TOWARDS RESILIENT ECOSYSTEMS: THE ROLE OF FORESTRY RESEARCH - SYNTHESIS AND A WAY FORWARD

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Proceedings of National Conference on
"Towards Resilient Ecosystems: The Role of Forestry Research"
held on 8 - 9 May, 2018 at IFGTB, Coimbatore.

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ISBN No. : 978 - 93 - 82387 - 17 - 6

Published by
Institute of Forest Genetics and Tree Breeding, Coimbatore - 641 002.

Citation : Mohit Gera, Buvaneswaran, C., Murugesan, S. and Sasidharan, K.R. (Eds.) (2018). *Towards Resilient Ecosystems: The Role of Forestry Research - Synthesis and A Way Forward* Proceedings of National Conference on Towards Resilient Ecosystems: The Role of Forestry Research held on 8 - 9 May, 2018 at Institute of Forest Genetics and Tree Breeding, Coimbatore. Pp. 1-204.

Acknowledgement : The funding support renderd by National Biodiversity Authority, Govt. of India for publication of this proceedings is gratefully acknowledged.

Printing: **Prdag Print,** Coimbatore - 641 012., Ph : 0422 3059034, E-mail : prdagprint@gmail.com

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FOREWORD

Forest ecosystems have a vital role in sequestering atmospheric carbon, both in vegetation and soil and thereby mitigation of climate change. However, forest sector also contributes to warming of global climate through continued deforestation and accelerated degradation and thereby acting as source of carbon. As per the fifth Assessment Report of IPCC, by 2100, the likely CO_2 concentration in the atmosphere may vary from 421 to 936 ppm with a corresponding temperature rise from 1.5 to 4.5 ^{o}C. This projected climate change is expected to have likely impacts on our forests such as shifts occurring between forest types, increased risk of frequent forest fires, pest and disease outbreaks. Studies conducted on likely impacts of Climate Change on forests of India also reveal that at national level, around 30% forests are likely to be adversely impacted by 2035. This warrants climate-smart forest management initiatives for enhancing adaptation potential of forests and in turn ecosystems resilience.

Scientific deliberations on "Ecosystem Resilience" are the need of the hour in order to chalk out strategies for ensuring sustainable flow of forest ecosystem services. Further, there is an imperative need to review and revisit research and forest management initiatives taken by various State Forest Departments and research organizations on the subject of 'Forest Ecosystem Resilience'. In this context, the national conference organized by the Institute of Forest Genetics and Tree Breeding (IFGTB), Coimbatore on 8th and 9th May, 2018 has high relevance to focus our preparedness to combat this imminent global challenge.

It is heartening to note that IFGTB has succeeded in bringing several eminent researchers, foresters and policy makers from different parts of the country on a common platform to deliberate on this important issue. I congratulate the editorial team for putting their best efforts to bring out this comprehensive proceedings of the national conference. I hope that the articles brought out in general and the recommendations in particular will open up new vistas for dealing with the forests and climate change issues in the country.

Dehradun
05.11.2018

(Suresh Gairola)
Director General

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PREFACE

There are increasing evidences of climate change and its adverse impact on forests of the country as well as in other parts of the world, making the forests extremely vulnerable. Hence, the forestry sector is confronted with one of the biggest challenges of the age. As the vulnerability of a system that makes the hazard a disaster, the forestry researches need to identify measures that make the ecosystems less vulnerable and adapt to the changing climate. In this context, the important issues relating to vulnerability of forest ecosystems and developing resilience in them needs to be understood. Further, there is also a need to synthesize and synergize research and development initiatives taken up by various stakeholders on this subject of contemporary importance. Considering the above need, a National Conference on **"Towards Resilient Ecosystems: The Role of Forestry Research"** was organized by the Institute of Forest Genetics and Tree Breeding (IFGTB), Coimbatore on 8th and 9th May, 2018 to provide a platform for discussing scientific and forest management issues relating to the themes, viz., vulnerability assessment, tree improvement & biotechnological strategies for climate resilience, harnessing forest genetic resources for climate resilience, forest health, issues and challenges in adaptive forest management and climate-smart forestry.

The National Conference was attended by more than 100 participants, which included policy makers from Ministry of Environment, Forest and Climate Change, Govt. of India practising foresters from State Forest Departments, eminent experts from National Institutes, faculty from Universities, researchers from ICFRE institutes and other institutions, retired forestry experts, NGOs and tree growers. The Conference was inaugurated by Director General of Forest and Special Secretary to Govt. of India, Ministry of Environment, Forest and Climate Change.

We thank Sh. Siddhanta Das, DGF & SS, MoEFCC and Dr. S. C. Gairola, Director General, ICFRE, for their gracious presence and support rendered for organizing the conference and bringing out this proceeding. We acknowledge the organizing team for smooth and successful conduct of the Conference. The funding support rendered by the National Biodiversity Authority, Chennai is gratefully acknowledged.

Coimbatore
05.11.2018

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VULNERABILITY ASSESSMENT OF FOREST ECOSYSTEMS IN INDIA

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Introduction

Ensuring survival of life forms on planet earth has been a matter of concern for mankind during the last many decades. The intricate dependence of human survival on the health of forests has long been recognized. Forest ecosystems play an important role in the global biogeochemical cycle and exert significant influence on the earth's climate (Stephenson, 1990). Around half of the increase in global average surface temperature has been attributed to human activities (IPCC, 2014). Rapid industrialization during the last century accelerated the impact of human activities on earth's climate and their cascading effects on the already fragile and threatened forest ecosystem has become more visible. Effects of climate on the evolution of a forest types have been recognized, and is considered as the most important determinant of vegetation patterns globally with significant influence on the distribution, structure and ecology of forests (Kirschbaum *et al.*1996). The boundaries of forest biomes are known to closely follow patterns of temperature and / or moisture regimes (Stephenson, 1990). This interconnected nature of climate and forests thus implies that a dramatic change in one will influence the other (FAO, 2013). Through the inferences from paleoecological records, it has emerged that forest vegetation has the potential to respond within years to a few decades of climate change (IPCC, 2014). Fischlin (2007) reports that 20–30% of the plant and animal species would be at increased risk of extinction if the global average temperature increase exceeded 2–3°C above the pre-industrial level. According to IPCC (2014), climate and non-climate stressors are projected to impact forests during the 21st century leading to large-scale forest die-back, biodiversity loss and diminished ecological benefits. It has been projected by IUFRO that the existing forests that are functioning as carbon sinks would later become a net source of CO_2 later in the century.

Significance of vulnerability assessment of India's forests

India is one among the 18 megadiverse countries and is endowed with 8 % of the world's biodiversity, and hosts 4 biodiversity hotspots including Western Ghats, the Eastern Himalayas, the Indo- Burma and the Sundaland. India is home to about 7.6 % of mammalian, 12.6 % of avian, 6.2 % of reptilian, and 6.0 % of flowering plant species (https://en.wikipedia.org/wiki/Portal:Indian_wildlife). India is home to 2.9 %, of IUCN-designated threatened species, that includes the Asian elephant, the Asiatic lion, the Bengal tiger, the Indian rhinoceros, the mugger crocodile, and the Indian white-rumped vulture (https://en.wikipedia.org/wiki/Wildlife_of_India). Habitat of these endangered flora and fauna are India's forests. As per the State of Forest Report, 2017, India has 708273 sq km of forests, which comes to 21.54 % of geographic area of the country (FSI, 2017). India is endowed with diverse forest types ranging from tropical wet evergreen forests in the northeast and the southwest, to tropical dry thorn forests in central and western India. The forests of India are classified under 16 major types comprising 221 sub-types (Champion and Seth, 1968). Around 200,000 villages are classified as forest villages (Ravindranath *et al*. 2004). In addition to the dependence on forest resources by these communities, the forests provide a range of ecosystem services like functioning as catchment areas for rivers and as carbon sinks. These diverse forests also make available a diversity of forest produce thereby helping to meet the wood, food and shelter demands of India's growing population.

Climatic stressors include rising CO_2 concentrations, increased/ decreased rainfall patterns and associated drought and flooding, drought associated risks like forest fires, rising sea levels and associated flooding and salinity. Global mean temperatures in 2017 were 1.1 °C ± 0.1 °C above pre-industrial levels (WMO, 2017). Global mean sea level has been rising at a rate of <"3 ± 0.4 mm/y since 1993 (Nerem, *et al*. 2018) and has been projected to rise by 0.2 meters to 2.0 meters by 2100 (Melillo, *et al*. 2017). These climatic stressors are known to affect forests in terms of species composition, biodiversity and productivity. Migration of species towards higher latitudes/ elevations, spread of invasive species, decrease in area of socio-economically important species, asynchrony of flowering plants and associated fauna and leading to threats on endangered species are the other likely impacts of these stressors. The changes in the vegetation or forest type may be taken as an indicator of the vulnerability of the forest ecosystems to projected climate change (Ravindranath *et al*. 2006). Available studies have reported the likely change in vegetation of India's forests to the extent of 30.6% by 2035 and 45.9% by the end of the century (Gera, 2018). IPCC defines vulnerability as "The degree to which a system is susceptible to or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (IPCC, 2001). The study of the vulnerability of natural systems to climate change and variability, and their ability to adapt to changes in climate hazards, is a relatively new field of research (Brooks, 2003). It has been widely recognized that certain forest types are more vulnerable to climate change while certain forests types benefit from the altered CO_2, temperature and moisture regimes. The importance of a identification and scientific evaluation of the most vulnerable forest types has therefore been recognized for focusing on climate mitigation efforts. The following are the methodologies used for assessment of vulnerable forest types and vulnerability assessment studies undertaken in the India's forests.

Methodology for forest ecosystem vulnerability assessment

Assessing the vulnerability of forest ecosystems to climate change is important to determine appropriate mitigation and adaptation strategies. The methodology provides full framework for guiding the assessment of vulnerability (UNFCCC, 2005). An ecosystem model can provide results about the vulnerability of ecosystem services to climate change. Various methods and tools are available for assessing the vulnerability of forests, forest ecosystem services and forest-dependent people or economic sectors (Locatelli *et al*. 2008). The tools and methods generally used for vulnerability assessment at different levels of complexity, range from simple tools and methods (e.g. using expert judgment or comparing with similar cases) to complex ones (e.g. simulation of integrated socio-ecological systems or dynamic vegetation modeling). The methodologies described in this section have essentially been quoted from the CIFOR's working paper 43 by Locatelli *et al*. (2008).

Generic methods and tools can be applied to diverse systems for analysing vulnerability interactively with stakeholders (e.g. cognitive mapping or expert judgment) and for building empirical models from observations (e.g. meta analysis or data mining). Indicators, fuzzy systems, and uncertainty analysis can be applied for various purposes. Numerous ecosystem models can be used for studying the impacts of climate change on forests. Some models are restricted to specific ecosystem processes (e.g. the productivity of managed forests, forest perturbations or specific ecosystem services). Simple bioclimatic models can represent the distribution of ecosystems and help assessing ecosystem vulnerability to climate change. Other simple ecosystem models deal with community and landscape dynamics, with an emphasis on the interactions between species or patches of ecosystems. Other simple ecosystem models work on biogeochemical cycles in ecosystems.

Generic methods and tools

Expert judgment is a method for eliciting informed opinions from experts of a specific topic. An expert is defined as 'anyone especially knowledgeable in the field and at the level of detail being elicited' (Meyer and Booker, 1991). It is a useful method when resources are lacking for conducting an in-depth analysis of scientific literature, collecting data or modeling.

Empirical models from observations When observations are available about a phenomenon (e.g. forest fires) and possible explanatory variables (e.g. climate or human activities), empirical models can be built. These models aim at establishing a relationship between an observed impact and explanatory variables and can be used for testing the effects of changes (e.g. climate change or adaptation practices) on the phenomenon.

Meta-analysis is a statistical technique for combining the quantitative findings of different studies. It has the advantage of producing quantitative results about impacts and uncertainties (Arnqvist and Wooster, 1995). In an impact or vulnerability assessment, meta-analysis can be used for example for summarising the results of different studies of the impacts of climate change on ecosystems or human health. Meta-analysis has been applied to study the effect of global warming on biodiversity (Root *et al*. 2003; Parmesan, 2006) soils (Rustad *et al*. 2001) and the effects of elevated CO_2 on plants (Curtis and Wang, 1998).

Data mining consists of sorting through large datasets and picking out relevant information. Data mining is a more powerful tool than classical statistics for searching patterns in voluminous data (Witten and Frank, 2005). It can reveal complex relationships between a dependent variable and explanatory variables. Data mining methods include classification of trees, classification rules and artificial neural networks. Examples of applications include modelling forest fire (Javier Lozano *et al*. 2008), forecasting drought (Mishra and Desai, 2006), modelling deforestation (Mas *et al*. 2004), modelling rainfall-runoff relationships (Dawson *et al*. 2006), or modelling the distribution of vegetation in future climate (Hilbert and Ostendorf, 2001).

Uncertainty analysis Many methods and tools exist for analyzing uncertainties (New and Hulme, 2000). The most common approach is the application of different climatic or socio-economic scenarios and the presentation of the range of outcomes. Another approach can involve applying different ecosystem models or different representations of a social system, for exploring a different sensitivity or adaptive capacity. It is also possible to combine different scenarios with different system models. In addition to the simple presentation of the range of outcomes, more formal methods can be applied, such as Monte Carlo analyses or Bayesian methods (Katz, 1999). Zaehle *et al*. (2005) describe uncertainty analyses in forest and global vegetation modelling.

Specific ecosystem services: Some models deal with specific ecosystem services, such as hydrological services. Empirical or process-based hydrological models can be used for assessing the impacts of climate and land-use change (or impacts of climate change on ecosystems) on hydrological regimes (Ewen and Parkin, 1996; Parkin *et al*. 1996; Bathurst *et al*. 2004).

Simple Ecosystem Models

Bioclimatic models are widely used tools for assessing the impacts of climate change on species or ecosystems. Such models are static and link the geographical distribution of species or ecosystems to their environment (Guisan and Zimmermann, 2000). The simplest bioclimatic methods applied to ecosystems are based on existing classifications using environmental characteristics to predict ecosystem distribution (Leemans *et al*. 1996). Empirical models are also used for modeling the distribution of ecosystems, e.g. with tools such as BIOCLIM (Beaumont *et al*. 2005) or with an artificial neural network (Hilbert and van der Muyzenberg, 1999). These models can be applied for studying the future distribution of ecosystems under climate change (Hilbert and Ostendorf, 2001).

Locatelli and Imbach (2008) studied the vulnerability of protected areas to climate change in Central America. The sensitivity was assessed with the displacement of Holdridge life zones under changing climate. Regarding the distribution of species, models can be built from observations and applied with climate change scenarios for predicting potential future distributions. Different methods can be used for modelling species distribution (Guisan and Zimmermann, 2000), such as rectilinear models (Miles et al. 2004), regression tree analysis (Iverson and Prasad. 2001), linear models, additive models, classification of trees and artificial neural networks (Thuillier *et al*. 2006).

Community and landscape dynamics: Goudriaan *et al*. (1999) studied the interactions between species in an ecosystem and between ecosystem patches in a landscape. Price and Flannigan (2000) developed the patch level, gap models to simulate dynamics of tree regeneration, growth and mortality and represent successional dynamics of forests over long periods of time. Examples of application include studying the distribution of trees under scenarios of climate change (Sykes *et al*. 1996) and developing forest management strategies for adaptation to climate change (Lindner, 2000). Schmitz *et al*. (2003) gave examples of models representing the trophic interactions in ecosystems for studying the effects of climate change, for instance a dynamic system, linking climate with three trophic levels (plants, herbivores and carnivores) and illustrating the interactions among different level in food webs. These interactions can determine the effects of climate change on ecosystems. Landscape models simulate the interaction between spatially connected patches (Goudriaan *et al*. 1999).

Integrated ecosystem models

Many models integrate different components, for example the distribution of ecosystem types and the functioning of these ecosystems in terms of biogeochemical cycles. These models are generally complex, especially the dynamic global vegetation models. They are generally applied at a global or continental scale but can also be used for studies at a more local scale.

Equilibrium models: Peng (2000) predicted the distribution and functioning of ecosystems under the assumption of equilibrium conditions of climate and vegetation. The BIOME3 model predicts ecosystem state in terms of plant types, total leaf area index and net primary production (Haxeltine and Prentice, 1996). These outputs allow classifying ecosystems into biomes for comparison with vegetation maps. MAPSS was applied in Mesoamerica for assessing the impacts of climate change on ecosystems' hydrological functions. The model requires input about monthly climate (precipitation, temperature, humidity and wind speed) and soils. The outputs of the model include vegetation characteristics (such as leaf area index of trees, shrubs and grasses), monthly soil moisture, surface runoff and base flow.

Dynamic models: Dynamic global vegetation models (DGVMs) are the most advanced ecosystem models for studying the impacts of climate change on ecosystems. They link dynamically vegetation structure and functioning, and simulate how climate change and natural disturbances affect ecosystem dynamics and processes (Peng, 2000). Opposite to equilibrium models, they can simulate transient changes in ecosystems. Examples include IBIS (Foley *et al*. 1996; Foley *et al*. 2005), LPJ (Sitch *et al*. 2003), MC1 (Daly *et al*. 2000), and Orchidee (Krinner *et al*. 2005). These models require a high level of expertise in ecosystem modelling.

Integrated ecosystem models, static or dynamic, consider many ecosystem processes and are generally complex. Many methods and tools are available for analysing the vulnerability of ecosystems or social systems, methods are lacking for integrating them into vulnerability assessments of coupled socio-ecological systems. Even if different tools and methods can be applied separately to ecosystems and social systems, the challenge is to link them into an integrated assessment. Ecosystem tools are generally quantitative, while social methods are often qualitative. Time horizons and spatial scale also differ greatly between large-scale, long-term ecosystem modelling and local, short-term social vulnerability assessment. The challenge is to build methods that facilitate the links among the different approaches of vulnerability.

