eastern region, become less abundant in the central region and are rare in the western region. Singh & Singh (1987) classified the forest vegetation of the Himalayas into 11 formations taking the basic information from Champion & Seth (1968) and factors such as the leaf characters, altitude and phenology of these forests. Satellite remote sensing opened unique opportunities to map forest and vegetation types using multispectral/hyperspectral temporal/seasonal satellite images. In India, vegetation type mapping was carried out for the first time by Roy et al. (1985) [7], using Landsat TM (30-m resolution). Roy et al. (1985) mapped the biological richness and concluded that the Eastern Himalayas, including the North-East region of India, has greater biological richness compared to the other three zones. Changes at the regional level are yet to be documented. The vegetation responds to climate changes in three ways: (1) changes in

5 Champion and Seth (1968): A revised forest types of India. Manger of Publications, Govt. of India.

6 Singh and Singh (1987): Forest vegetation of the Himalaya. Botanical Review: 53:80-192.

7 Roy et al. (1985): Forest type stratification and delineation of shifting cultivation areas in the eastern part of Arunachal Pradesh using LANDSAT MSS data. Int. J. Remote Sensing: 6:411-418.

phenology; (2) shifting of species towards higher altitudes; and (3) competition for resources, eventually leading to habitat loss and species extinction.

4.4.1 Biodiversity characterization at landscape level in the Himalayas

Biodiversity is dynamic in nature: species and their populations are in a constant state of evolutionary change. The changes, as well as human-induced modifications of biodiversity, must be considered against the background of its 3.5 billion years' history. The utility of landscape ecological principles for biodiversity characterization has been described. The use of satellite remote sensing and geographic information system and global positioning system techniques for assessing the disturbed and biologically-rich sites has been highlighted by many researchers. Satellite-derived vegetation maps and various landscape ecological parameters have been analyzed by various authors to characterize various habitat ecosystems. The present approach of prioritizing biodiversity-rich sites has the advantage of integrating spatial and non-spatial information with horizontal relationships and thus provides clues for conservation prioritization. Under the behest of the Department of Biotechnology and Department of Space, Government of India, a landscape ecological approach is being used to characterize the biologically-rich areas in six regions of the country, i.e., north-east India, Western Himalayas, Western Ghats, Andaman and Nicobar Islands, eastern India and central India. This method of biodiversity characterization has advantages over the traditional method of inventory. For example, it has an ecological basis since many ecological components are considered, and all the components have precise positional (locational) representations on the Earth's surface. In these days of pilferage of bio-resources and with a backdrop of intellectual property right issues, a quick and effective geospatial technique for characterizing biodiversity at the landscape level will go a long way in conservation and judicious management of bio-resources (Fig 5a and b) [3,8].

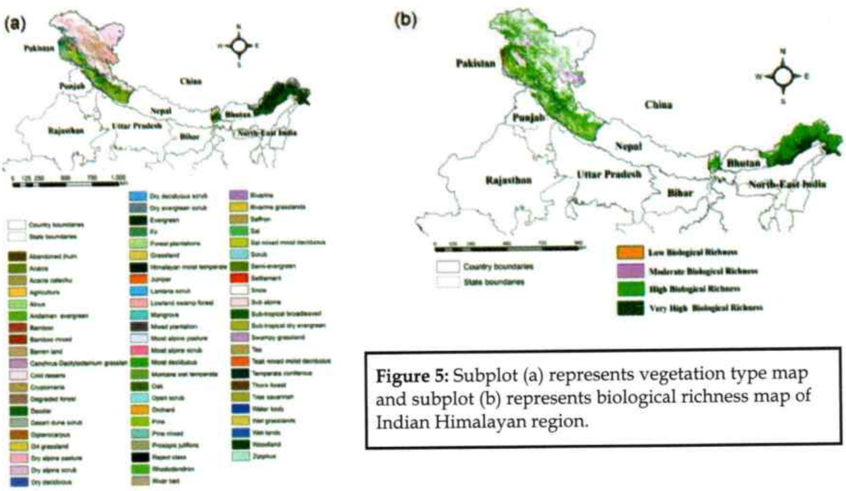

Figure 5: Subplot (a) represents vegetation type map and subplot (b) represents biological richness map of Indian Himalayan region.

8 Roy et al. (2012): Biodiversity characterisation at landscape level: National Assessment: Indian Institute of Remote Sensing, Dehradun, India: pp.140: ISBN 81-901418-8-0.

4.5 Land Use and Land Cover Change

Land use and land cover changes have been among the most important perceptible changes taking place in the Himalayas. Although perceptible, the magnitude, variety and spatial variability of the changes have made the quantification and assessment of land use and land cover changes a challenge to scientists. Furthermore, since most of the land use and land cover changes are directly influenced by human activities, they rarely follow standard ecological theories. There is need for estimation of land use and land cover change for inclusive growth and development in various spheres and sectors: the food and water security of the growing population needs to be met, and issues emerging from climate change need to be addressed. The various dimensions and relationships of di□erent sectors of society need to be recognized. In this context, land use planning and management are considered an interwoven complex system. The Remote Sensing and Geographic Information System has proved to be very important in assessing and analyzing land use and land cover changes. Satellite-based Remote Sensing, by virtue of its ability to provide synoptic and temporal information on land use and land cover at a particular time and location, has revolutionized the study of land use and land cover changes. Temporal information on land use and land cover helps identify the areas of change in a region. Land use and land cover of India during three decades and observed large-scale changes in north-eastern India (Fig 6). The long-term changes in the LULC affect the climate of a region, and the resultant changes in the climate can induce changes such as changes in the cropping pattern, and increase in the area of scrub and barren land, etc. Since historic times, human interventions had been influencing the land use and land cover of the Himalayan region. So far, only regional LULC studies have been carried out in different parts of the Himalayan region. The Global Land Cover Facility, a joint program of FAO and UNEP, with International Centre for Integrated Mountain Development (ICIMOD), has generated a regional-level land cover database for the Himalayas as part of the Global Land Cover Network–Regional Harmonization Program. The database contains LULC data for 1970–1980, 1990 and 2007, prepared using Landsat images at the 1: 350,000 scale. The evergreen broad-leaved forests exhibit a constant decrease in spatial extent during 1985–2005 with concurrent increases in the area of barren land. Similarly, the areal extent of snow cover also decreased considerably during the period. In contrast, the area under grassland expanded during 1985–2005. Interestingly, even though the percentage of built-up area is very small, there was a constant increase in the area during 1985–2005. Similar trends were observed with shrub land and mixed forest. The area under deciduous broad-leaved forests began declining during the period from 1995 to 2005, with a concomitant increase in cropland. However, there were no appreciable changes in the extent of evergreen needle-leaved forests, fallow land, plantations, permanent wetlands, water bodies and waste lands. In north-eastern India, one of the most diverse regions with respect the flora and fauna, deforestation and LULC changes are mainly attributed to shifting cultivation and commercial logging of timber. Regional studies conducted in different parts of the Himalayas bring out the fact that the ongoing developmental activities, agriculture, tourism and indiscriminate use of natural resources tend to exert pressure on the LULC of the Himalayas and this can lead to changes in the vegetation structure and composition. The long-term changes in the LULC can affect the climate, and the changes in climate can act as a driver for LULC changes and vegetation loss. The North-Eastern Region, which is a part of the Himalayas, represents 8% of the geographical area of India, is known to have 66.8% of the forest cover (25% of entire India) and is globally recognized as a biodiversity hotspot. The population is about 38 M (145 tribal communities and ~12% of the total tribal communities of India), with a population density of 149 (~313) (84% rural).Traditional shifting cultivation is still practiced in the region for producing food, and livelihood resources are drawn from forests. With plentiful resources, the poverty level 32% (~21.6) is very high compared with the rest of India. It is evident that though shifting cultivation is on the rise there is also an effort to practice intensive agriculture in parts of Meghalaya and Karbi-Anglong district, of Assam. There is an overall decrease in moist deciduous, dry deciduous and degraded forest cover. Most of these forests have been converted to agriculture in the North Brahmaputra Valley.

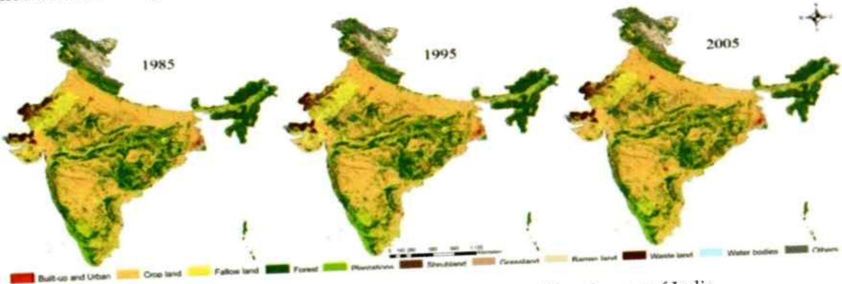

Figure 6: Decadal Change National Land use and Land cover of India.

4.5.1 Land use and land cover change modeling

For effective planning and developing strategies, we need to model scenarios in different socio-economic settings of LULC change. Land use change is a locally pervasive and globally significant ecological trend. The Himalayas have experienced the conversion of forest to other uses, particularly agriculture, hydroelectric projects and road construction, during the last four decades. Understanding the spatial dynamics of LULC change has been a challenge for geospatial scientists, and there is no single robust model that can capture the LULC dynamics of a region. Historical land use patterns and current trends in a region are used to model future land use. Land use change models include trend analyses of historical data that predict the rate and spatial pattern of land conversion on the basis of land use change or agent-based change models where the drivers define the change in land use. Numerous models have been used to build scenarios of the future—narrative method models and hybrid methods—using both qualitative and quantitative methods.