Vulnerability assessment of forests in India

Climate is one of the most important determinants of vegetation patterns globally and has significant influence on the distribution, structure and ecology of forests (Kirschbaum *et al*. 1995). India is a mega-diversity country where forests account for about 21.54% (70 million ha) of the geographical area (FSI, 2017). With nearly 200,000 villages classified as forest villages, there is obviously large dependence of communities on forest resources (Ravindranath *et al*. 2004). Thus it is important to assess the likely impacts of projected climate change on forests, develop and implement adaptation strategies for both biodiversity conservation and the livelihoods of forest dependent people (Ravindranath *et al*. 2006). Forests in India are already subjected to multiple stresses, including over extraction, pest outbreaks, fuelwood collection, livestock grazing, forest fires and other anthropogenic pressures. Climate change will be an additional stress, which may have an overarching influence on forests, through other stresses (pest incidence and diseases etc.) (Gopalakrishnan *et al*. 2011).

Despite utility of the forests and ecological importance, forests in India are degrading due to number of pressures like diversion of forest lands for development purposes, unsustainable harvest of forest products, encroachments, forest fire, invasive species and various other biotic interferences (Gera, 2016).

The impacts of climate change on forests in India are assessed based on the changes in area under different forest types, shifts in boundary of forest types, and net primary productivity (NPP) (MoEF, 2012). As per the Second National Communication to the UNFCCC, 2012, the existing assessments are based on (i) spatial distribution of current climatic variables, (ii) future climate projected by relatively high-resolution regional climate models for two different periods for the A1B climate change scenario, and (iii) vegetation types, NPP and carbon stocks as simulated by the dynamic model, Integrated Biosphere Simulator (IBIS v.2). The IBIS model is designed around a hierarchical, modular structure, which is based on four modules, namely, (i) the land surface module, (ii) vegetation phenology module, (iii) carbon balance module, and (iv) vegetation dynamics module. These modules, though operating at different time steps, are integrated into a single physically consistent model. The state description of the model allows trees and grasses to experience different light and water regimes and competition for sunlight and soil moisture determines the geographic distribution of plant functional types and the relative dominance of trees and grasses, evergreen and deciduous phenologies, broadleaf and conifer leaf forms, and C3 and C4 photosynthetic pathways. Scenarios of climate change: SRES scenario A1B is considered for two future time-frames: (i) timeframe of 2021–50 (atmospheric CO_2 concentration reaches 490 ppm), which is labelled as "2035" and (ii) time frame of 2071–2100 (atmospheric CO_2 concentration reaches 680 ppm), which is labelled as "2085". Observed climatology for the period 1961–91 was treated as the baseline for the simulations (MoEF, 2012).

Using climate projects of the Regional Climate Model of the Hadley Centre (HadRM3) and the dynamic global vegetation model IBIS for A2 and B2 scenarios Chaturvedi *et al*. (2011) reported that 39 and 34% of forest grids in India are likely to undergo change of forest type under the A2 and B2 scenarios, respectively by the end of this century. This study also concluded that the upper Himalayas, northern and central parts of Western Ghats and certain parts of central India are most vulnerable to projected impacts of climate change, while North-eastern forests are more resilient. In a similar study, Gopalakrishnan *et al*. (2011) have reported that at the national level, about 45% of the forested grids are likely to undergo change. The vulnerability assessment in the study showed that the vulnerable forested grids are spread across India. However, their concentration is higher in the upper Himalayan stretches, parts of Central India, northern Western Ghats and the Eastern Ghats. The study also reveals that in contrast, the north-eastern forests, southern Western Ghats and the forested regions of eastern India were estimated to be least vulnerable.

Himalayan ecosystems are projected to be extremely sensitive to future climate (Chaturvedi *et al*. 2011). Further, Himalayan ecosystems are highly vulnerable due to the stress caused by forest land diversion, increasing pressure from human population, exploitation of natural resources, infrastructure development, mining, and other related challenges. The effect of these stressors is likely to be exacerbated due to climatic changes, which would be additional (Ravindranath *et al*. 2006). Analysis of temperature trends in the Himalayan region shows that temperature increases are greater in the uplands than that in the lowlands (Shrestha *et al*. 1999). Gopalakrishnan *et al*. (2011) have reported that the high-altitude mountainous forests (sub-alpine and alpine forests, the Himalayan dry temperate forest and the Himalayan moist temperate forests) are susceptible to the adverse effects of climate change.

There are national level assessments for impact of climate change on forests, but, such studies are lacking at the regional level (Sujata *et al*. 2015). On regional level, Sharma *et al*. (2013) had attempted to assess the inherent vulnerability of forests using a methodological approach. This methodological approach was applied at local scale to Aduvalli Protected Forest, Kopal division of Chikamagalur district of Karnataka in Western Ghats South India, where a vulnerability index value of 0.248 was estimated. Results of the case study indicate that 'preponderance of invasive species' and forest dependence of community are the major sources of vulnerability for Aduvalli Protected Forest.

Climate change is expected to increase species losses. Changes in phenology are expected to occur in many species. The general impact of climate change is that the habitats of many species will move poleward. Species that make up a community are unlikely to shift together (MoEF, 2012). A study conducted by Singh *et al*. (2012) on the alpine forests of Uttarakhand reveals shift of treeline ie., *Betula utilis* from the year 1970 to 2006, due to the impact of ongoing warming under the background influence of increasing levels of GHGs. Bharali and Khan (2011) reported the phenological changes in some floral species (Rhododendron species and Orchids) in Arunachal Pradesh.

The second communication of India to UNFCCC, reports that ecosystems dominated by long-lived species will be slow to show evidence of change and slow to recover from the climate-related stress (MoEF, 2012). Climate change and modelling studies on tree species like Sal (*Shorea robusta*), Teak (*Tectona grandis*), Eucalyptus, and Pine (*Pinus* spp.) have been undertaken for A2 and B2 climate change scenario. Test run studies on Teak and Sal trees, highly characteristic of Central India, have indicated that there would be a net increase in primary productivity with increase in temperature and rainfall, but this would also lead to a dieback with the induced stress to nutrient availability. The report also states that the enhanced levels of CO_2 are expected to lead to an increase in the NPP of forest ecosystems, with more than 75%

of the grids showing an increase in NPP. Even in a relatively short span of about 50 years, most of the forest biomes in India seem to be highly vulnerable to the projected change in climate. Further, it is projected that by 2085, 77% and 68% of the forest grids in India are likely to experience shift in forest types under A2 and B2 scenarios, respectively. Indications point towards a shift to wetter forest types in the north-eastern region and drier forest types in the central and north-western region, in the absence of human influence. Increasing atmospheric CO_2 concentration and climate warming could also result in the doubling of NPP under the A2 scenario and nearly 70% increase under the B2 scenario (MoEF, 2012).

Ravindranath *et al*. (2006) had estimated the impact of climate change on net primary productivity (NPP in g C/m^2 per year) under the current and GHG scenarios. In their study it was observed that among the dominant vegetation types (tropical xerophytic shrubland, tropical deciduous forest, warm mixed forest and tropical semi-deciduous forest), the NPP increases by 1.35 to 1.57 times under the GHG scenarios (A2 and B2) over the current scenario of NPP. The NPP under tropical evergreen forest increases by 1.5 times under the GHG scenarios. The rate of increase on NPP was lower for cool conifer forest, cold mixed forest and temperate deciduous forest. Generally the rate of increase is higher for warmer vegetation types.

Assessment of vulnerability is an urgent task because any adaptive measures undertaken would need time to develop before the adaptive capacities actually build-up (Seidl and Lexer, 2013). Vulnerability assessments are necessary at local scale (forest stand or patch) as well as larger scales like landscapes, eco-regions and biomes which serve different objectives. While the assessments at larger scales would assist in identification of vulnerable forest areas and to prioritize them for efficient resource allocation (Næss *et al*. 2006), the assessments at local scale are necessary for designing site specific forest resilience enhancement measures. The results of inherent vulnerability assessment of forest would inform development of appropriate forest management practices and policies to restore disturbed forests, as restored forests would have higher adaptability than un-restored forests under climate change (Ciccarese *et al*. 2012).

Knowledge gaps in vulnerability assessment

According to MoEF (2012) although climate change is a global issue for discussion, there are some gaps and constraints visible in the knowledge of vulnerability assessment, adaptation and mitigation aspect of forestry. Key knowledge gaps include the linkages between impacts of climate change and adaptation and mitigation options. Despite the emergence of more and more regional and country specific studies on climate change in India in recent years, knowledge gaps remain huge. There is an urgent need for undertaking more research at regional level to better understand the climate change and its impact, risks and vulnerability, adaptation needs, and mitigation potential at local levels.

The forestry sector in India has the potential to be a major source or sink of CO_2 in the future. The uncertainty in the estimates of inventory in the forestry, land use and land use change is shown to be higher than other sectors such as energy transformation, transportation, industrial processes, and even agriculture. The availability and access to information on activity data, emission coefficients, and sequestration rates in the forestry sector in India are limited, and the uncertainty of the data is high, as in most countries. Thus, there is a need for improvement in the information generation processes for the inventory so as to reduce the uncertainty involved in the estimation of GHG inventory in the forestry sector (MoEF, 2012).

Conclusion

Considerable knowledge gaps exists for the purpose of modelling future climate change impacts and bringing up with robust adaptation strategies. Knowledge gaps include uncertainty in the estimates of inventory in the forestry, land use and land use change, and inadequate knowledge on the relationship between climate and ecosystem responses. There is therefore an urgent need for developing regional and national level dynamic vegetation models for assessing climate change impacts on forest ecosystems and biodiversity. Ecological studies on endemic and endangered species in relation to climate variability and change, and understanding changes in the phenological patterns of vegetation and its impact on associated fauna, primarily at the species level are pre-requisites for developing adaptation strategies and practices to reduce vulnerability of forests to climate change.

Summary

India's forests harbours several endemic and endangered species. The rapidly growing human population and increasing development needs have already pushed the forests and their dependent life forms to the precipice of irreversible destruction. The added dimension of climate change and its potential impact on the survival of forests calls for immediate studies for the identification of the most vulnerable forest areas wherein concerted conservation/ mitigation efforts could be taken up. In this context, various vulnerability assessment methodologies including generic approaches, simple ecosystem models and integrated ecosystem models could be adopted for understanding the vulnerability.

Few studies have already been taken up in India for assessment of vulnerability of India's forests to climate change. The impacts of climate change are assessed based on the changes in area under different forest types, shifts in boundary of forest types, and Net Primary Productivity (NPP). Several studies have tried to evaluate the changes in the forest ecosystems due to the changes or projected climate change scenarios. It is projected that by 2085, 77% and 68% of the forest grids in India are likely to experience shift in forest types under A2 and B2 scenarios, respectively. In another study a it has been observed that the upper Himalayas, northern and central parts of Western Ghats and certain parts of central India are most vulnerable to projected impacts of climate change, while North-eastern forests are more resilient. Himalayan ecosystems are projected to be extremely sensitive to future climate.

Besides national level assessments, there are a number of studies on regional basis assessing the vulnerability of the forests. Regional level climate change studies have assessed shift in tree line of *Betula utilis* in the alpine vegetation in Uttarakhand. In similar studies, phenological changes in Rhododendron and orchids have been reported from Arunachal Pradesh. However, such studies are staggered spatially and do not reveal changes occurring to the landscape. More such regional studies could help better understand the climate change and its impact, risks and vulnerability, adaptation needs and mitigation potential. Importantly, there is urgent need to devise research strategies to evaluate the ecological assessment of endemic and endangered species vis-a-vis the climate change scenarios. Uncertainty in estimates of inventory in forestry, land use and land use change calls for refinement of information generation processes in the forestry sector.

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CHANGING ORTHOPTERA (ARTHROPODA: INSECTA) DIVERSITY IN NILGIRI SHOLAS AND GRASSLANDS - A SIGN OF CLIMATE CHANGE?

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Introduction

Orthoptera is one of the largest orders of the class insecta and includes the well known grasshoppers, locusts, crickets and katydids. They form a dominant group of herbivorous insects throughout the world, and their high diversity, functional importance and sensitivity to disturbance make them potentially useful bioindicators for land management. They are known to occur in a wide variety of habitats, ranging from the littoral zone of the sea shore to grasslands, forests and mountain tops, well above the tree line. There are models that explain that the number of species in the 100m altitudinal bands increases steeply with altitude until 1,500 m above sea level, and between 1,500 and 2,500 m, little change in the number of species is observed, while above this altitude, a decrease in species richness is evident (Mathew and Mohandas, 2001). However, certain models indicate that insect distributions should be expected to shift towards higher latitudes and altitudes (Régnière *et al*. 2009). The montane forests are the stunted evergreen forests locally known as 'sholas'. They are found only above 1500 m in the glens, hollows and valleys of the mountains. Nilgiris sholas are situated in the higher mountain tracts of the southern Western Ghats, at an altitude above 1800 m, interspersed with rolling grasslands. In the sholas, the trees are stunted with crooked branches thickly laden with moss and other epiphytes. Nilgiris sholas are unique in terms of their vegetation and species diversity. The natural vegetation in the sholas and the grasslands depleted very fast due to introduction of commercially valuable fast growing trees like Wattle, Eucalyptus, Cypress and Pine by the Britishers in 19th century to provide pulp for the Rayon and paper industries. Fortunately, by late eighties, there was a shift in Government policies. Further plantations of wattle and Eucalyptus were stopped. Experiments are now on to reconvert these plantations into sholas. Studies have shown that majority of the endemic plants of the Nilgiris tract are highly threatened and many are already extinct because of loss of habitat due to anthropogenic pressure. Since orthopteran insects are good indicators of climate and landscape changes and no authentic record of Orthoptera in theses sholas was available, an attempt was made to study the diversity of Orthoptera in Nilgiris shola forests.

Study sites

There are three locations each with a total of six sites under Nilgiri North and South Forest Divisions *viz*. Kotagiri Longwood shola, Uppati shola, Nedugula shola in former and Avalanche cauliflower shola, ninth mile shola and Parson's valley shola in latter respectively were selected for the study. They are located between 11º 12' 68.2" N and 11º44' 18.00" N latitude and betwen 76º35' and 76º62' E longitude with the elevation ranging from 1937 m MSL to 2295 m MSL.

Sampling and analysis of data

The entire vegetation was covered during the intensive search out method, which involved hand picking the insects from the vegetation after locating them; sweep nets were also used for collecting specimens. Sanjayan (1994) showed that this was the best sampling method for species of Orthoptera. Orthoptera were observed between 0700 hrs to 1300 hrs and specimens collected. Collected specimens were narcotized with menthol crystals, brought to the laboratory and air-dried for identification. All the specimens were examined carefully and identified specimens were labeled and preserved in insect boxes. A cotton wad immersed in preservative (Phenol, Naphthalene, and Para dichlorobenzene in equal ratio) was kept in the corner of the box to restrict ant and fungal attack. The specimens collected were identified using various publications of Rentz (1979), Tandon and Shishodia (1972), Ingrisch (1990, 2002), Ingrisch and Shishodia (1997,1998,2000), Shishodia (2000a, b), Shishodia and Tandon (1990), Naskrecki (1994, 1996a,b, 2000), Naskrecki and Otte (1999) and Senthilkumar *et al*. (2001, 2002). As a measure of a-diversity (diversity within a habitat), the most popular and widely used Shannon's diversity index (H') was calculated since it is well accepted that all species at a site, within and across systematic groups contribute equally to its biodiversity (Ganeshaiah *et. al*. 1997). In addition, Simpson's diversity index (I) and coverage estimators were also calculated as per Colwell (2004) using the software Estimate S 7.

Results and discussion

Orthopterans belonging to fifteen genera and 15 species, including an unknown gryllid and two unidentified acridids were recorded from the shola forests and grasslands (Table-1). Seven species belonged to the family Acrididae and 6 species to Tettigoniidae. The family Gryllidae was represented by only two species. A greater diversity of short-horned grasshoppers was recorded in all the shola forests under study followed by tettigoniids. It is a common belief that natural ecosystems, still untouched by human beings, are characterized by a great diversity of animal and plant species. These heterogeneous conditions form the basis of a stable and well-balanced environment in which population oscillates within certain limits (Senthilkumar *et al*. 2006). The present study on Orthoptera has again supported the fact that a heterogeneous and undisturbed habitat like the forest lands harbour greater number of insect species. This observation is supported by the study of acridids diversity in Tamil Nadu (Senthilkumar *et al*. 2009). The species recorded namely, *Orthacris maindronii*, *Hetracris pulcher*, *Gastrimargus africanus*, *Phaleoba infumata*, *Mecopoda elongata*, *Mirrollia cerciata* and *Hexacentrus major* were earlier found in the low to mid elevations, mostly in lowland forests in particular (Sanjayan *et al*. 2002; Senthilkumar *et al*. 2009) None of these species were reported earlier in high altitudes. (Senthilkumar, 2002). It is evident from the study of Ching Chen *et al*. (2009) that tropical insect species have undertaken a shift towards higher altitudes, confirming the global reach of climate change impacts on biodiversity. The species richness in shola forests under Nilgiris North and South divisions were similar (Table-2.). However, the species composition differed. The species such as *Mirrollia cerciata, Hexacentrus major, Hetracris pulcher, Elaemaea securigera* and *Phaneroptera gracilis* were found only in the Cauliflower shola, Parson's valley shola, Nedugula shola and Uppati sholas respectively. The species namely *Orthacirs maindronii*, *Gryllodes sigillatus, Gastrimargus africanus* and *Phaleoba infumata* were recorded in more than four locations. The occurrence of the rare species like *Mirrollia cerciata*, unknown gryllid and unknown acridid in Avalanche Cauliflower shola indicate that the habitat is unique with characteristic vegetation types. Grasshoppers diversity was predicted to decrease significantly and species rich locations were predicted to move towards higher altitudes (Maes *et al*. 2010). The large turnover rates were predicted to occur at higher altitudes for grasshoppers.