Most LULC models incorporate three critical dimensions. Time and space are the first two dimensions and provide a common setting in which all bio-physical and human processes operate. The third dimension is the human process or the human decision-making dimension. The three dimensions of land use change models (space, time and human decision-making) and the two distinct attributes of each dimension (scale and complexity) are the foundations of land use change models. It is very significant that shifting cultivation will steadily stabilize and the population will settle in an intensive and permanent agriculture system. This is attributed to education and ongoing extension efforts to promote agro-horticulture, agroforestry and other practices. The moist deciduous and temperate forests and grasslands will show a continued decline progressively.

4.6 Climate Change Signatures

4.6.1 Species Niches and Vulnerabilities

IPCC predicts that the average annual mean temperature over the Asian landmass, including the Himalayas, will increase by about 3°C by the 2050s and about 5°C by the 2080s. Similarly, the average annual precipitation in this region will increase by 10-30% by 2080. The impacts of the projected climate changes on the vegetation of the lowland tropics are currently poorly understood. Changes in animal distributions have also been projected, in response to both direct impacts of climate change and indirect impacts through changes in the availability of suitable habitats. During the last few decades, the Himalayas have experienced increasing temperatures, but the precipitation has showed localized changes, increasing in some areas and decreasing in other areas. Although there is little research into the climate-influenced phenology of plants in the Himalayas, it is very clear that climate change in this region may alter the phenology at both individual species and community levels. Yogita et al. (2018)[9] studied LULC changes in high-altitude regions of Garhwal to unravel the intricate relationship between the climatic variability and exchange of energy in these regions. These changes are also important for understanding the role of land cover as a component of the global and regional climate systems and its relationship with other components, including vegetation and snow cover. Land cover information is time sensitive and is one of the key variables contributing to the overall dynamics of Earth systems. Satellite observations have been used to understand and evaluate the decadal changes in the land cover characteristics of high-altitude areas (>3000 m asl). The most important changes are a decrease in the snow cover and its replacement with alpine grasslands and alpine scrub particularly (Fig 7). Some of the projected effects are decreasing the extent of forests in the higher altitudes, shifting species, causing a spread of invasive/alien species, and changing the agricultural systems in different parts of the Himalayan range. Very little research has been conducted in the Himalayas to quantify the possible impacts of climate change induced vegetation changes, but the footprints of climate change in terms of the vegetation are very clear in the region.

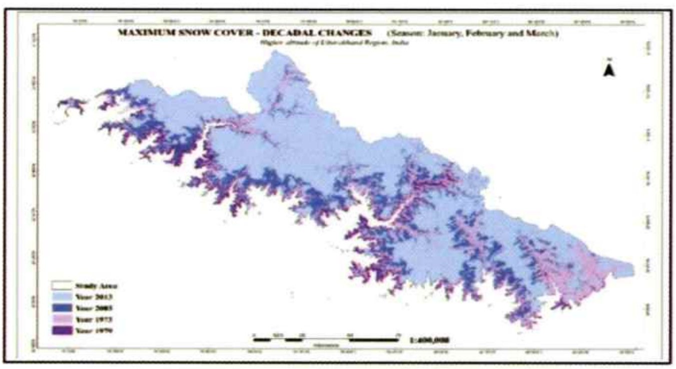

Figure 7: Maximum Snow cover area during 1979 and 2013 assessed using multi-date Landsat satellite data of Jan-March months (*Source: Yogita et al. 2018*).

9 Yogita et al. (2018): Land Cover and Land Use Changes (LCLUC) over last 40 years in Garhwal Himalayas for altitudes above 3000 m and their impact on Vegetation Types in different altitudinal zones using Geospatial Techniques. (Communicated).

Studies on vegetation shifts due to climate change in the Himalayan hill ranges have primarily focused on snow cover and snow melts. The Himalayas constitute an important global biodiversity hotspot; yet, studies on species' responses to climate change in this region are lacking. Studies indicate species' shift and species distribution changes in the light of climate change in two alpine valleys of Sikkim using historical (1849–1850) and recent (2007–2010) using temperature and endemic species data. The study shows that the ongoing warming in the alpine Sikkim Himalayas has transformed plant assemblages. The study recorded a shift of 23–998 m in species' upper elevation limits and a mean upward displacement rate of 27.53 ± 22.04 m/decade. Rashid et al. (2011)[10] mapped the current vegetation distribution in the Kashmir Himalayas from NOAA AVHRR data and projected them under A1B SRES, RCP-4.5 and RCP-8.5 climate scenarios using the vegetation dynamics model (Integrated Biosphere Simulator Model) to study the distribution of vegetation with changing climate. Grasslands and tropical deciduous forests in the region would be severely affected, while savannah, shrub land, temperate evergreen broadleaf forest, boreal evergreen forest and mixed forest types would colonize the area that is currently cold desert/rock/ice. It is also predicted that a substantial area of land, presently under permanent snow and ice cover, would disappear by the end of the century. The study indicates that the climate change evidence in the region is clear and most of the naturally occurring vegetation is likely to be affected. These studies point out that the climate change is playing significant effects on the vegetation types and distribution of the Himalayan hill ranges and this will finally affect the products and services provided by these forests. The impacts include the extinction of endemic and medicinally valuable species, changes in biogeochemical cycles and changes in hydrological cycles. There will be outbursts of invasive species, which will exert pressure on the natural vegetation.

Ecological niche-based models are used to map the current and future habitat suitability for species, using precise coordinates of species occurrences, along with climatic and various environmental variables. Despite the high dependence on forest resources in the Himalayan region, the direct impacts of climate change on major forest tree species are not well documented. MaxEnt (or maximum entropy) modelling was used to predict the current distribution, and changes in the future distributions of four ecologically and economically dominant forest tree species (*Quercus leucotrichophora, Q. semecarpifolia, Q. floribunda* and *Pinus roxburghii*) in the central Himalayan region. The future predictions were based on representative concentration pathways (RCPs) for two time periods (the 2050s and 2070s). The use of MaxEnt was demonstrated by combining different climatic, geomorphologic and pedologic variables as predictor variables to model potential climatic niches. Depending upon the RCPs, the results show both increases and decreases in the suitable habitat ranges of these species across all future climate scenarios. The shifts in geographic distributions of climatic niches show unusual patterns, implying a need for urgent adaptive forest management strategies. The approach can be used as a baseline database for broad-scale use in forest tree species restoration and conservation planning (Fig 8a and b, and 9).

10 Rashid et al. (2011): Geospatial tools for assessing land degradation in Budgam district, Kashmir Himalaya, India: J Earth Sys Sci: 120:423.

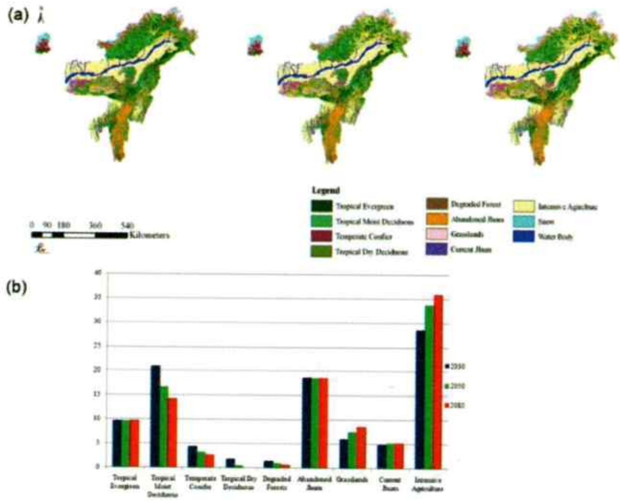

Figure 8: Subplot (a) represents spatial maps of land use and land cover change in 2030, 2050 and 2080 and subplot (b) represents spatial extent of change in land use change in different climate scenarios (Source: Joshi et al. 2009).

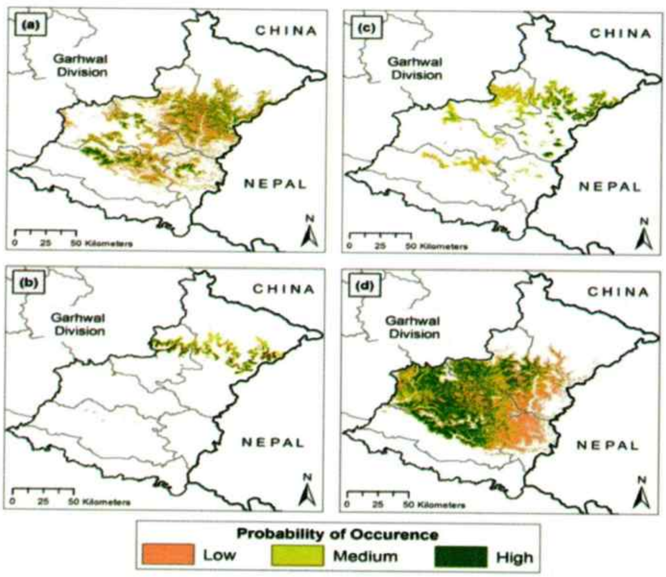

Figure 9: Potential geographic distributions of current climatic niches for (a) *Quercus leucotrichophora* (Banj), (b) *Quercus semecarpifolia* (Kharsu), (c) *Quercus floribunda* (Moru), and (d) *P. roxburghii* (Chir). In this case, the probability of occurrence of the tree species is categorized as low, medium and high suitable areas, however, this may vary depending on varying conditions on field sites particularly moisture, slope and aspect. (Source: Chakraborty et al. 2016 [11]).