Shannon's diversity index was calculated as a measure of diversity within a habitat. The diversity indices H', and 'D' appear useful as they incorporate both species richness and evenness into a single value. The present study indicates that orthopteran species are more diverse in Nilgiris shola forests, the Shannon's index gave high values in Nedugula followed by Longwood and Avalanche shola forests (Table-3). Simpson's diversity index, 'D', also gave high value for these sites. It indicates that the shola forests and grasslands in these locations are occupied by species with more individuals. The availability of host plants in the habitat is vital for insect colonization. The type of vegetation in a habitat influences not only species presence, but also the number of individuals. Though the study sites fall under Nilgiris North and South divisions, the assemblage of orthopteran community varies as observed from the similarity index. The dendrogram (Fig.1.) showed similarity between sites of two different divisions in relation to Orthoptera diversity. Nedugula shola forest in Nilgiris North division is grouped under Ninth mile and Avalanche sholas in Nilgiris South division. However, Parsons' valley shola in Nilgiris South is grouped under Longwood and Uppati sholas in Nilgiris North Division. At middle latitudes, distribution shifts towards higher latitudes and altitudes seem to be prevalent, especially in highly mobile and polyphagous species (Ching Chen *et al*. 2009). Detailed models of the responses of each insect species to climate are needed to predict distribution changes with any accuracy. However, it seems difficult to make general predictions about the responses of major forest insect species from the point of view of climate change in their current ranges. There is an increasing risk of "invasion" into increasingly hospitable temperate ecosystems by the more mobile species. However, certain models indicate that insect distributions should not be expected to expand, but rather to shift towards higher latitudes and altitudes (Régnière, *et al*. 2009).

It may be concluded that upward elevation shifts of grasshopper species in Nilgiris shola forests and grasslands are consistent with responses to the climate change observed in the region, either as a direct physiological response to climate or as a consequence of altered interactions with other species. If plants shift to highter elevation, this could be facilitating shift in associated insects that feed on them too. It is too early to judge whether these responses are due to climate change. But, the Nilgiris shola forests become important climate change refugia for low elevation species. However, high mountains will only become important refugia for low-elevation species if surrounding lowland forests and other natural habitats are maintained. The conservation of lowland forest will permit lowland species to survive locally and so be available to colonize upwards while also minimizing additional regional impacts on climate change associated with lowland deforestation. High tropical mountains and their surrounding lowland habitats represent some of the most important locations in the world to maintain biodiversity in the face of climate change. Our study would advocate that possible conservation and policy measures to mitigate the potentially strong impacts of climate change on insect diversity in Nilgiris should be much more proactive and flexible. Considering the importance of the sholas and to protect this cluster of rare and endangered species permanently, Tamilnadu Forest Department, has made chain-link fence under the Hill Area Development Programme. In 2008, 225 hectares of plantation was again reconverted into Shola forests by Nilgiris North Forest Division. 100 hectares of the exotic species were cleared in the Mukurti National Park. It has resulted in the up-gradation of the degraded area and augmentation of the dwindling shola species.

Conclusion

Climate change and habitat destruction have been linked to global declines in vertebrate biodiversity, including mammals, amphibians, birds, and fishes. However, invertebrates make up the vast majority of global species richness and the combined effects of climate change and land use on invertebrates remain poorly understood. The vast majority of research on insect responses to altered climatic factors has focused on butterflies and beetles in temperate ecosystems, with a strong bias on diversity of Orthoptera. Studies regarding, tropical forest insects are still very incipient. The present study fulfils the felt need. The study on distribution and diversity of Orthoptera in

Nilgiris upland shola forests and grasslands showed that the species distributed in lowland forests are now occurring in high altitude evergreen forests. At higher elevations, we observed clear upward shifts in the elevational ranges of species, with the influence of global warming. It supported the prediction that the shifts of species towards higher altitudes seem to be prevalent, especially in highly mobile insects. It is evident from our study on the diversity of grasshoppers in Nilgiris shola forests that tropical insect species have undertaken refuge at high altitudes, confirming the global reach of climate change impacts on biodiversity.

Summary

Orthoptera in Nilgiris shoal forests and grasslands viz., Kothagiri Longwood shola, Uppati shola, Nedugula shola, Avalanche cauliflower shola, Ninth mile shola and Parson's valley sholas have been studied to understand the diversity of this group of insects. These shoals are located with the elevation ranges from 1937 m to 2295 m MSL. Fifteen species of Orthoptera belonging to fifteen genera have been recorded in the said study sites. The species namely, *Orthacris maindronii*, *Hetracris pulcher*, *Gastrimargus africanus*, *Phaleoba infumata*, *Mecopoda elongata*, *Mirrollia cerciata* and *Hexacentrus major* were found distributed only in lowland forests are now recorded in the high altitudinal stunted wet evergreen forests locally known as sholas. The diversity of this group of insects was also found to be low in high altitude forests and was expressed in Shannon's diversity index of 1.43. This study is a case where upland forests provide refuges when lowland sites are disturbed and subject to climatic fluctuations.

Acknowledgements

The authors are grateful to the Director, IFGTB, Coimbatore for providing facilities during the course of the study and Forest Department, Tamilnadu for granting permission to work in protected areas.

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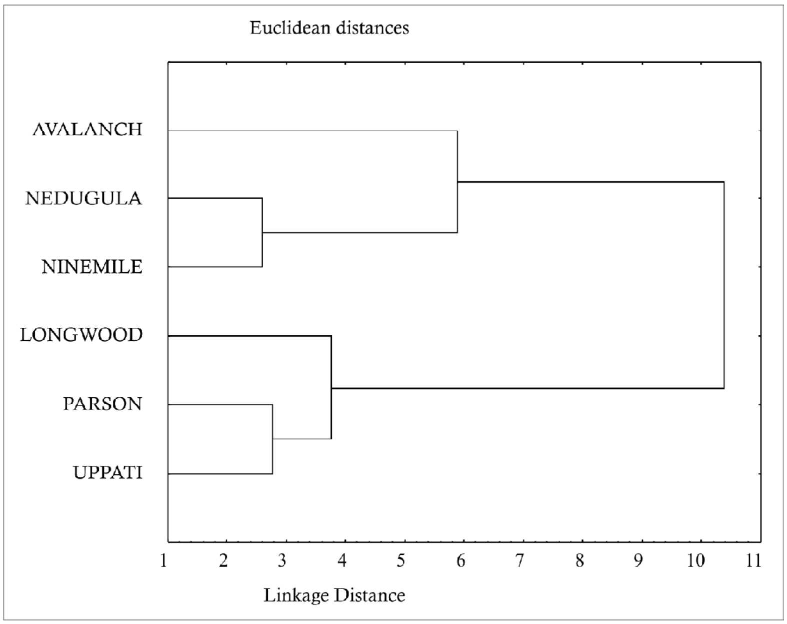

Fig. 1. Dentrogram showing the similarity of sites in realtion to Orthoptera species assemblages

Table 1. Orthoptera insect fauna in Nilgiri sholas

S. No.	Diversity index	Family	Avalanche	Longwood	Nedugula	Ninethmile	Parson's valley	Uppati
1.	*Orthacris maindroni* Bolivar	Acrididae	-	+	-	+	+	-
2.	*Oxya fuscovittata* (Marsh.)	Acrididae	-	+	-	-	-	-
3.	*Gryllodes sigillatus* (Walker),	Gryllidae	-	+	+	+	-	-
4.	*Phlaeoba infumata* Brun.	Acrididae	+	+	+	+	-	-
5.	*Elimaea* (Orthelimaea) *securigera* (Brun.)	Tettigoniidae	-	-	-	-	-	+
6.	*Phaneroptera gracilis* Burm.	Tettigoniidae	-	-	-	-	-	+
7.	*Heteracris pulcher* (Bol.)	Acrididae	-	-	+	-	-	-
8.	*Gastrimargus africanus* (Saus.)	Acrididae	+	-	+	-	-	-
9.	*Mirrolia cerciata* Hebard.	Tettigoniidae	+	-	-	-	-	-
10.	*Mecopoda elongata* (Linn.)	Tettigoniidae	+	-	-	-	-	-
11.	*Euconocephalus incertus* (Walk.)	Tettigoniidae	-	-	-	+	-	-
12.	*Hexacentrus major* Redtenb.	Tettigoniidae	-	-	-	-	+	-
13.	Unknown Acridid 1	Acrididae	-	-	-	-	-	+
14.	Unknown Acridid 2	Acrididae	+	-	-	-	+	-
15.	Unknown gryllid 1	Gryllidae	-	-	+	-	-	-
	No. of species		5	4	5	4	3	3

Table 2. Species richness and diversity of Orthoptera in Nilgiris sholas

S. No.	Location	Division	Latitude° N	Longitude° E	AltitudeM (MSL)	No. of species	H'- Shanon's index
1.	**Longwood shola**	Nilgiris North	11.26	76.52	1970.6	4	1.34
2.	**Uppati shola**	Nilgiris North	11.30	76.54	1937.1	3	0.91
3.	**Nedugula shola**	Nilgiris North	11.36	76.53	1941.2	5	1.43
4.	**Avalanche shola**	Nilgiris South	11.12	76.35	2036.0	5	1.29
5.	**Ninthmile shola**	Nilgiris South	11.44	76.62	1946.0	4	1.24
6.	**Parson's valley shola**	Nilgiris South	11.38	76.58	2295.0	3	0.99

Table 3. Diversity indices of Orthoptera in Nilgiris sholas

S. No.	Diversity index	Avalanche	Longwood	Nedugula	Ninethmile	Parson's valley	Uppati
1.	Species richness	5	4	5	4	3	3
2.	Singletons	2	0	0	1	0	0
3.	Unique	2	0	0	1	0	1
4.	ACE	7.01	4	5	4.34	3	3
5.	ICE	7.16	4	5	4.42	3	3.88
6.	Chao 1	5.75	4	5	4.5	3	3
7.	Chao 2	5.75	4	5	4.5	3	3.12
8.	Jack 1	6.75	4	5	4.87	3	3.87
9.	Jack 2	7.60	4	4.55	5.62	1.71	3.98
10.	Bootstrap	5.79	4	5.12	4.37	3.20	3.44
11.	M M mean	5.99	4.52	5.75	5.30	4.30	5.59
12.	Colewel	4.73	3.91	4.99	3.87	2.98	2.98
13.	Alpha diversity index	2.29	1.07	1.50	1.59	1.35	1.35
14.	Shannon index	1.29	1.34	1.43	1.24	0.99	0.91
15.	Simpson's index	3.47	3.99	3.91	3.82	2.89	2.81

TREE IMPROVEMENT AND BIOTECHNOLOGICAL STRATEGIES FOR CLIMATE RESILIENCE

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Introduction

Climate change poses a major threat to all life forms. Forest trees, being climate dependent perennial species, are vulnerable to climate changes. The long life span and generation time exhibited by several forest trees places them in a precarious position when changes in their growing environment occur rapidly. The environmental challenges associated with climate change include increased incidences of drought, heat, fire, flood, insect pest and pathogen pressure, change in growing seasons and forest fragmentation. This adversely affects both natural and managed forests, limiting survival, growth and reproductive fitness (Dai, 2013). The pressure on water and nutrient foraging and increased disease and pest infestations will economically and ecologically affect forests and tree plantations. Unlike breeding of annual crops, trees require several seasons of vegetative and reproductive phases to select or identify best performing individuals for a defined utility. During these cycles, trees are susceptible to the rapidly changing environmental conditions. Although increase in atmospheric CO_2 concentration may increase photosynthesis and plant growth, still climate change side effects will not compensate the general reduction of productivity (Rustad *et al*. 2011). Low rainfall and increased temperatures are already contributing to spreading of desertification, mostly in arid and semi-arid regions, and the situation is expected to worsen in the near future. Therefore, it is imperative to develop and implement new strategies for improving forest productivity.

In India, the climate change can amplify the impact on the plantations due to poor soil conditions, less water availability, the greater magnitude of air polluation, poor water quality and faster urbanization and industrialization. When compared to other sectors, introduction of advanced technologies in forestry sector is not adequate; as a result the forest ecosystem becomes more vulnerable to climate change effects. Although lot of importance is given to tree planting, considering the advantages of forests, very less knowledge available about the species requirements and its environmental interactions. Along with exotics, native tree species plays major role in combating the climate change issues, as these species are naturally selected for various climatic conditions of the local environments. In the recent days, there are studies and recommendations at the clonal level on the suitability of the clones for matching the clones to specific site conditions.

The most important strategy for forest climate adaption is identification and planting of well-suited tree species in a phased manner. At the same time, diverse climate resilient species, well-adapted to future conditions needs to be maintained. It is also critical to preserve within species diversity for a more stable forest plantations with resilient populations. These activities need to be given at most importance as it will take few decades to shift from routine planting programmes to climate resilient tree species plantations.

Current selections focus on the vigorous growth of the trees on the present day climatic factors and not envisaging climatic conditions of the future. Right trees need to be selected considering the factors that may influence performance in the future. The basic information available on the tolerances and responses of a species is frequently incomplete, adding uncertainty to decision-making (Sjoman and Nielsen, 2010).

According to Harris *et al*. (1999), selection is a compromise among proposed function of the plant and its adaptation to the site. Miller (1997) proposed a species se-lection model that included site factors like environmental and silvicultural con-straints, social factors like aesthetics, functions and disservices and eco-nomic factors like cost of plant, establishment and maintenance. Sæbø *et al*. (2005) considered climate adaptation as primary selection criteria in addition to growth and pest resistance for street and park trees. Yang (2009) evaluated the potential effects of climate change on the biology of pests in Philadelphia, Pennsylvania, as well as the suitability of tree species to future predicted climatic condition.

Plantation forestry is the source of industrially important products such as paper pulp, timber, fuel wood, biofuel and charcoal. Plantations reduce pressure on natural forests and provide ecosystem services, while contributing to economic growth and livelihood opportunities. These plantations are continuously subjected to various challenges posed by climatic conditions and associated threats, regardless of their contribution to mitigate climate change. Under such conditions, productivity of plantations decrease significantly due to change in phenology, increased challenges from native and exotic pests, enhanced salinity/acidity/alkalinity and reduced rainfall, soil fertility and water availability. Evidences are mounting on climate change risks of drought and heat induced mortality in forests trees (Allen *et al*. 2010). With burgeoning human population and increased demand for food production, plantations are likely to be pushed to the marginal areas in the near future. Additionally, the requirement of wood is on rise, necessitating optimal productivity from traditionally un-cultivable land. At this juncture, development of appropriate adaptation strategies in response to these challenges will require a comprehensive approach. Various technologies from the fields of tree improvement, breeding and biotechnology have an important role to play in mitigating the impending climate change.

Strategies for breeding climate resilient trees

Trees are in continuous interaction with below and above ground environments and over the period, trees adapt to changes in climate. Such adaptations acquired are imprinted through epigenetic modifications in the tree genome. The general strategy used by tree breeders to alleviate the effect of climatic variation is by using seed zones and breeding regions which ensures seedlings are well adapted to their planting environments. (Gray *et al*. 2016). It has been argued that breeding for adaptive traits can be a long term goal in genetic improvement programs, while delineation of breeding zones and deployment of planting material from relatively homogenous local environments can ensure sustainable productivity and reproductive fitness in the face of climatic changes (Mijnsbrugge *et al*. 2010). The strong linkage between climate and genetic differentiation has been reported from several tree species. A study in *Pinus contorta* has demonstrated that local populations are significantly climate resilient when compared to introduced populations and hence can be a short term adaptive measure (Gray *et al*. 2016). Recently, climate based provisional seed zone delineation, based on minimum temperature and aridity index was conducted in Mexico (Castellanos-Acuña *et al*. 2018), which recommended moving seed sources from warm, dry locations towards currently wetter and cooler planting sites, to compensate for climate change that has already occurred and is expected to continue for the next decades. Such climate based seed zone system allows practitioners to match seed procurement regions with planting regions under observed and anticipated climate change.

Insect outbreaks due to climate change are significant disturbances in forests ecosystems. Mountain pine beetle infestation in western North America is a classic example of pine forest devastation due to increase in temperature. Ponderosa pine (*Pinus ponderosa*) and lodgepole pine (*Pinus contorta*) are the suitable hosts for this insect. It developed adaptive seasonality, synchronous emergence of adults from host trees at an appropriate time, to overwhelm tree defenses. Recently, a strategy for selection on growth rates over time was proposed to control the insect pest by selecting fast (at juvenile stage) and slow (mature stage) growing genotypes thus maintaining genetic diversity for growth rate in pine populations instead of fast growing families (de la Mata et al. 2017). Including pest resistance traits in the breeding programs may contribute to a sustainable protection. Warming climate is thought to be a major cause of epidemic outbreaks of native diseases and pests that are causing relatively new and catastrophic problems; recent examples include spruce bark beetle damage in Finland (Neuvonen and Viiri, 2017) and *Larix* defoliaters in China (Fan and Bräuning 2017).

Biotechnological applications in forestry has been mainly focused on improving productivity, monitoring diversity status at ecosystem and landscape levels and reducing vulnerability to biotic and abiotic pressures. One of the main contribution of this technology was in energy saving, waste reduction and remediation of toxic chemicals by using microbial enzymes in pulping process (Ahuja *et al*. 2004). However, these applications of biotechnological tools are limited to six genera (*Pinus, Populus, Eucalyptus, Picea, Quercus* and *Acacia*) (FAO, 2010), mostly of temperate origin. Use of markers (DNA based and biochemical) in operational plantation management is an area where the technology has expanded over decades and three major areas were identified like genetic fingerprinting suitable for less intensively managed plantations; markers tagging industrially relevant traits for intensively managed commercial plantations and the third area includes the most sophisticated group of technologies like genomics approaches and genetic modification of targeted traits (FAO, 2010; Gartland and Gartland, 2013).

Maintenance of genetic diversity

In trees, the extent of genetic diversity determines the ecosystem integrity, evolutionary capacity, adaptability and economic potential of the species. Knowledge on genetic diversity is important for planning breeding strategies and provides a basis for improving the management of genetic resources in forest tree species (Graudal *et al*. 2014). Long-term breeding is aimed at achieving a balance between continuous genetic gains and maintenance of adequate levels of genetic variation. High levels of heterozygosity in the population have been repeatedly shown to confer resistance to environmental change.

Climatic conditions, mainly temperature determine the genetic differentiation and evolution of locally adapted population (Linhart and Grant 1996) and temperature is the key parameter governing natural selection and adaptive genetic variation as documented in conifers (Gray *et al*. 2016; Thomson and Parker, 2008) and *Eucalyptus* (Merchant *et al.* 2006). Adaptation and phenological plasticity in trees with response to temperature presents strong differences between species.

Landscape genomics determines the relationship between genetic and environmental heterogeneity in populations and is a powerful tool for discovery of genes underlying complex patterns of adaptation in forest ecosystems. In *Acacia koa*, an endemic species to Hawaiian Islands, a strong association between genetic structure and mean annual rainfall was detected, despite that genome level association studies predicted changing rainfall pattern may lead to genetic offsets or maladapted population (Gugger *et al.* 2017). Similarly, In *Eucalyptus melliodora*, a foundation species of a critically endangered community in Australia, landscape genomic model revealed that seed can be sourced broadly across the landscape, providing ample diversity for adaptation to environmental change (Supple *et al.* 2017). Such knowledge on genetic changes due to climate change would help in devising seed transfer guidelines across various ecological zones of a species distribution. Such vulnerable geographic regions demand transfer of seed material from pre-adapted germplasm. Recently, key considerations for planning genomic assessment and monitoring of locally adaptive variation to inform species conservation has been identified (Flanagan *et al.* 2017).

Assisted gene flow to mitigate climatic influence

The immediate response to environmental challenges is migration and changing spatial boundaries. Existing models predict long-distance migration by seed dispersal in trees at 100–200 m yr^{-1} (Nathan *et al.* 2011), which is much slower than the temperature change rates across geographical gradients. This was reported for temperate broad-leaf and mixed forests of North America, where the expected migration rate predicted was 350 m yr^{-1} (Loarie *et al.* 2009) suggesting that trees would need to migrate at 10 times the present rate to keep up with their suitable habitats. This is further impeded by landscape fragmentation (Pearson and Dawson, 2005), indicating that integrated interventions are required to develop stress adapted trees to improve forest lands and commercial plantations.

Transfer of seeds from such pre-adapted individuals or transfer of seeds within existing species range is considered to be one of the effective tools in climate resilient tree generation. This type of human assisted movement of plants is known as Assisted Gene Flow (AGF). It will facilitate planted forests adaptation, where these planting stock will have the capacity to maintain production and fitness in a changing climate. Genecology, defined as knowledge on relationships between genetic variation of natural populations and their geographic (native environment) variations, would be the pre-requisite for assisted gene flow to facilitate rapid adaptation of species to climate change. In temperate and boreal forest species including *Abeis*, *Pinus*, *Picea*, *Quercus* and *Populus,* sufficient knowledge and rich history of research is available to initiate managed translocation within the species range across climate gradients (Aitken and Bemmels, 2015).

It is suggested that along with conventional strategies like within and between population variation in phenotypic traits, height and girth, comprehensive understanding on clinal variations, cold and drought hardiness, variation in adaptive and neutral genetic markers at population level, genomic scans, along with well designed provenance trials are essential for translocation of species and generation of climate resilient trees. Aitken and Bemmels (2015) had listed several recommendations for AGF of forest trees, after synthesizing the broad knowledge that has accrued on local adaptation over the past several centuries. Local adaptation involves alleles that are beneficial in one environment and neutral elsewhere, hence, understanding the genetic basis of adaptation to climate is of paramount importance for preserving and managing genetic diversity. Studies of adaptive traits in temperate forest trees revealed the presence of clinal variation in phenotypes, as well as genetic differentiation among populations, suggesting that local adaptation is present in trees (Kramer *et al*. 2017). In conifers, considerable amount of research was carried out to characterize the genomic basis of adaptation to local climate. Such studies provided an important resource for breeding and conservation genetics in a changing climate.

Markers assisted selection for adaptive traits

Marker Assisted Selection (MAS) is one of the methods for a successful breeding for adaptive traits, which relies on the identification of Quantitative Trait Loci (QTL) linked molecular markers associated with traits of interest. In the past decades, few studies have been conducted to map genes or QTL associated to drought tolerance in Conifers (Moran *et al*. 2017), *Populus* (Viger *et al*. 2016), *Eucalyptus* (Mora *et al*. 2017; Sumathi *et al*. 2018), *Quercus* (Brendel *et al*. 2008) and salt tolerance in *Salix* (Zhang *et al*. 2017) and *Eucalyptus* (Subashini 2017). Genetic basis of elevated CO_2 was studied in *P. trichocarpa* x *P. deltoides* and 3 genomic regions in 6 different linkage groups were recognized to determine above ground growth and root growth response (Rae *et al*. 2007). However, till date, conversion of marker-QTL information to breeding programs is highly limited mainly due to dependence of the QTL effects on genetic background and environment.

The new genomic approaches like Next Generation Sequencing (NGS) allow massive discovery of molecular markers to obtain ultra-high density genetic maps, which are very useful to precisely locate genomic regions governing the trait. Moreover, Single Nucleotide Polymorphisms (SNPs) generated through NGS can be used in high-throughput genotyping platforms, which permit the simultaneous analysis of many markers and many individuals. Presently, it is possible to move from the exploration of recent recombination through the analysis bi-parental mapping populations to the Genome-Wide Association (GWA) studies, which use the natural diversity to identify genetic loci associated with phenotypic trait variation and provides better resolution.

Foliar and floral budburst timing is an important component of the fitness of trees. Chilling and forcing temperature requirements are key traits determining a tree’s response of the date of foliar budburst to temperature. In Sitka spruce (*Picea sitchensis*), association mapping for quantitative trait variation in bud set timing and autumn cold hardiness was analyzed with SNPs and associations were detected in several candidate genes, which cumulatively explained 28 and 34% of phenotypic variance in cold hardiness and bud set, respectively (Holliday *et al*. 2010). The genetic basis of adaptation to climate using mean annual temperature and total annual precipitation in *Picea glauca* was explored through association genetics and found that 43 genes are most important for adaptation to climate which involves genes related to development, metabolism, and stress response and most of them were related to bud set phenology (Hornoy *et al*. 2015). By analysing the provenance trials of European beech (*Fagus sylvatica*) established in the year 1995 over a wide geographic and climatic range in Europe, Kramer et al (2017) concluded that adaptive differences exist between provenances in the critical chilling and forcing requirements triggering budburst and they show plastic response to local environmental conditions. In a recent report, several genomic regions that strongly influenced cold hardiness in Douglas-fir was documented (Vangestel *et al*. 2018). Similarly, numerous structural, functional and regulatory genes were identified by analysing the transcriptome, small RNA, and degradome for drought-responsiveness in *Paulownia* which is expected to provide new direction for drought tolerance breeding (Zhao *et al*. 2018).

Genetic modification for adaptive traits

In the last three decades, genetic transformation has become an indispensible tool in gene discovery programs. In trees, transgenics is considered as an efficient alternate for introgression of essential traits, since conventional breeding is slow due to long generation time; high background polymorphism and outcrossing nature of most trees (Busov *et al*. 2005).

Robust transformation systems are reported in trees from Populus (Busov *et al*. 2005; Han et al. 2013; Maheshwari and Kovalchuk, 2016); Eucalyptus (Matsunaga *et al*. 2012; Prakash and Gurumurthi, 2009; de Alcantara *et al.* 2011) and conifers (Tang and Newton, 2003; Malabadi and Nataraja, 2007; Pijut et al. 2007). The study is limited to few genera and traits like wood formation, biomass enhancement and tolerance to pest and disease. Studies on adaptive trait introgression are few due to limited genomic knowledge, inefficient regeneration/transformation systems in species relevant to tropical ecosystems and regulatory issues in conducting field trials.

In *E. camaldulensis*, *CodA* from *Arthrobacter globiformis* was ectopically expressed and the transgenic lines showed tolerance to high salinity and temperature (Yamada-Watanabe *et al*. 2003). Similarly, uptake of inorganic phosphate in acidic soil was achieved through heterologous expression of mitochondrial citrate synthetase gene into *E. grandis* × *E. urophylla* (Kawasu *et al*. 2003). In subsequent studies, drought enhanced drought tolerance was demonstrated in transgenics expressing the transcription factor *DREB1*(Kondo *et al*. 2003; Ishige *et al*. 2004) while freezing tolerance was imparted by ectopic expression of *EguCBF1a/b* in Eucalyptus hybrids (Navarro *et al*. 2010).

In Populus simonii × Populus nigra, over-expression of ERF76 enhanced salinity tolerance in transgenic line (Yao *et al*. 2016). In recent reports, expression of Arabidopsis stress tolerant genes AtSRK2C and AtGolS2 enhanced abiotic stress tolerance in transgenic P. tremula × tremuloides (Yu et al. 2017), while expression of PtDRS1 enhanced both drought and salinity in transgenic hybrid poplar (Mohammadi *et al*. 2018). Poplar transgenics expressing the ABA signaling receptors, PtPYRL1 and PtPYRL5 significantly enhanced tolerance to drought, osmotic and cold stresses (Yu *et al*. 2017). Further, expression of effector genes in hybrid poplar revealed tolerance to multiple-stresses including drought, salinity, water logging and insect tolerance (Su *et al*. 2011).

Tree improvement strategies to combat climate change

The following are the major tree improvement strategies to combat climate change

- **Identification of promising tree species:** Economically important tree species are grown widely by farmers and other planting agencies to meet the raw material demand of industries. A number of native tree species are being planted by forest department in government estates. Similarly, various tree species are being identified for planting in urban areas for the purpose of shade and better climatic conditions. No specific emphasis is given for climate change and need to have a resilient tree species. Available native trees need to be relooked and identified for various end uses and can be grown with altered climatic conditions.

- **Delineation of common habitats and their characteristics with reference to climatic conditions:** These are unique agroclimatic conditions presently available, wherein specific cropping pattern is present according to the climatic conditions and suitability of the tree species in those areas. A detailed study would help to identify the extent of climatic variation that the species withstand, the possibilities to continue with the existing tree species in these agroclimatic conditions and the vulnerability of the existing tree species in the changed climatic scenario.

- **Selection of plus trees that are resilient to climate change:** Characters that are related to economic importance is given priority while selecting the trees. The economic importance of the characters varies depending on the species and the selection criteria are fixed depending on the end use. Even within a species, the selection criteria changes while selecting for timber and fruits. However, pest and disease are considered for every end use. Similarly, relevant parameters for climate change resilience need to be considered while selecting plus trees.

- **Collection of germplasm of resilient tree species with wide range of variability:** A wide germplasm is essential for every tree breeding program, although only a part of the germplasm is largely exploited for commercial cultivation. The climate change scenario is not explicit and the test conducted in expected change in scenario is also not complete. Hence, a wide germplasm is required for actual testing of the germplasm during the changed climatic conditions.

- **Study the physiological and biochemical adaptations of selected tree species:** Studies have been carried out on the physiological and biochemical mechanisms of the tree species with reference to various environmental conditions. Detailed studies would help us to identify the possible physiological and biochemical characters that are to be considered while selection trees for the changed climatic conditions.

- **Study the genotype and environmental interactions:** Genotype Vs environmental interaction studies have been conducted in many species. However, these studies have been conducted under the prevalent environmental conditions. Studies are meagre in the expected changed climatic conditions. GxE interaction studies in the expected altered climatic conditions would be a key area for finding the climate resilient tree species.

- **Testing of selected plus trees under extreme climatic conditions:** Most stable genotypes would be the better climate resilient trees to combat with the climate change situations. Conducting the GxE studies in the extreme climatic conditions of the present day would help us to find the extremely stable genotypes for future.

Conclusion

Forests of the future will require more resilient trees than those of the past and trees that are more resistant to temperature extremes. Impacts like drought, diseases and insects need to be studied and data generated to keep the land healthy and productive. Combination of various approaches of breeding and biotechnology would pave way for production of climate resilient tree crops. Change in genetic composition of forest stands, increased diversity by altering species consortium are inevitable in developing forest trees adapted to changing climates and environments. Most of the climate change related information generated is from temperate tree species, while tropical trees need special attention in this context.

Summary

Changing climate and increases in biotic and abiotic pressures will economically and ecologically affect forests and plantations. Climate change manifestations include spatial and temporal changes in temperature, rainfall pattern, wind speed, humidity and related elements. These parameters directly or indirectly contribute to adaptive genetic variation in survival, shoot phenology, growth rate, drought and frost hardness, morphology and physiology. Information on effects of climate change on temperate and boreal trees and adaptation to climate are well documented, whereas, in tropical trees such information is very limited. Tree improvement and biotechnological strategies recommended include the following: (i) Conservation and maintenance of genetic diversity, where the genetic variations for adaptive traits will be recorded to

understand the genetic basis of adaptation. Conventional breeding requires identification of genetic variability to various stress tolerance within a species or among sexually compatible species and introducing these unique features into identified genotypes (ii) Assisted migration and assisted gene flow, where seed zones and tree breeding regions will be delineated to translocate the propagules of pre-adapted populations. Genetic variations across latitudes and altitudes need to be assessed to guide the assisted gene flow. Composite seed sources from multiple provenances are recommended to increase diversity and buffer against future climate uncertainty. Genomic explorations are carried out to reveal local adaptation at gene level, which facilitates movement of germplasm across geographical gradients. (iii) Marker assisted selection for adaptive traits such as biotic and abiotic stress tolerance and growth through phenotype-environment associations and phenotype-genotype-environment associations. Complementing the traditional approach of trait improvement, Quantitative Trait Loci (QTL) analysis is an important component of tree improvement strategy, where correlation between DNA markers and adaptive traits will allow breeders and geneticists to hasten the development of stress tolerant genotypes. (iv) Genetic modification for adaptive traits to enhance the tolerance level of pests and diseases, salt and drought by introducing stress-inducible genes into the genome of target species.

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TREE IMPROVEMENT AND BIOTECHNOLOGICAL STRATEGIES FOR CLIMATE RESILIENCE: THE CASE OF NATURAL RUBBER

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Indian rubber industry is a key driver of different sectors of the national economy. With a value of output of about Rs. 75,000 Cr in a year, Indian rubber industry constituted close to 3.3% of the manufacturing GDP and 0.64% of the total national GPD during 2014-15. Sixty five per cent of the total rubber consumed by the industry in India comes from Natural Rubber (NR) and the rest are Synthetic Rubbers (SRs) produced from petroleum stock.

Per capita rubber consumption in India is one of the smallest among similar economies of the world. India is poised to double its NR consumption by 2030 or even sooner, if the current GDP growth rate is to sustain. To meet its rising demand, NR cultivation, which was traditionally confined to Kanyakumari district of Tamil Nadu and Kerala has now expanded along the foothills of the Western Ghats on the Malabar coast up to Thane district of Maharashtra. This plantation crop is also grown in the Sub-Himalayan regions of North Eastern India as well as in pockets along the Eastern Ghats in Andhra Pradesh, Odisha and Jharkhand etc. *Hevea*, although a native of the Amazon forests, is normally not treated as a candidate species for afforestation programs in India, even as several State Forest Departments (such as Kerala, Tamil Nadu, Karnataka, Assam, Tripura etc.) have taken up massive rubber cultivation programs for social (e.g. settlement of displaced PIO) or environmental (e.g. soil conservation) causes, often after clear felling large swathes of virgin forests.

Sustained economic growth of India demands more rubber, both NR or SRs. Rubber plays crucial roles in several critical sectors of the economy such as automobile, transport, health, hygiene, defense, aerospace, engineering, construction, electronics, communication etc. NR is increasingly getting deficient in India, prompting the industry to increase its dependence on SRs. Unlike NR, SRs have a large carbon foot print and hence their increased use does not auger well with India's nationally determined commitment (NDC) for reduction of greenhouse gases at the Paris Agreement. As per our NDC, the country is to reduce the emissions intensity of its GDP around 33-35%

by 2030 from the 2005 level, which will be adversely affected if the country increases its share of SR consumption. It may be pointed out that the CO_2 sequestration capacity of NR plantations is one of the highest (15-20 tonnes/ha/yr) which is higher than most mature virgin forests and forest plantations. India has more than 8 lakhs ha of NR plantations which stock well above 1.3 billion tonnes of CO_2 in the biomass in addition to large amounts of carbon sequestered in the soils as a result of NR cultivation. As per the NDC, India should create an additional carbon sink of 2.5-3 billion tonnes of CO_2 equivalent through additional forest and tree cover by 2030 and expansion of NR cultivation can significantly contribute towards achieving this target.