10 Rashid et al. (2011): Geospatial tools for assessing land degradation in Budgam district, Kashmir Himalaya, India: J Earth Sys Sci: 120:423.

11 Chakraborty et al. (2016): Predicting distribution of major forest tree species to potential impacts of climate change in the central Himalayan region. Ecological Engineering: 97: 593–609.

The climate change also affected the fire frequency and rise of fire incidence to higher elevation. (Fig 10)

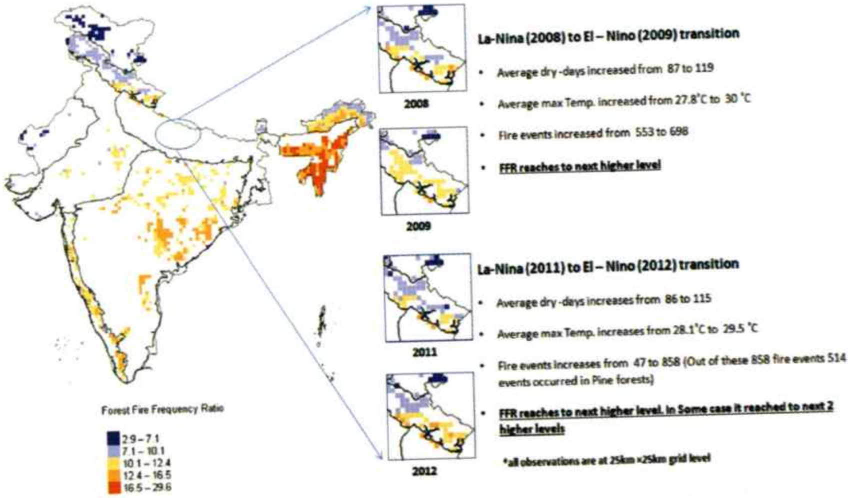

Figure 10: Extreme climates and alterations in 'Forest Fire Frequency Ratios' in Uttaranchal. (Source: Kale et al. 2017[12]).

4.6.2 Vegetation in north-eastern region under stress?

The vegetation in north-east India, has undergone changes in terms of productivity and species richness due to various reasons. To understand whether such changes are associated with climate variability and change, the NDVI datasets for 2000–2014 from the Moderate Resolution Imaging Spectroradiometer on board the MODIS-Terra satellite, field-sample data of vegetation types and rainfall datasets from the India Meteorological Department were used. The evaluation was done for three seasons, the wet season (June–October), winter (November–February) and the dry season (March–May).

All the seasonally-stratified NDVI datasets relating to the region indicate a positive trend till 2006–2007 and a prominent negative trend, particularly for winter. The summer monsoon precipitation has a direct impact on the NDVI during winter, many vegetation types exhibiting stress with the decrease in precipitation. Interestingly, the concurrent rainfall in the region also exhibits similar trends, which was reconfirmed from analysis of long-term rainfall datasets for the 1970–2014 period. Linear regression analysis of the NDVI rainfall data reveals a strong correlation, particularly between winter rainfall and winter NDVI at the 0.05 significance level. Thus, the first evidence of stress in different vegetation types associated with climate change has been obtained though the magnitude varies with the season. In addition, a sharp decline in the winter NDVI due to a decrease in summer monsoon rainfall has been highlighted, which

12 Kale et al. (2017): Are climate extremities changing forest fire regimes in India? An analysis using MODIS fire locations of 2003-2013 and gridded climate data of India Meteorological Department, Proceedings of National Academy of Science, India.

shows the lag relationship. The long-term rainfall (1970–2014) also decreased for all the three seasons in the north-eastern region (Fig 11 a, b).