All NR growing regions of India have witnessed marked changes in the local climate in recent years. The most striking expression of climate change has been a steady rise in temperature, particularly mean daily maximum temperature (Tmax) and to a lesser extent minimum temperature (Tmin). Number of hot days/year and the highest temperature experienced on the hot days consistently increased over the years. Changes in rainfall varied among the regions. In most cases, the total amount of rainfall received per year did not show much variation. However, the rainfall distribution pattern was markedly changed. Prolonged and unseasonal rains had a bearing on fungal diseases in rubber.

Results of empirical studies using historical data and ecological niche modeling indicated that rising temperatures had different impacts on rubber yield in different agro-climatic regions, where rubber is cultivated in India. For example, in the Western Ghats States where temperatures are higher than the North Eastern region, for a unit concomitant rise in Tmax and Tmin, rubber yield is decreased by 10-12%, but there was hardly any impact in the North Eastern regions. Modeling studies showed that rise in temperatures will become more stressful for rubber cultivation in the Western Ghats States than in the North Eastern states in the coming decades. Our studies also show that in the coming years, more area will become agro-climatically better suitable for rubber cultivation in the North Eastern region, which the Forest Departments in the region may want to take cognizance of.

Developing climate resilient rubber clones through classical breeding, marker-assisted selection and genetic transformation is a priority area of research at the Rubber Research Institute of India. Rising temperatures and soil moisture deficit are the most common and challenging aspect of climate change in many parts of India. Therefore, developing climate resilience in rubber requires developing tolerance to drought stress which normally occurs concomitant with high temperature and high light stresses. Intrinsic drought/high temperature/high light stress tolerance traits have been identified in several cultivated Asiatic (Wickham clones) and wild germplasm accessions collected from Amazonian forests. Genetic variability existing in cultivated Asiatic clones and wild Amazonian germplasm lines of *Hevea* has been successfully exploited through classical breeding. In terms of survival (establishment) and growth (biomass production) there exists large genetic variability in germplasm accessions as well as progenies of selected bi-parental mating between Wickham and germplasm accessions. A large number of physiological and molecular markers associated with high drought/ high temperature/high light stress tolerance have been identified. The biggest challenge is to combine the intrinsic drought tolerance traits found in the parent lines with high latex rubber in the offspring. *Hevea* is a highly cross bred heterozygous species and therefore, offspring from any bi-parental mating combination will present a highly segregating population. However, using a combination of physiological and molecular markers that show a close association with high rubber yield and tolerance traits, large populations can be screened to identify and select promising individuals which can then be multiplied vegetatively for production of planting materials. Bud grafting is the most common plant propagation technique in this crop. Therefore, once a single plus plant with the desired traits is identified, the same can be multiplied for large scale field planting without losing its genetic purity. This is a huge relief for the *Hevea* breeder and possibly most tree breeders working in forestry who indulge in a patently hard endeavor that promises poor rate of success.

Biotechnology research started in the Rubber Research Institute of India in the 1990s led to successful production of Genetically Modified (GM) rubber plants in 2000. This was the first ever GM rubber plant developed anywhere in the world and the GM tree species developed in India. Genomic studies started in recent years led to identification of large number of genomic markers associated with drought/high temperature/high light stresses.

Apart from classical breeding and biotechnological approaches, there are agronomic management practices for achieving climate resilience. Retaining soil moisture and organic matter content, particularly during summer period is central to this approach. This can be achieved through intercropping with annual and perennial species both in mature and immature rubber plantations. Our studies also show that retaining native natural flora in mature rubber holdings improves the above properties of soil even as growth and yield of rubber are not adversely affected.

Desired stomatal behavior for achieving high water use efficiency in response to changes in ambient light conditions is a crucial factor determining the survival potential of a species during water deficit stress. Our studies at the single leaf (IRGA technique), whole tree (sap flow technique) and at the whole landscape level (eddy covariance method) clearly indicate that transpiration is not in sync with changes in light intensity as photosynthesis is. This has particular relevance for water use efficiency in plantation crops like rubber and forest canopies where most of the leaves are exposed to shaded conditions and therefore photosynthetic rates are extremely low, but transpiration rates may not be particularly low.

GENETIC IMPROVEMENT AND GENOMIC APPROACHES TO BREED CLIMATE RESILIENT TREES

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Introduction

Shifts and changes in temperature and precipitation patterns associated with global climate change are likely to influence large areas of natural forests and forest plantations. Climate change can potentially influence the frequency, duration, and severity of drought, flooding, pest, and heat-wave events in forest ecosystems. Combined with abiotic threats, emergence of new biotic agents is also a major concern for Foresters. In temperate forest ecosystems, warmer winters can encourage pests, both native and exotic, to expand rapidly and affect areas more quickly and extensively, while more extreme weather patterns and episodic forest events are likely to increase the intensity of wildfires in the tropics. Thus a variety of threats, most importantly insect and disease infestation, will increase the risk that forest trees could experience either population-level extirpation or species-level extinction.

Other milder consequences of climate change on forests may include reduced growth or promoting a shift in some native and cultivated ranges of species. Species distribution models predict a wholesale redistribution of trees in the next century due to climate change. Although tree species can naturally migrate, they do so slowly, averaging less than one-half of a kilometer per year (for subtropical and temperate conifers). Some climate models predict that trees would need to migrate at 10 times this rate to keep up with suitable habitats. Hence the tree populations would be maladaptive in a rapidly changing climate and it is necessary to correct these through targeted planting. Typically in temperate forest ecosystems, on an average about half million saplings are planted every year, and it is essential to control their genetic composition to be adaptive to the rapidly changing climate. Therefore, alternative sources of seed for immediate deployment so as to address climate change are needed.

Planting stress-adapted trees can improve the health of all forest types, including commercial plantations and non-commercial natural forestlands. Adaptation strategy could be to select and breed commercial species for optimum biomass production for the expected future climate. Developing such next-generation trees that can withstand climatic and pest threats needs an integrated approach considering above issues.

This article discuss about evidence for climate-change-driven increased tree mortality across globe, highlights a frame work that can possibly be adopted to prioritize the species / traits for tree breeding; reviews common garden experiments that show some leads on the strategy to improve tree species as well as touch upon genomic approaches for tree breeding to cope with climate change effects.

Is there evidence to suggest climate induced forest tree mortality is on the rise?

By reviewing over 150 global references, Allen *et al*. (2010) documented 88 examples of forest mortality that were driven by the climatic water / heat stress. The examples range from modest, but significant local increases in background tree mortality rates to climate-driven episodes of regional-scale forest die-off. Examples from each of the wooded continents that collectively span diverse forest types and climatic zones were given. Although examples from North America, Europe, and Australia were comprehensive, mainland Asia and Russia were under-represented in this review. Further, events of tree mortality have increased with a jump in 1998 and particularly during 2003-2004.

Climate-induced tree mortality and forest die-off is relatively well documented for North America (Allen *et al*. 2010). Drought and warmth across western North America in the last decade have led to extensive insect outbreaks and mortality in many forest types throughout the region, affecting >20 million ha and many tree species since 1997 from Alaska to Mexico. Examples of forest die-off range from >1 million ha of multiple spruce species in Alaska and >10 million ha of *Pinus contorta* in British Columbia to drought-induced *Populus tremuloides* mortality across a million hectares in Saskatchewan and Alberta. In the southwestern U.S., die-off of *Pinus edulis* on over a million hectares was specifically linked to ‘‘global-change-type drought’’. In the eastern portion of the continent, declines and increased mortality among oaks, particularly in the red oak family, have been reported from Missouri to South Carolina in relation to multi-year and seasonal droughts in the 1980s–2000s (Allen *et al*. 2010).

There are many more examples that have gone unnoticed because of poor documentation and reporting. It is very essential that such an attempt be done in the Indian context by reviewing a large number of gray literature.

Vulnerability assessment of tree species to climate change

Priority setting frameworks are becoming increasingly important when climate changes are rapid although capacity / resources / time to conserve are less. Species vulnerability assessments allow managers to allocate limited resources to the management of those species that are most threatened. By considering trait data of 339 native tree species and predictions of expected climate change pressure, Potter *et al*. (2017) have prioritized and tree species for conservation, monitoring, management and restoration across United States and Alaska. About 43 tree species were identified to be most sensitive and had high exposure to potential climate change effects.

Understanding the adaptive genetic potential of forest tree populations is crucial for evaluating their risk to climate change. Intensive efforts have been implemented to assess the diversity of ecologically important traits and their underlying genes by combining genomic and more traditional approaches. The traits that have received the most attention are apical bud phenology, drought resistance and resistance to pests. The integration of functional traits into vulnerability assessments is a promising approach to quantitatively capture differences in species sensitivity and adaptive capacity to climate change, allowing the refinement of tree species distribution models.

Aubin *et al*. (2016) have identified such functional traits that help in drought resistance, coping with fire and in migration to be focused while breeding. Traits that help in drought resistance include: (i). Rooting depth (ii). Stomatal sensitivity (iii). Leaf mass (iv). Xylum conductance (v). Xylum recovery capacity. Traits that help in cope with fire regime include: (i). Bark thickness (ii). Leaf an bark flammability (iii). Seed dispersal ability and (iv). Resprouting ability. Traits that help in dispersal to newer areas following a climate change include (i). Ecological amplitude (ii). Age at sexual maturity (iii). Seed and pollen dispersal abilities (iv). Bud burst timing.

Assessing the extent of genetic variations for and developing simpler protocol to measure the above functional traits in tropical trees of India is one of the major tangential goal of a modern tree improvement programme.

Common garden experiments to arrive at tree selection strategy for climate adaptation

Common garden experiment is essentially a plantation in which tree populations corresponding to different geographical origins (provenances) are compared using statistical designs. Such experiments yield good information on the level of genetic variation at a phenotypic level and on genetic differentiation among natural populations. In a comprehensive regional case study, Gray *et al*. (2016) have tested over 1800 families and provenances of lodgepole pine (*Pinus contorta* Dougl.) across six breeding regions of Canada, to assess genotype x environment interactions, and show how this information allows the development of a regional climate change adaptation strategy. The results indicated that local populations perform well, but that some transfer opportunities do exist. With the exception of the highest elevation populations, the general assumption guiding seed transfer policy, ‘‘local seed is best for reforestation” appears largely valid for most of the lodgepole pine breeding programs in Alberta. Hence the seed transfers suggested were minimum in geographic range. They also found that some breeding regions could be amalgamated based on the observation of high positive correlation of population performance and very low genotype by environment interactions. They also showed that a large portion of the genetic variation resides within breeding populations, and therefore an alternate adaptation strategy could be the selection of families within breeding regions to enhance resilience to climate change.

MacLachlan *et al*. (2017) argue that as climates shift, breeding zones are no longer optimal seed deployment zones because base populations are becoming dissociated from their historical climatic optima. In response, Climate-Based Seed Transfer (CBST) policies incorporating Assisted Gene Flow (AGF) are being adopted to pre-emptively match reforestation seedlots with future climates, but their implementation requires accurate knowledge of genetic variation in climatically adaptive traits. They compared 105 natural stands and 20 selectively bred lodgepole pine seedlots from Alberta and British Columbia grown in a common garden of 2200 seedlings. The effects of selection on phenotypic variation and climatic associations among breeding zones were assessed for growth, phenology and cold hardiness. They found substantial differences between natural and selected seedlings in growth traits, but timing of growth initiation was unaffected, growth cessation was delayed slightly (average 4 days, range 0.7 days to 10 days), and cold injury was slightly greater (average 2.5%, range 7% to 11%) in selected seedlings. Clearly, selection, breeding and progeny testing combined produced taller lodgepole pine seedlings that are not adaptively compromised relative to their natural seedling counterparts. Selective breeding produces genotypes that achieve increased height growth and maintain climate adaptation, rather than reconstituting genotypes similar to populations adapted to warmer climates.

The above two cited case studies point to different strategies to select trees for climate resilience. The first one emphasizes on the naturally selected local seeds for adaptations with little or no seed transfers; while the latter points to the requirement of fresh selections based on the progeny tests and climate-based seed transfer. However, in India with a lack of strict restrictions on seed transfers, it may too difficult to achieve climate-based seed transfer. Even for economically most important species such as teak, the seed transfers are unregulated and undocumented in India, since the last two centuries, resulting in admixtures of natural populations and plantations raised from seeds of unknown origin. It is now time to achieve some level of discipline in seed transfers and a have seed transfer policy in place for the country.

The role of hybridization in forest management and conservation under climate change

Hybridization is broadly defined as the successful mating between individuals from two populations, or groups of populations, that are differentiated on the basis of one or more heritable traits. A hybrid zone refers to an area in which genetically distinct parental individuals form hybrids of mixed ancestry, often resulting in genetic clines from one parental genotype to the other across a variety of spatial contexts. Zones of mixed ancestry are important sources of novel recombinant genotypes, in which hybrids are considered the raw material of evolution and a source of functional novelty. Thus, hybrid zones are important sources of genetic variation for examining the mechanisms that underlie evolution in natural environments.

Hybrid zones are valuable sources of genetic variation across a shifting landscape. With the increasing availability of genomic tools, high-throughput phenotyping, and association with a wealth of climatic data, forest hybrid zones are primed to address fundamental questions in speciation, conservation, and community ecology under changing environments. The mechanisms influencing species divergence, particularly the relative contribution of environmental and non-environmental barriers to reproduction remains an area that has not garnered much attention in forest trees. However, integrating genomic tools, provenance tests, and experimental crosses holds great promise for teasing apart the mechanisms contributing to species barriers, their frequency and the extent of the incompatibilities (Jasmine and Hamilton, 2017).

New directions for tree breeding and genomics

Tree breeders today live in a rapidly changing world faced with climate change and need to create completely new forest (unknown?) products to cope with the climate change. White *et al*. (2014) have proposed three philosophical ideas for ‘‘Breeding for Value in a Changing World’’ *viz*.:

1) Adopt a robust philosophy that aims to ensure maximum value produced per ha even in a future world that will be quite different.

2) Embrace technology at every phase in the tree improvement process.

3) Encourage interdisciplinary teams of scientists to solve complex problems that require expertise ranging from molecular to landscape scales.

Putting resources towards restarting or increasing the capacities of tree breeding programs can accelerate development of stress-adapted tree species and enhance deployment decisions by:

i) Increasing capacity to predict adaptability of improved selections in various environments, *i.e.*, genetic x environment interaction.

ii) Promoting understanding of tree species and forest physiology to enhance tree resilience.

iii) Advancing novel ways to perform early screening and field testing for pest-resistance traits, an important challenge in non-commercial and commercial tree species.

iv) Providing institutional support for maintenance and archiving of longterm studies essential for understanding forest interactions with climate and pests.

Common garden experiments can be informative in breeding for climate change, but their power is dependent on the number of different test environments, the duration of the tests and the genetic diversity of experimental populations. In addition, it is logistically challenging, costly and time consuming to extract the full value of information from these resources. These limitations impose a practical constraint on how much information can realistically be obtained through common gardens in the time frame needed by resource managers.

An alternative to the common garden approach is to estimate adaptive genetic potential on the basis of information from DNA sequences and other genetic marker information from population samples. This approach involves estimating population genetic parameters, such as measures of nucleotide diversity and divergence, and performing tests for departure from neutrality. Genomics is a foundational science for developing stress-adapted trees. It provides information and tools for accelerating tree breeding, discovering genes useful for genetic enhancement and improving deployment and conservation decisions.

Molecular population genetics and landscape genomics approaches are just beginning to be applied to forest tree populations, and the practical application of this work will be the development of diagnostic tools, database and Geographical Information System (GIS)-based tools to facilitate the management, conservation and restoration of forest tree populations. Neale and Kramer (2011) have highlighted the following five priority research areas for genomics research in forest trees *viz.,* (i) Acquiring reference genome sequences for many genera of tree species which is a necessary step for cataloguing the largely unknown diversity of tropical tree species. (ii) Greater attention to be payed to the ecological functions of trees in terrestrial ecosystems since the trees are major drivers of terrestrial biodiversity. (iii) Next generation sequencing technologies should be used for assessing adaptive differentiation and species divergence in natural populations. Genome-scanning approaches will allow the identification and localization of the genomic regions that are responsible for the maintenance of phenotypic species differentiation. (iv) There must be a greater investment in genome database resources, particularly construction of geo-referenced databases of genomic diversity data that will in the long term allow the inference of the main ecological drivers of genomic and phenotypic diversity in natural ecosystems. (v) Development of improved phenotyping technologies, though forest trees are difficult to phenotype. Geneticists will need to work more closely with physiologists, ecologists and engineers to develop informative, precise and standardized high-throughput phenotyping technologies.

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TRANSGENIC APPROACHES FOR ENGINEERING CLIMATE ADAPTATION IN TREES: INITIATIVES AT THE INSTITUTE OF FOREST GENETICS AND TREE BREEDING, COIMBATORE

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Introduction

Following industrial revolution, developmental activities for meeting the needs of a growing population has resulted in increased greenhouse gas emissions and consequent global warming. The global mean temperature in 2017 was reported to be 1.1 °C ± 0.1 °C above pre-industrial levels (WMO, 2017). Global warming has resulted in rising sea levels estimated at an average yearly rate of ~3 ± 0.4 mm, since 1993, (Nerem *et al*. 2018). A projected sea levels rise by 0.2 meters to 2.0 meters is expected by 2100 (Melillo *et al*. 2017). Rising sea levels and droughts together with increased groundwater extraction cause sea water ingression and increased groundwater salinity. Around 1 % of agricultural lands are estimated to deteriorate every year due to salinity (Mahajan *et al.* 2008). More than 800 Mha of land are affected by salinity worldwide (FAO, 2008). In India, around 9 Mha of lands are already affected by salts (Mandal *et al.* 2010), and these could potentially be reclaimed and productively used by planting commercially important salt tolerant trees. Changes in climatic variables also affect life cycles of flora and fauna thereby altering the delicate ecological equilibrium and increasing the potential of pest outbreak especially in the context of planting of few clones selected for improved biomass productivity.