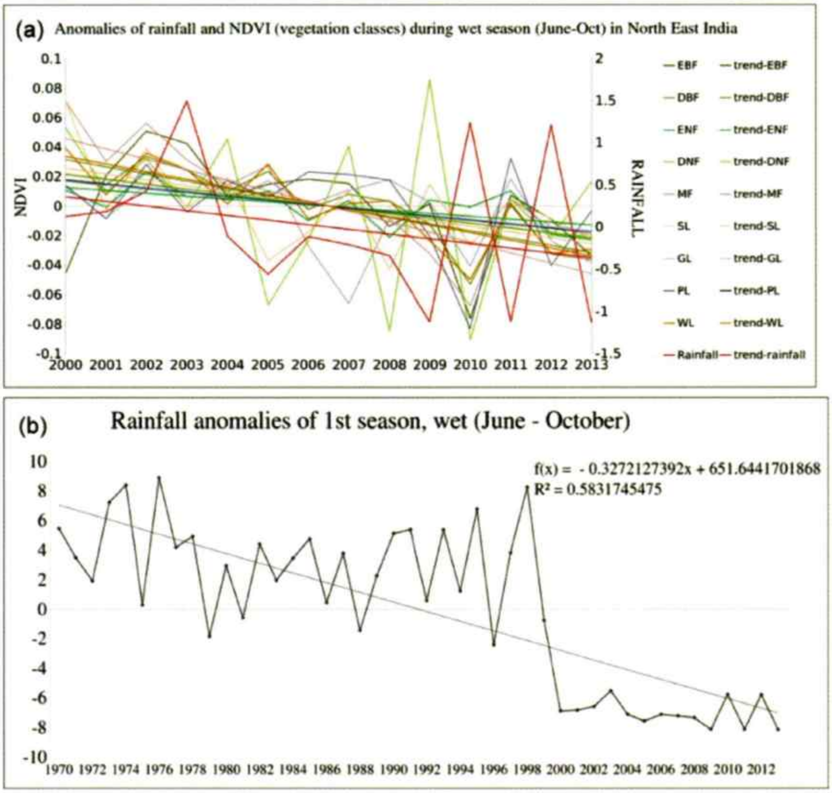

Figure 11: Subplot (a) represents anomalies of rainfall (mm) and NDVI data sets for vegetation classes: Evergreen Broad Leaf Forest (EBF), Deciduous Broad Leaf Forest (DBF), Evergreen Needle Leaf Forest (ENF), Deciduous Needle Leaf Forest (DNF), Mixed Forest (MF), Shrub Land (SL), Grassland (GL), Plantations (PL) and Waste Land (WL) during the wet season (June–October) for the period 2000–2013 over the whole of North East India. Subplot (b) represents long term rainfall (mm) anomalies during the wet season (June to October) for the period 1970 to 2014 over north east India. (Source: Bidyabati et al. 2018[13]).

4.6.3 Melting Himalayas

The HKH region extends over 2000 km from east to west across the Asian continent, spanning several countries: Afghanistan, Bangladesh, Bhutan, China, India, Nepal and Pakistan. This region is the source of numerous large Asian river systems, including the Indus, Ganges and Brahmaputra, which provide water for over a billion people. The surface water of these rivers and associated groundwater constitute a significant strategic resource for all of Asia. Glaciers carve and transform the surrounding and underlying landscape through erosion, abrasion, plucking, movement and deposition.

13 Bidyabati et al. (2018): North East forests are facing stress due to precipitation anomaly: an analysis based on MODIS NDVI for the period of 2000-2014. (Communicated).

Like huge conveyor belts, glaciers transport earth down from the lofty mountains, carving valleys and discharging the material along the sides and at the end of the glacier. Mountain glaciers normally terminate in a fluvial system that carries the soil, sediments and boulders along the river valleys, depositing and transporting, to ultimately join the oceanic system.

The glaciers in the HKH region are retreating at rates comparable with those in other parts of the world. There is confirmation that the rate has accelerated in the past century. In this region, the glacial melt-water is an important supplement to the naturally occurring run-off from precipitation and snowmelt. The watersheds of the area each exhibit a complex hydrology and magnitude of contribution of glacial melt-water to the total water supply. However, the implications of accelerated rates of glacial retreat and the resulting increase in glacial wastage for downstream populations have not been characterized precisely. The eastern and western areas of the HKH region differ in climate, especially in the timing and type of precipitation, and in glacier behavior and dynamics. The precipitation at the eastern end of the region is dominated by monsoonal activity in summer, while the precipitation at the western end is dominated by mid-latitude westerlies in winter. The region is vast and complex both climatologically and hydrologically, and this complexity is dynamic and possibly changing. This large spatial variability makes it very difficult to generalize the observations and findings over the entire region. In the Himalayas a substantial proportion of the annual precipitation falls as snow, particularly at high altitudes (above 3000m). In the higher reaches, snowfall builds up from year to year to form glaciers that provide long-term reservoirs of water stored as ice. The high Himalayan and inner Asian ranges have the most highly glaciated areas outside the polar region, although accurate data are lacking. Several of the largest concentrations of glaciers are found in the middle and low latitudes. The climate controls the river flow–glacier mass balance in the Himalayan region, and this varies considerably from west to east.

Evidence suggests that the Eastern Himalayas are warming, and this trend is more pronounced at higher elevations. In the western part of the Indian Himalayas, absorbing aerosols such as desert dust and black carbon may contribute to the rapid warming of the atmosphere, and model results indicate this may in turn contribute to accelerate melting of the snowpack and glacier retreat. The overall implications are still a matter of research. Advanced remote sensing and GIS techniques offer abundant potential for mapping and monitoring the glaciers in high and remote mountain areas, but conducting a survey based on conventional methods demands a great deal of time and capital and involves enormous risks. Auden was the first geologist to map the snout and geomorphic features of Gangotri Glaciersystematically using a plane table survey. This map was reproduced at the 1:9600 scale by Auden and formed the basis of more than a dozen studies on the recession of the Gangotri Glacier conducted by the GSI (Fig 12). Several scientists from the GSI resurveyed the Gangotri Glacier and marked the position of the snout on Auden's plane-table map as well as cairns on the ground. A large number of Indian and British surveyors thus used contemporary techniques and instruments to survey unexplored Himalayan ranges and paved the way for future generations of explorers to map the Himalayan peaks and glaciated terrain in extreme climatic and high-altitude conditions. In the 1960s, the Survey of India published topographical maps of Himalayan glacier terrain on the basis of aerial photographs with limited field work at a scale of 1:50,000. Since the beginning of the

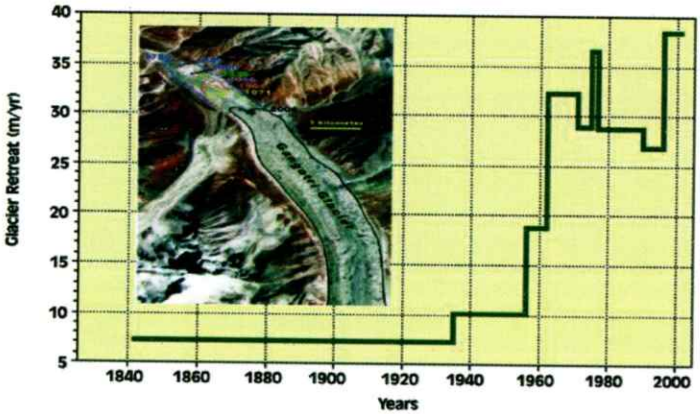

Figure 12: Increasing rate of retreat of the Gangotri Glacier in India (Source: Srivastava 2004[14] satellite image showing the position of the terminus in different years)

20th century, GSI have mapped several glacier snouts and the surrounding glacio-geomorphic features such as Gangotri, Pindari, Milam, Shankulpa, Gor-Garang, Triloknath, Poting and many others to monitor glacier recession and advance using plane-table mapping. The Survey of India parties visited several Himalayan glaciers along with GSI. The remote sensing data facilitate rapid glacier mapping as field work is only necessary for ground truthing and for obtaining ground control points. Initial glacier inventory studies using remote sensing started in Iceland and Austria. This method is time consuming for larger areas, and its accuracy depends on the efficiency of identification and recognition of glacier terrain features on satellite imagery. Almost all glacier inventories based on satellite imageries have been carried out by manual delineation. These studies used FCC of coarse-resolution satellite data (MSS and LISS I) to high-resolution data (LISS IV and PAN) and SOI topographic maps (scale from 1:250,000 to 1:50,000). Few inventories based on remote sensing and topographical maps included cartographic errors in their studies. In the early 1990s, the Space Application Centre (SAC) completed a glacier inventory program for the entire Indian Himalayas at a scale of 1:250,000.

5. Conclusions

Geospatial information and EO data, together with modern data processing and big data analytics, offer unprecedented opportunities to modernize national statistical systems and consequently make a quantum leap in the capacities of countries to track all facets of sustainable development efficiently. EO data (from satellites, airborne instruments, UAVs and in-situ sensors) provide accurate and reliable information on the state of the atmosphere, rivers, soil, crops, forests, ecosystems, topography, natural resources, ice, snow and built infrastructure, as well as changes in these over times. These observations are directly or indirectly necessary for all development programs, all economic sectors and many day-to-day activities of the community. The Satellite EO programs represent the largest investment globally in relation to satellite applications

14 Srivastava D (2004): Recession of Gangotri glacier. Geol Surv India Spec Pub: 80:21-32.

by national governments, typically through their national space agencies. The Committee on Earth Observation Satellites (CEOS) reports that its member agencies are currently operating or planning more than 300 different satellite EO missions, carrying over 900 different instrument payloads. These systems span a diverse range of measurements of the atmosphere, ocean and land and support hundreds of applications related to matters that can affect the lives of citizens. In addition, privately funded EO missions, including large constellations of smaller satellites with the capability to provide frequent coverage or repeat measurements, have been increasing in number rapidly in recent years. Data Driven Development (DDD) provides baseline information, enables monitoring and creates scenarios in space and time for sustainable development planning and implementation (Fig 13). Thus, effective use of the information from satellite observations can have a transformational impact on many of humanity's most significant challenges, such as helping monitor and protect fragile ecosystems, ensuring resilient infrastructure, managing climate risks and public health, enhancing food security, building more resilient cities, reducing poverty and improving governance in a realistic time frame.

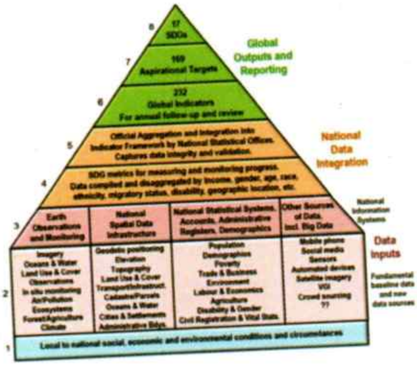

Figure 13: Model national information system with data inputs, data integration and reporting. (Source : UN-GGIM).

comprehensive national level database on biodiversity with participation of lead national institutions (http://bis.iirs.gov.in).