Transgenic tools like RNA interference (RNAi) and more recently, CRISPR/Cas9 based RNA directed editing of genomic sequences have emerged as simple yet powerful tools for plant science researchers for functional validation of genes and genetic modification of desired traits (Wang *et al*. 2001; Waterhouse *et al*. 2001; Waterhouse and Helliwell, 2003; Lowder *et al.* 2015; Ran *et al.* 2015). While existing genetic variability could be harnessed for planting in lands affected by salinity or pests, not always options are available in a long generation tree species for combining high productivity and tolerance to biotic/ abiotic stresses. It is in this context that gene silencing and genome editing tools offer potential for creating novel genetic variants that tolerate these stresses thereby contributing to adaptation strategies that aid in utilization and increased productivity of wastelands.

Genes controlling abiotic stress tolerance in plants: Development of IGBAAS - *In silico* gene bank for adaptation to abiotic stresses

Abiotic stresses like drought, salinity, flooding and freezing are the most important factors affecting plant productivity and then primarily affect rural livelihood. Tolerance to abiotic stresses is determined by a number of genes making its understanding and manipulation a challenge. Voluminous gene sequence information from model plant species and a wide variety of other plant species are already available. Sequence information pertaining to abiotic stress tolerance from these different organisms were thematically integrated with direct connectivity to bioinformatic tools (like ClustalW, BLAST, Primer BLAST, SiRNA design) and reference resources (like PubMed and Wikigene search). The PHP-MySQL based online database comprises 2500 nucleotide and protein sequences of genes available in NCBI database and is hosted in the web server of the Indian Council of Forestry Research and Education (ICFRE) which can be accessed at http://igbaas-ifgtb.icfre.gov.in/. Provision exists for uploading new sequence information making the database dynamic and interactive. The IGBAAS database thus provides a ready reference of gene sequences implicated in stress tolerance, their conserved motifs and consensus primer sequences, for use in isolation of gene homologues from other species and development of gene based markers for salt tolerance (Vivekanandan *et al.* 2010, Nambiar-Veetil *et al.* 2014;).

Bioprospecting of sodium transporter genes from salt tolerant trees

Soil salinity is one of the most important environmental factors that cause a negative impact on the productivity of agricultural crops. In saline and sodic soils, the harmful effects of salinity on most species are principally due to a combination of osmotic stress and ionic stress exerted by the sodium ions. Sodium transporter genes play a role in the uptake of salt from the soils, transport of salt within the plant and compartmentalization into vacuoles, thereby controlling the ionic and osmotic balance in the roots and shoots. Perennial tree species like *Prosopis juliflora, Millettia pinnata, Acacia nilotica, Casuarina equisetifolia* and *Eucalyptus camaldulensis* are known to tolerate high levels of salinity and may harbour novel variants of genes conferring salt tolerance that could be used for development of climate resilient crops. Using degenerate primers, PCR amplicons were generated, sequenced and analysed using NCBI BLAST for sequence similarity. The partial sequence of the gene homologues of sodium-hydrogen antiporter genes (*NHX*) from *Casuarina equisetifolia* (330 bp), *Eucalyptus camaldulensis* (494 bp), *E. tereticornis* (614 bp), *Pongamia pinnata* (385 bp), *Acacia nilotica* (348 bp), *Prosopis juliflora* (371 bp), *Kandelia candel* (725 bp), *Bruguiera gymnorhiza*, (355 bp), *B. cylindrica* (445 bp), *B.*

sexangula (351 bp), *HKT1* gene from *E.tereticornis* (638 bp), *P. juliflora* (220 bp), *AKT1* genes from *C. equisetifolia* (236 bp), *E. camaldulensis* (280 bp), *P. juliflora* (300 bp), *B. sexangula* (325 bp), *B. cylindrica* (230 bp), *K. candel* (310 bp), and *A. nilotica* (361 bp), and the Actin genes from *B. cylindrica (293 bp), B. gymnorhiza (265 bp), B. sexangula* (255 bp), *K. candel* (234 bp), *A.nilotica* (201 bp), *P. pinnata* (213 bp), *E. camaldulensis* (311 bp) and *C. equisetifolia* (204 bp) were sequenced and published with accession Numbers at the GenBank Database of the National Centre for Biotechnology Information (NCBI), National Library of Medicine, National Institute of Health, USA.

Understanding adaptive mechanisms in Casuarina and Eucalyptus to high salinity

In saline, water logged soils, tree plantations help in lowering the height of water table in addition to reducing the salt content of soil (Tomar, 1997). Tree species like Eucalyptus and Casuarina are used for reclamation of salt affected lands, and therefore enhancing their tolerance to salt could increase the productivity of these wastelands thereby providing support for rural livelihood. A pre-requisite to genetically engineer a polygenic trait like salt tolerance is to have an understanding of the physiological bottlenecks, so that potent genes that could ameliorate them could be targeted.

Casuarina equisetifolia Forst., a member of the *Casuarinaceae* family, is widely planted in coastal areas due to its ability to function as potential barrier against wind and waves and grow in harsh environmental conditions. Significant variation has been reported in the ability of *C. equisetifolia* to grow under salinity stress (Balasubramanian, 2001; Warrier and Venkataramanan, 2003). In order to understand the adaptive mechanisms in *C. equisetifolia*, 82 clones of *C. equisetifolia* were assessed for their response to 50 mM incremental NaCl concentrations ranging from 50 mM to 550 mM in Hoagland's solution and clones contrasting for their salt tolerance were identified (Selvakesavan *et al*., 2016). Several earlier reports attribute salt sensitivity in Casuarina species to the toxic effect of sodium. Intraclonal variation in the levels of sodium accumulation was therefore analysed. However, sodium content in the shoots and roots showed little correlation (0.351 and -0.171) with salt tolerance in *C. equisetifolia*. Similarly, sodium to potassium ratio in the shoots and roots of NaCl treated and untreated clones also did not show correlation with mortality although certain tolerant clones exhibited selectivity of potassium over sodium under salt stress. Analysis of the shoot to root ratio of sodium however, showed better correlation (0.448) with salt tolerance, suggesting that restricted translocation of sodium to shoots and its relative retention in roots might play a crucial role in the salt tolerant clones of *C. equisetifolia*, and that shoot to root ratio of sodium could be a better parameter for salt tolerance in *C. equisetifolia* clones.The tolerant clone, TNIPT 4, which accumulated high concentrations of Na^+, had low shoot to root ratio of Na^+, and also a higher constitutive as well as NaCl induced accumulation of the compatible osmolyte, proline. The higher salt tolerance observed in certain clones despite higher sodium accumulation or shoot to root ratio of sodium suggested the presence of different multiple adaptive mechanisms that may be operating in different clones to help protect the cells from the toxic effects of sodium (Selvakesavan *et al*. 2016). In another study on 20 clones of *C. equisetifolia* subjected to increasing concentrations of NaCl from 0 to 350 mM, no consistent pattern in proline accumulation, or correlation between proline accumulation and intraclonal variation in salt tolerance were observed (Jayaraj, 2014). This lack of correlation was attributed to varying presence of adaptive mechanisms other than proline accumulation among the sub-species and provenances. These studies thus emphasized the need for characterising the genetic components involved in sodium transport, proline metabolism and other mechanisms contributing to salinity tolerance.

Eucalyptus is the most widely planted tree species in India, because of its ability to grow in wastelands and its utility in pulp and paper industries. Tolerance to abiotic stresses, fast growth, and improved wood properties are important traits attempted for breeding of *Eucalyptus* trees. *Eucalyptus tereticornis* and *E. camaldulensis* tolerates salinity levels up to 10 dS/ m (Ansari *et al.* 2007). Transgenic approaches for enhancing salt and drought tolerance in Eucalyptus have included the overexpression of choline oxidase (Yu *et al.* 2009; 2012; Kikuchi *et al.* 2009; Matsunaga *et al.* 2012), mangrin (Yamada-Watanabe *et al.* 2003; Lelmen *et al.* 2010; Yu *et al.* 2013) and DREB1A (Hibino, 2009).

In a trial of 31 trees under saline irrigation, *E. tereticornis* was shown to accumulate a high percent (3.37 %) of Na^+ when compared to the mean of 1.04 % in other tree species (Tomar *et al.* 2003). In another study by Balasubramanian (2016) using contrasting clones of Eucalyptus identified by Chakravarthi *et al*. (2009), it was shown that the salt susceptible clonal selection, *Eucalyptus tereticornis* ET- 88, accumulated 3.41 % of Na^+ in the leaves, while the salt tolerant *E. camaldulensis* clonal selection EC-7, accumulated only 0.49 % Na^+. We therefore, reasoned that targeting Na^+ uptake in Eucalyptus could be a potential strategy for enhancing salt tolerance in Eucalyptus.

Functional genetics approach for determining major genes implicated in salt tolerance: Composite transgenic strategy

As the major port of entry of Na^+ ions into the plants is via the roots, engineering Na^+ transporters in roots of Eucalyptus is expected to be a potent strategy for enhancing salt tolerance. Sodium transporters play diverse roles like limiting Na^+ uptake to shoots (*HKT1* and *SOS1*) and sequestering Na^+ into vacuoles (*NHX1*) thereby protecting plant cells and whole tissues from Na^+ toxicity. Genomic sequences available for model species enable isolation of homologues of Na^+ transporters from non-model species. Functional analysis of these homologues by overexpression or silencing is crucial for validating the role of these genes in Na^+ transport in the genomic context of non-model plants.

However, low transformation efficiencies in Eucalyptus ranging from 0.05 % to 7 % (Matsunaga *et al.* 2012) limit rapid gene function analysis. In order to study the feasibility of screening major gene conferring salt tolerance in roots of Eucalyptus a GFP based composite strategy having hairy roots was developed in Eucalyptus by our group (Balasubramanian *et al.* 2011). The high transformation efficiency (~ 60 %) and a less protracted procedure of 5 months required to generate hardened composite transgenic enables rapid analysis of the phenotypic effects of the transgene. During the last decade, RNA interference (RNAi) emerged as a powerful tool for functional characterisation of genes. Composite transgenics approaches in which GFP tagged transgenic roots are generated on non-transgenic shoots have been used in conjunction with RNAi for a more rapid functional analysis of genes involved in root growth and development in difficult to transform tree species like Casuarina and Eucalyptus (Gherbi *et al.* 2008; Svistoonoff *et al.* 2013; Plasencia *et al.* 2016). The composite transgenic strategy developed in Eucalyptus has been successfully used in functional validation of the lignin biosynthesis gene (Plasencia *et al.* 2016). Roots being a major portal of entry for sodium offers a good system for understanding genes involved in sodium transport.

HKT transporters are known to be an important component of salinity tolerance in several species, including *Arabidopsis*, rice and wheat. The *HKT* transporter functions both as a selective Na^+ uniport or Na^+-K^+ symporter and even Mg^{2+} / Ca^{2+} permeation depending on the low or high affinity towards Na^+ (Su *et al.* 2015). The *HKT1* family of genes shows wide functional diversity. Some members of the *HKT* family function as sodium transporter and contribute to Na^+ removal from the ascending xylem sap and recirculation from the leaves to the roots via the phloem vasculature (Platten *et al*. 2006). In wheat, silencing the sodium transporter gene *TaHKT2:1* resulted in improved Na^+ tolerance under saline conditions (Laurie *et al.* 2002). However, in Arabidopsis, loss of function mutants in the *AtHKT1;1* gene rendered the plants Na^+ hypersensitive (Maser *et al.* 2002; Berthomieu *et al.* 2003). In planta functional studies of *EcHKT1:1* was therefore taken up by our group using the composite transgenic strategy to understand the function of *EcHKT1* (Balasubramanian, 2016; Nambiar-Veetil, 2016). Using the composite transgenic approach, we have identified *EcHKT1* as a potential target for engineering salt tolerance in Eucalyptus. We are currently generating trangenics using *Agrobacterium* mediated transformation. Stable and efficient transformation protocols are available in Eucalyptus (Prakash and Gurumurthi, 2009, 2010; Nambiar-Veetil *et al.* 2010). To overcome biosafety issues, transgraft strategies are envisaged.

Insect tolerance

The last decade saw the emergence of the invasive hymenopteran gall pest, *Leptocybe invasa* Fisher & La Salle, as a major pest of Eucalyptus plantations in India

(Jacob *et al*., 2007). Large scale plantations of a few superior clones of Eucalyptus and a conducive climate provided the right conditions for outbreak. Ruling high biomass but susceptible clones are thus not considered for plantations anymore. As the insect exclusively feeds within the gall tissue for a period of 4 months, transgene encoded dsRNA could be a potent approach to incorporate tolerance in such clones. Whole transcriptome sequence of *L. invasa* was generated using insect larvae isolated from gall tissues and analysed to remove possibile eucalyptus contamination in the generated transcriptome. Five insect specific genes of the ecdysone and chitin metabolism pathways were analysed to identify unique sequences by BLAST search. Sequences that did not yield siRNA in pssRNAit analysis were deleted, followed by BLAST search in FlyBase and NCBI databases to delete sequences that matched with hymenopterans, humans, and beneficial microbes associated with Eucalyptus. The sequences from five genes were then combined together in different permutations to design a single construct for targeting multiple genes. The combined sequences were re-analysed again and used to synthesize a chimeric multigene targeting hpRNAi construct that showed no sequence similarities to potential non- target organisms, like the insect pollinators, parasitoids, or other beneficial microbes. The construct is being used for development of transgenic Eucalyptus for incorporating tolerance to *L. invasa* (Nambiar-Veetil *et al.* 2017).

Conclusions

To meet the adaptation challenges of future climate change scenarios, and to productively make use of the existing swathes of wastelands, and to improve rural livelihood, there is an urgent need to breed trees that are able to adapt to these climatic stressors. Informed breeding, utilizing the knowledge of the interplay of genome on the phenotype and incorporating new molecular breeding tools like gene silencing and genome editing are therefore a prospective option available to researchers for developing climate resilient trees. The Institute of Forest Genetics and Tree Breeding, Coimbatore, has led initiatives and made considerable advances in understanding adaptive mechanisms in tree species with reference to salt stress, developed composite transgenics approaches and characterized sodium transporter genes, generated transcriptome sequence of *L. invasa* and using these leads developed transformation constructs for use in generating transgenic trees that can tolerate salt and insect pest attack.

Summary

Tree plantations are preferred for reclamation and productive utilization of lands affected by environmental stresses. Climate change is expected to exacerbate environmental conditions like drought and salinity, and increased pest outbreaks in plantations. The Institute of Forest Genetics and Tree Breeding, Coimbatore has

been undertaking research for engineering adaptation strategies to salt stress and insect pests in fast growing plantation tree crops like Eucalyptus and Casuarina. This paper charts the course of the advances made in these areas, including development of an interactive online database of genes conferring abiotic stress tolerance in plants, identifying gene sequences of sodium transporters from salt tolerant tree species, understanding adaptation mechanisms involving sodium transport and proline accumulation, developing composite transgenic protocol for functional analysis of genes and its use in characterising a sodium transporter gene in Eucalyptus, and developing RNAi constructs for incorporating tolerance to the Eucalyptus gall pest, *Leptocybe invasa*.

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HARNESSING FOREST GENETIC RESOURCES FOR CLIMATE RESILIENCE

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Introduction

Forest Genetic Resources (FGR) are the heritable materials maintained within and among tree and other woody plant species that are of actual or potential economic, environmental, scientific or societal value and benefit to humans in present or future. FGR are essential for the adaptation and evolutionary processes of forests and trees as well as for improving their productivity.

Trees and other woody species differ from other living organisms;they are generally long-lived,and over the years, develop natural mechanisms to maintain high levels of genetic variation within species. This is achieved through high rates of out-crossing and long-distance dispersal of pollen and seed. These mechanisms, combined with the variable native environments, have enabled the evolution of forest tree species into some of the most genetically diverse organisms.

Research, development, conservation and use of tree species, in particular tropical species, has been insufficient with inadequate taxonomic knowledge (Newton and Oldfield, 2008). Based on a literature review, it is conservatively estimated that more than 34000 tree species in more than 1000 genera are of socio-economic, environmental and scientific importance and used on a regular basis by people throughout the world. It includes trees, large woody shrubs attaining more than 2 to 3 m in height, fruit and nut-trees and their wild relatives. The total comprises both angiosperms (33,500 species in 976 genera and 131 families, including bamboos and palms) and gymnosperms (530 species in 67 genera and nine families).

FGRs and their role in nation building

Rural livelihood support: FGRs have the potential to liberate people from hunger and alleviate poverty. FGRs provides wood, medicine, food, fibre, timber etc. In addition, FGRs are the source material for the development of improved varieties. It also contributes to the most basic needs for sustainable development of the forest dependent communities. Forests can provide a crucial contribution to Millennium Development Goals, especially in achieving environmental sustainability, poverty alleviation and women empowerment. With new policies in place, planted forests and trees outside forests will also provide an increasing share of forest products.

Forests have traditionally been valued as a source of timber, pulp and fuel. All other products, have been classified as Non Timber Forest Products (NTFPs). NTFPs are obtained from about 3,000 species in the country and form an important source of livelihood for communities, particularly tribals and rural poor, living adjacent to forests. Rural populations depend on NTFPs for food and environmental services. It is estimated that 340 million poor rural people in India depend on NTFPs for their livelihood. In some areas, forests are the primary source of energy, oils, medicines and even staple foods. Edible wild fruits, bamboo seeds and wild legumes have played a very vital role in supplementing the diet of the rural communities. Tribal communities and ethnic tribes use wild edible plant species, including roots and tubers, leafy green vegetables, bulbs and flowers, fruits, seeds and nuts. These foods gain significance due to their seasonality, in the wake of periodic famines or shortages of crop-based foods. Rural populations also use, protect and create forests as sources of agricultural inputs; they depend on tree products to feed livestock and to maintain water flows.

In India, NTFPs contribute an income equivalent of US$ 2.7 billion per year and absorb 55% of the total employment in the forestry sector. NTFP sector with annual growth rate between 5-15% contributes to 75% of forest sector export income. They provide 50% of the household income for approximately one-third of India's rural population. The undisclosed indigenous knowledge on medicinal trees held by the tribal communities is one of the valuable resources integrated with biodiversity (FAO, 2012).

*A potential source of revenue:*Forests supply products for export in the form of wood, fibre, processed goods, medicinal and ornamental products.Timber has been a major source of investment for many tropical countries. In some countries, wood is processed into finished goods to enhance employment and increase income. For example, Thailand derives substantial foreign exchange from trade in furniture, orchids, specialty foods, medicines and wildlife. Forests also attract recreational users.

FGR generate in-kind forest incomes, which in many instances, goes unaccounted.It is essential to consider this contribution to the national economy, as hundreds of millions of people depend on the forest as their only source of cash income.

Forests store carbon; maintain diverse, unique and rare forms of life; store biotic potential and encompass a wonderful natural phenomena that have yet to be understood. These global attributes are gaining value rapidly as institutions evolve to protect them and develop means to translate them into tradable forms in the international market. Some examples of FGR in international trade in global environmental services include debt-for-nature swaps, long-term purchases of forest carbon storage for industrial atmospheric emissions, environmental conditions in trade agreements and international contracts for biological prospecting rights.

Social, cultural, medicinal and scientific value: FGR have major social, cultural and spiritual values, mainly at tree species level, with many individual tree species distinguished and named in local languages. In India 100000 - 150000 sacred groves have been preserved. These groves are natural temples, ancestral places and spiritual retreats that contribute to the strength of the community. Certain tree species have tremendous social and cultural importance, e.g. *Ficus religiosa* in religious ceremonies, *Santalum album* in burial ceremonies and *Azadirachtaindica* in traditional medicines. FGRs are of major scientific value also. Intraspecific diversity can be used, for example, to help understand the genetic, biochemical and physiological basis for resistance to pests and diseases or environmental stresses such as extreme climatic events (drought, flooding etc.) and edaphic extremes (salinity, acidity, etc.). It can also be used to identify biosynthetic pathways for production of important products and metabolites.

Status of FGRs in India

The forests of India are classified into 16 major forest types and these forests house a wide array of species diversity. In terms of plant diversity India ranks 10thin the world and 4thin Asia. It is reported that 48158 species of plants occur in India, representing 11% of world flora, of which flowering plants account for 18465 species. Of this 2863 are trees that include some of the highly valued timbers of the world about 145 species are under domestication and breeding efforts are in progress.

The initiation of tree improvement programmes has been the motivation for studying the intraspecific variation in many of the species. In these species, there is production and supply of Forest Reproductive Material (FRM) in the form of seeds, seedlings and clones. Various SFDs, research organizations and universities have established the FGR in the form of Seed Production Areas, Clonal Seed Orchards, Seedling Seed Orchards, Vegetative Multiplication Gardens, modern nurseries, provenance stands etc. for production of quality planting stock. Recently, attention towards improvement of fast growing native species and economically important indigenous species to support the TOF programme has become the priority.

A mechanism and monitoring body (Variety Release Committee) for release of clones/ varieties of forestry species has been evolved by the ICFRE. In species like Eucalypts, Casuarinas and Poplar, genetically improved elite clones have been released in the market. Simultaneously, DUS (Distinctness, Uniformity and Stability) descriptors have also been developed for species like Eucalyptus, Casuarina, Neem, Artocarpusheterophyllus, Poplars, Melia, Salix, Pungam etc. as per the guidelines of Protection of Plant Varieties and Farmers' Rights Act, 2001 (PPV & FRA) to mark specific identity to clones and ensure authority over the clones developed. Guidelines are being developed for teak, sandal, red sanders and other species of commercial importance.

The Government of India has plans to establish a National Bureau of Forest Genetic Resources (NBFGR) and as a precursor to that, a Forest Genetic Resources Management Network (FGRMN) has been established in 2011, under ICFRE with its nodal centres at IFGTB, Coimbatore and Forest Research Institute (FRI), Dehradun. The FGRMN has been established with the objectives to plan, prioritize, organize, conduct and co-ordinate exploration, collection and documentation of indigenous and exotic forest genetic resources to strengthen *in situ* and *ex-situ* conservation. It shall also undertake introduction, exchange and quarantine of genetic resources of forest origin. It shall characterize, evaluate and conserve forest genetic resources and ensure their sustainable management in collaboration with the user agencies. In this process a large number of studies would be undertaken to understand the intraspecific diversity of the economically important species and those of conservation importance. The FGRMN will also be required to develop and maintain a national information network on FGR, develop molecular tools, techniques and approaches to characterize and validate the germplasm and conduct research, teaching and generation of public awareness on FGRs.

In situ conservation: India has 104 National Parks, 544 Wildlife Sanctuaries, 77 Conservation Reserves and 46 Community Reserves. Besides these, there are 26 wetlands declared as Ramsar sites and 18 areas in different biogeographic zones declared as Biosphere Reserves. The extent of protected area (PA) network is around 1,62,099.47 sq. km over 4.93% of the land area. The National Wildlife Action Plan envisages increase of this to 10% of the land area. The conservation of biodiversity within the PA network takes care of the FGRs also. Other means of *in-situ* conservation like Sacred Groves (SG), Gene Pool Conservation Areas (GPCA), Medicinal Plant Conservation Areas (MPCA), Seed Production Area (SPA) and Permanent Preservation Plots (PPP) are maintained. To conserve wild germplasm, revitalize the indigenous health care and livelihood security a 'National Programme on Promoting Conservation of Medicinal Plants and Traditional Knowledge for enhancing Health and Livelihood Security' is under implementation.

Ex situ conservation: More than 150 species are conserved *ex-situ* with a focus on tree improvement, productivity and species conservation. India has more than 100 botanical gardens under the Indian Botanical Garden Network (IBGN). There are ongoing long-term breeding programmes for a large number of species, including provenance trials, progeny trials, clonal trials, and seed orchards. Though these trials and seed orchards are established primarily for genetically improved seed, they are also put under selective conservation, as one of the objectives in *ex-situ* conservation.

Germplasm banks and clone banks have also been established for economically important tree species. The germplasm in these banks are characterized for morphological characters for the purpose of identification and registration of clones and biochemical and physiological characters for the purpose of selection and breeding.

Defence Institute of High Altitude Research (DIHAR) under Defence Research and Development (DRDO) has created a National Perma Frost Based Germplasm Storage Facility at an altitude of 5360 m above mean sea level which will serve as a germplasm storage facility for current and future food security in the era of global warming and climate change, and the same can also be used for *ex situ*conservation of FGR for the country.

Organizations involved: The main organizations actively engaged in forest genetic resource conservation are the State Forest Departments, directly concerned with *ex-situ* and *in-situ* conservation of forest genetic resources. Around 25 per cent of forest area extending over 22 m ha is under Joint forest management (JFM) with the people of villages adjoining forests. The forestry research organizations, NGOs and wood based industries are mainly concerned with the *ex situ* conservation of forestry species of their interest. The ICFRE Institutes maintains a large number of seed production areas, seedling seed orchards, clonal seed orchards, clone banks and vegetative multiplication gardens, as part of FGR conservation and use. The Indian Council of Agriculture Research (ICAR) and its institutes concerned with agroforestry, the National Bureau of Plant Genetic Resources (NBPGR), New Delhi and the Agricultural Universities which conduct courses on forestry also maintain collections of forestry species as National Active Germplasm (NAG) sites and as orchards in their *ex situ* conservation and tree improvement programmes. The Botanical gardens under the Indian BotanicalGarden Network (IBGN) maintains forestry species in their collections all over India. There are also Non-governmental organizations, private research organizations and nurseries and wood-based industries maintaining collections of germplasm of forestry species.

FGRs prioritised by national and international bodies

The degree of endemism in plant species is high in India. About 11058 species are endemic to Indian region, of which 6 200 are flowering plants. As per IUCN Red List, India has 246 globally threatened plant species, which is about 3% of the world's threatened plants. About 1500 species of flowering plants and few hundreds of Pteridophytes, Bryophytes, Lichens and Fungi have been identified as threatened. After critical evaluation of their status and threat perceptions, data sheets on 1182 species have been prepared, out of which account of 708 species have already been published as Red Data Book of Indian Plants.

Based on the economic utility and conservation value, a large number of forest tree species have been prioritized for conservation and use, by the APFORGEN (Asia-Pacific Forest Genetic Resources Network), the State Forest Departments and in the 'Consultative Workshop on Strategies for Formulation of Forest Genetic Resources Management Network' held at the Institute of Forest Genetics and Tree Breeding (IFGTB), Coimbatore in 2011.

Apart from this, Indian Council of Forestry Research and Education (ICFRE) has identified important tree species for research under All India Co-ordinated Programme (AICP). While some of these species are extracted from the natural forests, many are raised in the planted forests and agroforestry systems.

Climate vulnerability and FGRs

The major cause of concern for FGR in the global context is the increasing levels of atmospheric CO_2 resulting from human activities such as burning of fossil fuels and forest destruction. Deforestation and forestdegradation, due to human activities,account for nearly 20 percent of greenhouse gasemissions. Elevated levels of CO_2 are predicted to contribute to more extreme climatic events (IPCC, 2013). Climate alterations and increased occurrence of extreme climatic events are considered a threat to FGR.Prolonged drought, high mortality due to extreme climatic events, in combination with regeneration failure, can result in local population extinction and the loss of FGR,particularly at the receding edge of a species'distribution.

Climate change could alter the frequency and intensity of forest disturbances such as insect outbreaks, invasive species, wild fires, and storms. A greater incidence of intense cyclones, extreme drought, fires, flooding and landslides has been observed in tropical forest ecosystems which have experienced increased temperatures and more frequent and extreme El Nino–Southern Oscillation (ENSO) events. Some climate changemodels predict substantial dieback in parts of the Amazon and other moist tropical forests (Bernier and Schoene, 2009).

Predictions regarding the impact of climatechange on FGR in natural forests, in planted forests and on farms vary. Hamrick (2004) in his report supports that trees have sufficient phenotypic plasticity and genetic diversity at the population level to withstand the negative effects of climate change. On the contrary, another group predicts severe impacts on FGR depending on the types of species and environments in which they exist. (Vendramin and Fady, 2009; Rehfeldt *et al.* 2001). Many countries urgently need to generate baseline information on the impacts of climate change on FGR and to promote and use of FGR to help with climate change adaptation and mitigation.

In India, there has been a simultaneous depletion of state forests and rapid growth of farm forests outwards from urban centres. Natural forest depletion has been driven by the growth of population relative to non-farm employment opportunities and the resulting quest for additional land. The most extreme depletion has occurred just outside protected forests, displaying a backwash effect against the protective boundaries. Forest growth and investment in tree crops occurring outwards from cities are driven by market incentives, including rising prices for wood products relative to agricultural crops, input prices and wage differentials. Forest growth also occurs within irrigated areas, where tree crops fit in with other production activities through complementary uses of the same inputs, household management systems and market networks. This shift in the aggregate forest cover towards settled areas is accompanied by significant changes in the species composition and social organization of forests. An added factor of climate change is likely to worsen the scenario.

An example of the vulnerability of Indian forests to climate change is given below:

- Himalayan mountain system is highly fragile and sensitive to climate change, the rate of warming is greater than the global average warming (IPCC, 2013; Pradhan and Shrestha, 2007; Xu *et al.* 2009)
- Studies indicate shifts in the Himalayan forests; western and central Himalaya more vulnerable to projected impacts of climate change (Chaturvedi *et al.* 2011; Gopalakrishnan *et al.* 2011; Joshi *et al.* 2012; Shrestha *et al.* 2012)
- Himalayan forests are also prone to serious ecological degradation (Ives and Messerli, 1989; Pandit *et al*. 2007)

However, an understanding of how adaptive the current Himalayan forests are, and how heterogeneity in regional vulnerabilities influence such changes to broad range of ecosystem functions and services, is lacking. This, in turn, enhances the vulnerability in the complex Himalayan landscape. Further, current management practices have decreased adaptive capacities of forests. The ever-increasing anthropogenic pressure and competition for forest-based resources leads to additional stress beyond the capacities to withstand continuity of change from nature. Under these circumstances, an amalgamation of new scientific approaches based on empirical evidence, along with traditional knowledge from communities, a holistic approach for forest resource utilization needs to be implemented. The anticipated future impacts of climate change, identified by the Government of India (GOI) in its Initial National Communication to the United Nations Framework Convention on Climate Change (UNFCCC) mention that over 50 per cent of India's forests are likely to experience a shift in forest types, adversely impacting associated biodiversity and regional climate dynamics, as well as livelihoods based on forest products (GOI, 2004).

Impacts of climate change on FGRs

Temperature and precipitation are the twomain climate drivers for forest ecosystems; any significant changes in either of these will have an impact on species composition and forest cover.Impacts can range from extreme disturbances such as forest fires or pest outbreaks to effects on physiological processes from more subtle changesin temperature.

It has been reported that many trees have sufficient phenotypic plasticity and genetic diversity at the population level to significantly reduce the negative effects of climate change. Climate change impacts are expected to be severe in dry and high temperature regions where trees are at their adaptive limit (Lindner *et al*. 2010).

Based on the data available to date, expected impacts of climate change on FGR will be experienced through demographic , physiological and genetic process, like high mortality due to extreme climatic events in combination with regeneration failure will result in local population extinction and the loss of FGR, pest and disease attack may be more severe, asynchronous flowering resulting low seed production,new species invasions, altered patterns of gene flow and the hybridization of species and populations (Loo *et al.* 2011). High mortality reduces the size of available gene pool, may increase inbreeding among survivors, resulting reduction in products and services to people.

In Asia, where key biodiversity hotspots are found, endemic species are predicted to decline, with changes in ecosystem structure and function (FAO, 2010). Changes in precipitation may have a greater influence than temperature for these species (Dawson *et al*. 2011). Changes in water availability are a major emerging threat to FGR; they will be a key factor for the survival and growth of tree species. The response to prolonged droughts will vary among tree species and within genotypes of the same species (Lucier *et al*. 2009). In arid and semi-arid lands, increased duration and severity of drought has increased tree mortality, resulted in degradation, and reduced distribution of forest ecosystems, including *Cedrus atlantica* forests in Algeria and Morocco (Bernier and Schoene, 2009). The indirect impacts also need addressing. When drought becomes a limiting factor for agriculture, there will be a tendency to shift to forests for crop cultivation, grazing and illicit harvesting of wood and other forest products, aggravating the loss of FGR (Bernier and Schoene, 2009).

Even small changes in climate are likely to affect the timing and intensity of flowering and seeding events, which would in turn have negative impact on forest biodiversity and ecosystem services. Increased frequency and intensity of extreme events, such as cyclones,may result in shifts in species composition. Mangrove ecosystems are vulnerable and a projected sea-level rise poses great threat to the mangrove ecosystems.They could potentially move inland to cope with sea-level rise, but anthropogenic pressures or the lack of necessary sediment would restrict their spread. Temperature stress will also affect the photosynthetic and growth rates of mangroves (McLeod and Salm,2006). Climate change impacts are expected to be severe in dry, high-temperature regions where trees are at their adaptive limit (Lindner *et al*. 2010) and in confined islands of moist forest that are surrounded by drier land (Williams *et al.,* 2003).

Choat *et al.* (2012) found that of 226 forest trees pecies from 81 sites worldwide, 70 percent have narrow safety margins in the event of injurious levels of drought stress and therefore could face long-term reductions in productivity and survival if temperature and aridity increase as predicted. While gymnosperms were found to be more tolerant of reduced hydraulic conductivity than angiosperms, safety margins were seento be largely independent of mean annual precipitation, with all forest biomes equally vulnerable to hydraulic failure and drought-induced forest decline. These findings help to explain why drought and increased heat are resulting in forest dieback across a broad range of forest and woodland types around the world (Allen, 2009). These dieback problems haveoccurred at a time when increases in temperature have been relatively modest, which does not bode well for forests, given future temperature predictions. Under a scenario of a 4^{o}C increasein global temperature, greater mortality rates can be expected as well as significant long-term regional drying in some areas.

***Plasticity*: Changed hydrological conditions associated with climate change include increases in severity and duration of flooding, which can kill whole stands of trees. Even inundation-tolerant species, such as *Eucalyptus camaldulensis* and *Coco snucifera* are killed by water-logging, if the trees have not been regularly exposed to water-logging and inundation through their development. Inundation due to sea-level rise is beginning to kill vegetation in coastal areas. In temperate and boreal regions, reduced snow cover, changed timing of snow melt and shorter frost periods are contributing to forest changes and stresses.

***Changes in phenology*:** In FGR, changes in the climate could have an impact on seed production; asynchronous timing between flower development and the availability of pollinators could result in low seed production for out-breeding species that depend on animal vectors. Pollinators worldwide are being affected by climate change, and this will likely have a major detrimental impact on breeding systems and seed production, with consequences for forest health and regeneration.

***Invasives*:** A changing climate also provides the opportunity for some plant species more suited to a wide range of climate conditions to invade new areas (Dukes, 2003). The spreadof *Leucaena* spp. and *Chromolaena* spp. is known to have adverse impacts on biodiversity in subtropical forests in India. In addition to new species invasions, changing climates will result in altered patternsof gene flow and the hybridization of species and populations. Shifting ecological niches will increase the risk of invasion by more competitivetree species that are more precocious or can move more quickly than the present species. Invasions of new genes via pollen and seed dispersal may disrupt local evolutionary processes, but could also be a welcome source of new adaptive traits (Hoffmann and Sgro, 2011).