- Most significant contribution in an international research initiative was made by Prof. Roy by developing methodology on biophysical Spectral Response Model for forest canopy stratification initiated by International Tropical Timber Organization in South East Asia and South Asia. He has been principal investigator of a team for carrying out vegetation and land use cover type mapping of south central Asia using SPOT VEGETATIO. The dataset is going to be a part of Global Vegetation Mapping Monitoring Program of European Commission. The dataset has become a part of Millennium Ecosystem Analysis.
- Prof. Roy implemented first cycle of National Natural Resource Census (NRC) under National Natural Resource Programme during 2005-2011 by generating geospatial information on geomorphology, wetland, snow and glaciers, soil type, land degradation, forest cover and land use and land cover maps. He also led inter-institutional teams to create decadal land use and land cover maps (1985-1995-2005) and new vegetation type map of India using satellite remote sensing.
- He has also made significant contribution in education and training program in Geoinformation science and its application. As Dean of Indian Institute of Remote Sensing (IIRS), he has brought major changes for quality education, curriculum revision, establishing linkages with university education and international organizations. Most importantly he has developed new collaborative M.Sc. programme and postgraduate diploma level course in Environmental Analysis & Disaster Management and Geoinformatics with international institutions such as ITC, University of Twente, The Netherlands, Wageningen University and International Institute of Hydraulic Engineering, Delhi.
- Adding to his contributions, planning, designing and execution of the National Database for Emergency Management (NDEM) - a multi-institutional initiative of Ministry of Home Affairs is revered by many leading scientists for direct social benefits. He made key contributions in establishing the 24/7 Decision Support Centre (DSC) at this centre. The geodata bases generated under NRC project have been integrated in NDEM, which have led to new paradigm in disaster risk assessment and reduction. Towards the later part of professional career, he developed a unique project entitled "*Space based Information Support for Decentralised Planning*" with Planning Commission, Govt. of India, under NNRMS. The project is presently being implemented with the objective of involving grass root people in planning and information collection using geospatial information.

His innovative contribution to the field of geoinformation science has ushered in the era of modern land resource management practices, laying the foundation subject-knowledge for issues of global environmental change. He consciously advocates remote sensing application and geospatial technologies, while his primary goal remains promotion of sustainable development using appropriate cost-effective technologies.

G.B. Pant Memorial Lectures

I

Dr. M.S. Swaminathan, Director, CRSARD, Madras - 1991

II

Dr. T.N. Khoshoo, Jawaharlal Nehru Fellow, TERI, New Delhi – 1992

III

Mr. V. Rajagopalan, Vice President, World Bank, Washington – 1993

IV

Prof. U.R. Rao, Member, Space Commission, New Delhi – 1994

V

Dr. S.Z. Qasim, Member, Planning Commission, New Delhi – 1995

VI

Prof. S.K. Joshi, Vikram Sarabhai Professor, JNCASR, Bangalore – 1996

VII

Prof. K.S. Valdiya, Bhatnagar Research Professor, JNCASR, Bangalore - 1997

VIII

Prof. V.K. Gaur, Distinguished Professor, IIA, Bangalore – 1998

IX

Prof. Y.H. Mohan Ram, INSA Senior Scientist, University of Delhi, New Delhi – 2000

X

Prof. J.S. Singh, Emeritus Professor, BHU, Varanasi – 2004

XI

Prof. Madhav Gadgil, Centre for Ecological Sciences, IISc, Bangalore – 2005

XII

Dr. S.S. Handa, Ex-Director, PRL (CSIR), Jammu – 2006

XIII

Dr. Lalji Singh, Director, CCMB, Hyderabad – 2007

XIV

Prof. Roddam Narasimha, Chairman, FMU, JNCASR, Bangalore – 2008

XV

Dr. R.S. Tolia, Chief Information Commissioner, Govt. of Uttarakhand, Dehradun – 2009

XVI

Prof. Raghavendra Gadagkar, CES & CCS, IISC, Bangalore – 2010

XVII

Prof. V. Nanjundiah, JNCASR, Bangalore – 2011

XVIII

Dr. Kirit S. Parikh, IRADe, New Delhi & Former Member Planning Commission – 2012

XIX

Prof. Jayanta Bandopadhyay, Former Prof. & Head, IIM, Calcutta – 2013

XX

Prof. T.S. Papola, Honorary Professor, ISID, New Delhi - 2014

XXI

Dr. David Molden, Director General, ICIMOD, Nepal - 2015

XXII

Prof. K. Vijayraghavan, Secretary-DBT, New Delhi - 2016

XXIII

Prof. S.P. Singh, Former Vice Chancellor, H.N.B. Garhwal University, Nainital – 2017