***Changes in tree physiology*:** Teak (*Tectona grandis*), which is native to south and southeast Asia, but is now grown throughout the tropics for its valuable wood, is especially sensitive to changes in temperature and moisture. This sensitivity is reflected in the development of wood and tree rings, and has led to Teak's widespread use in dendrochronology for the reconstruction of past climate, particularly rainfall, throughout south Asia (Jacoby and D'Arrigo 1990; Sinha 2012). Changes in rainfall and moisture availability may therefore affect the development of cambium and the quality or grain of teak wood. Teak also grows faster than other hardwoods and has been estimated to store 2 $MgCha^{-1}$ yr^{-1} of atmospheric carbon (Kaul *et al.* 2010).

***Shift in ranges*:** Bamboos are also increasingly important plants to the global economy. However, with a warming global climate the natural limit of bamboo forests is expected to move northward (Rui, 2002), which may open up new areas for the cultivation of these unique grasses. Although bamboo can form dense tall stands throughout much of the Asia Pacific, bamboo forests do not store carbon effectively. Rather mature stands are in equilibrium between carbon taken up for growth, and carbon released from stem death and decomposition (Düking *et al.* 2011).

Adaptations of FGRs to climate change

Climate change adaptation includes carbon management as a part of the forest management paradigm. Kaul *et al*. (2010) found that in the Teak and Sal (*Shorea robusta*) forests of India, the length of rotation and the thinning regime utilised by forest managers can influence the carbon stored by forests and the value of timber harvested. For instance maximum primary productivity was seen at 60 year rotations, but declined as the rotation length was extended. However, average carbon stock increased by approximately 12% when rotation length was increased from 120 years to 150 years.

The ability of a tree species to survive the current rapid climate changes will depend on its capacity to adapt quickly to new conditions at existing sites, to survive changing conditions through a high degree of phenotypic plasticity without any genetic change, and/or to migrate to an environment with the desired conditions for that species.

A number of climate-related traits, such as the timing of bud break in spring, leader shoot growth cessation in summer, bud set in autumn and annual ring lignification, are regulated by temperature during female reproduction; temperature-induced regulation of the level of gene expression in the developing embryos is apparently maintained in the developing trees as an “epigenetic memory”. Many such epigenetic responses have been documented in plants exposed to environmental stresses (Madlung and Comai, 2004), but the mechanisms involved are not fully understood.

Gaps in knowledge

The gaps in knowledge listed by FAO (2011) are as follows:

- Adaptive potential of traits of importance under climate change and the underlying genetic mechanisms: Field and nursery experiments to understand patterns of variation; harness genomic tools to improve understanding of genes that are important in drought tolerance and resistance, flood tolerance, phenology, response to elevated CO_2 levels, etc. Transfer of knowledge obtained from model species in temperate regions to less known “local” species that are of high importance to people in the developing world.

- The degree of phenotypic plasticity and its underlying genetic and epigenetic basis: Phenotypic characterization through more field trials designed to understand impacts and responses to environmental changes.

- Effect of changes in interspecific competition and reproductive potential in relation to changing growth rhythms as temperature changes, but photoperiod stays constant. Small-scale assisted migration operations should be carried out and monitored to determine whether the expected disconnect between temperature regimes and photoperiod can be mitigated by mixing genetic sources and allowing natural selection.

- Population dynamics and environmental limits for pollinator species: In all areas where trees depend on pollinator species, action is needed to understand and respond to threats.

- Species distributions and effects of fragmentation on gene flow: Map species distributions, accounting for rapidly expanding agricultural land and other developments, and considering historical data; develop predictive models that take into account life-history characteristics, the effects of fragmentation and levels of gene flow, in different parts of a species range.

- Requirements for maximizing productivity of trees in agricultural landscapes under changing climate: Develop a portfolio of varieties that have phenotypic plasticity and that perform well across a range of environments (national/ regional level)

- Past and current flows of germplasm, including quantities, origin of material and survival at the destination: Improve documentation of germplasm flows, molecular typing of origin.
- Design of effective germplasm delivery systems for large-scale plantation establishers and smallholders: Improve international transfer of germplasm to make available high-quality site-matched planting material of high-value trees to planters, with a broad genetic base to ensure adaptive potential. Improve linkages between international exchange and smallholders through revitalizing the role of national tree seed centres in developing countries
- Cultivation requirements of currently or potentially useful species: Improve access to information through education and training.
- Regions, where high genetic diversity and significant threats coincide: Implement risk assessments and threat analyses to identify coincidence. Prioritize conservation of populations on the basis of importance to people, high diversity and significant threat.
- Most effective mix of *in situ, circa situ* and *ex situ* approaches to ensure conservation and maintain evolutionary processes: Increase population representation and genetic diversity of important and threatened species in conservation areas, in farmland and in seed collections.
- Seed storage behaviour and germination requirements for many important species: New approaches for “gene-banking” for many tropical species through seed physiology research, cryopreservation, pollen storage etc. Active conservation measures are needed for species that are important for human well-being and are seriously threatened.
- Costs and benefits of FGR conservation: Application of economic valuation approaches developed for other sectors to FGR, with an emphasis on high-value species for foresters and small-scale farmers.

Approaches to develop resilient FGRs

Under changing environmental conditions, trees must first survive and then reproduce. To be useful to humans, they must also continue to produce the products and services for which they are valued. Some important traits needed for adaptation to different climatic conditions, but which are not often considered in breeding programmes include the following:

Drought resistance: This is a complex trait that may include deep rooting systems, water use efficiency and deciduous habit. For many tree species, altered moisture regimes will be of greater concern than temperature changes. Information on these aspects would prove useful.

Pest and disease resistance: Pest and disease resistance has received little attention in tree breeding. Climate-change mediated changes in pest and disease attacks are becoming a crucial issue in plantation forestry (Yanchuk and Allard, 2009).

Fire resistance/tolerance: Increased fire frequency results from decreased precipitation and elevated temperatures combined with human activities such as forest clearance (Malhi *et al*. 2009). Many tree species growing in semi-arid regions have developed mechanisms to confer a degree of resistance to periodic fires, but this may not be the case in more humid forest. Increased fire frequency will require adaptations such as thicker bark.

Cyclone resistance/salt tolerance: The combined effects of a rising sea level and increased storm frequency have the potential to wreak heavy damage on coastal forests. A differential ability to withstand storms and salt may be found more commonly among species than within, but the possibility of selection for suitable types within species needs to be explored.

Phenotypic plasticity: This information is vital for an adaptive response to changing climate and can vary at intraspecific level.

Broadly, the climate change research on FGRs can be grouped into Climate change modeling, mitigation and adaptation.

i. Climate change modelling

- In addition to global models, development of regional models are required at finer spatial resolutions for decisions at micro-level. Besides the primary variables of temperature and precipitation, information on secondary variables like heating degree days, heat index, starting and ending days of seasonal monsoon rainfall, storm surge, need to be incorporated in the model.
- In order to tackle natural hazards, physico-chemical stresses faced by plants, pest and disease spectrum, species migration, there is a necessity for GIS based framework for risk assessment and to assist in decision making on spatio-temporal scale.
- Impact assessment and modeling taking all relevant factors including socio-economic impact assessment is essential to take the required measures for mitigation.

ii. Mitigation

- Integration of low-rainfall species into farming systems will provide green cover as well as insurance in case of failure of agriculture.
- Production of electricity using woody biomass, will help in reducing the use of fossil fuels. The plantation that is cut for production of biomass can again be regenerated for sequestration of more carbon. Species suitable for high-density plantation can be raised as energy plantations for providing the feedstock for power generation.
- Quantification of impacts of management practices on soil carbon dynamics due to agronomic practices and irrigation are required for optimizing the management practices for efficient carbon sequestration in soils.
- Development of improved models of sequestration is required on the basis of carbon sequestered, with a view to enhance the sequestration potential.
- Quantification carbon fixed in timber and timber products that are maintained for longer durations is essential.
- Methods have to be developed for inclusion of wood products in carbon trading.

iii. Adaptation

- New varieties that are climate change ready have to be developed through conventional breeding or molecular breeding. Breeding for increased tolerance to water stress, improved nutrient use efficiency is the ‘need of the hour’.
- Selection of broad leaved species tolerant to high temperature for CO_2 exchange and other physiological mechanism is important.
- Breeding for tolerance/ resistance to pests and diseases may also become necessary. As there may be an increase in intensity and distribution range of pests and diseases.
- Interactive effects of increased carbon dioxide and water/ nutrient deficiency need further study with changing climate.
- The anticipated beneficial effects of elevated carbon levels on grass land productivity may increase the population of herbivores, which can pose a threat to the regeneration of forests. The weeds showing phenotypic plasticity may increase in their invasive potential and expand the range. These are required to be studied for appropriate remedial action.

Conclusion

The Forest Departments, research organizations and other stakeholders handling the forest genetic resources in association with other government departments have to contribute to management and conservation of FGRs through an integrated approach (MoEF, 2009). The areas that need urgent attention in FGR conservation and management are:

i) Integrated database development at all organizational and management levels, to effectively utilize the data for decision making and establishment of a national information system.

ii) Skill development at all levels,especially related to new biotechnologies, benefit sharing mechanisms and tools in monitoring FGR diversity.

iii) Develop modelling for economically important and threatened species due to climate change.

iv) Monitoring and assessing biodiversity for representative landscapes on long term, in continuous basis.

v) Study genetic diversity, gene flow, seed characteristics and regeneration.

vi) Establish tree species with mixed mating system.

vii) Develop *ex situ* conservation stands, seed bank, field gene bank etc for FGR prioritized species.

viii) Elimination of invasive alien species, that threaten the diversity.

ix) Incentives for sustainable utilization of resources.

x) Sustained research on genetic diversity.

Forestry is one of the biological sciences whose study can contribute to a better understanding of the role of forests in climate change mitigation. There is a need for an integrated approach to study the problem cutting across disciplines of physical, social, biological, health and engineering sciences for sustaining the FGRs for posterity.

Summary

Forest genetic resources are essential for the adaptation and evolutionary processes of forests and trees as well as for improving their productivity. FGR provides food fiber and medicine forest dependent communities. FGR generate in-kind forest incomes contributing to the national economy, as hundreds of millions of people depend on the forest as their only source of cash income. FGR have major social, cultural and

spiritual values, mainly at tree species level. The forests of India with 16 major forest types house a wide array of species diversity.

The Government of India has plans to establish initially a Forest Genetic Resources Management Network (FGRMN) and a National Bureau of Forest Genetic Resources (NBFGR) later.The degree of endemism in plant species is high in India. Based on the economic utility and conservation value, a large number of forest tree species have been prioritized for conservation and use. The major cause of concern for FGR in the global context is the increasing levels of atmospheric CO_2 resulting from human activities such as burning of fossil fuels and forest destruction. An understanding of how adaptive the current Himalayan forests are, and how heterogeneity in regional vulnerabilities influence such changes to broad range of ecosystem functions and services, is lacking. The ability of a tree species to survive the current rapid climate changes will depend on its capacity to adapt quickly to new conditions at existing sites, to survive changing conditions through a high degree of phenotypic plasticity without any genetic change, and/or to migrate to an environment with the desired conditions for that species. Some important traits needed for adaptation to different climatic conditions, but which are not often considered in breeding programmes include drought resistance, pest resistance, fire resistance/ tolerance, cyclone resistance/salt tolerance, and phenotypic plasticity. There is a need for an integrated approach to study the problem cutting across disciplines of physical, social, biological, health and engineering sciences for sustaining the FGRs for posterity.

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FOREST HEALTH AND CLIMATE RESILIENCE

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Introduction

Forests are subjected to a variety of disturbances that are themselves strongly influenced by climate. Disturbances such as fire, drought, landslides, species invasions, insect and disease outbreaks and storms such as hurricanes, windstorms and ice storms influence the composition, structure and function of forests (Dale *et al.* 2001). Climate change is expected to impact the susceptibility of forests to disturbances and also affect the frequency, intensity, duration and timing of such disturbances. Increased temperatures and high levels of carbon dioxide in the atmosphere along with changes in precipitation are having notable impacts on the condition of the world's forests, They affect the frequency and severity of extreme weather events by making winters warmer or affecting the length of growing seasons. Such climate change events can affect forest pests and the damage they cause by directly impacting their development, survival, reproduction and spread; altering host defences and susceptibility; and indirectly impacting ecological relationships such as changing the abundance of competitors, parasites and predators. Insects and diseases may be the first indicators of climate change.

All of these impacts on trees and forests will inevitably have widespread impacts on the forest sector. Changes in the structure and functioning of natural ecosystems and planted forests due to climate changes will have negative impacts on the productive function of forest ecosystems, which in turn will affect local economies (FAO, 2005). Decreased forest ecosystem services, especially water cycle regulation, soil protection and conservation of biological diversity, as a result of climate change may imply increased social and environmental vulnerability. While climate change is likely to increase timber production and lower market prices in general, the increases in production will certainly not be evenly distributed throughout the world some areas will experience better conditions than others (Pérez-García *et al.* 2002). For example, forests with low productivity due to drought will be likely to face further decreases in productivity, while areas where temperature limits productivity may benefit from rising temperatures.

Research has suggested that insect outbreaks can significantly affect the carbon sink or source status of a large landscape. Thus preventing and reducing pest impacts on forests would provide an opportunity to mitigate climate change. Management of pests and prevention of their spread ensure that forests remain healthy, reducing the risk of forest degradation and increasing resilience to climate change.

As forests are very stable ecosystems in time, a study of the evolution of the forests could help to understand the effects of climate change. Holling (2001) notes that an adaptive capability to climate change is a necessary component of sustainability, whereas other researchers have determined that forest health is mainly affected by environmental stress, as critical ozone levels, meteorological stress factor, air pollution stress,critical deposition level or nutrient deficiencies (Garcia *et al.* 2001). Indicators of sustainable forest management and forest health indicators could be used for climate change assessment (Ferretti, 1997).

Increased fuel loads, longer fire seasons and the occurrence of more extreme fire weather conditions as a consequence of a changing climate are expected to result in increased forest fire activity (Mortsch, 2006). A changing climate will also alter the disturbance dynamics of native forest insect pests and pathogens, as well as facilitating the establishment and spread of non indigenous species. Such changes in disturbance dynamics, in addition to the direct impacts of climate change on trees and forest ecosystems, can have devastating impacts, particularly because of the complex relationships between climate, disturbance agents and forests. Any of these disturbances can increase forest susceptibility to other disturbances.

Impacts of climate change on forest pests

Changes in the patterns of disturbance by forest pests (insects, pathogens and other pests) are expected under a changing climate as a result of warmer temperatures, changes in precipitation, increased drought frequency and higher carbon dioxide concentrations. These changes will play a major role in shaping the world's forests and forest sector.

Climate change can exacerbate invasions of forest pests as well as impacts of native pests. For example, climate change can facilitate the range expansion of both native and exotic pests (insects and pathogens), or affect tree resistance to pests (Jactel *et al*. 2012) and there is increasing evidence that this is a widespread phenomenon (Anderegg *et al.* 2015). There is evidence in the fossil record that previous episodes of rapid global warming were accompanied by increased levels of insect herbivory (Currano *et al.* 2008).

Insects and pathogens have been noted to respond to warming in all the expected ways, from changes in phenology and distribution to influencing community dynamics and composition (Menéndez, 2007). While some impacts of climate change may be beneficial in terms of protecting forest health (e.g. increase winter mortality of some insect pests due to thin snow cover; slower larval development and increased mortality during droughts), many impacts will be quite detrimental (e.g. accelerated insect development rate; range expansions of pests) (Ayres and Lombardero, 2000).

Climate change can affect forest pests and the damage they cause by directly impacting their development, survival, reproduction, distribution and spread; altering host physiology and defences; and impacting the relationships between pests, their environment and other species such as natural enemies, competitors and mutualists.

Direct impacts

Climate, temperature and precipitation in particular, have a very strong influence on the development, reproduction and survival of insect pests and pathogens and as a result, it is highly likely that these organisms will be affected by any changes in climate. Because they are cold blooded organisms, forest insects and pathogens can respond rapidly to their climatic environment impacting directly on their development, survival, reproduction and spread. With their short generation times, high mobility and high reproductive rates, it is also likely that they will respond more quickly to climate change than long-lived organisms, such as higher plants and mammals (Menéndez, 2007) and thereby may be the first predictors of climate change.

Physiology: Climate influence on insects can be direct, as a mortality factor, or indirect, by influencing the rate of growth and development. Some information on the impacts of increased CO_2, and O_3, is becoming available, but only for specific environments (Karnosky *et al.* 2008) and only very partial information is available on changing Ultraviolet - B radiation levels and altered precipitation regimes.

Temperature: It is considered to be the most important factor of climate change influencing the physiology of insect pests (Bale *et al.* 2002). Precipitation however can be a very important factor in the epidemiology of many pathogens that depend on moisture for dispersal. Flexible species that are polyphagous, occupy different habitat types across a range of latitudes and altitudes, and show high phenotypic and genotypic plasticity are less likely to be adversely affected by climate change than specialist species occupying narrow niches in extreme environments (Bale *et al.* 2002).

Increases in summer temperature will generally accelerate the rate of development in insects and increase their reproductive capacity while warmer winter temperatures may increase over winter survival. Decreased snow depth associated with warmer winter temperatures may also decrease the winter survival of many forest insects that overwinter in the forest litter where they are protected by snow cover from potentially lethal low temperatures (Ayres and Lombardero, 2000).The impact of a change in temperature will vary depending on the climatic zone. In temperate regions, increasing temperatures are expected to decrease winter survival while in more northern regions, higher temperatures will extend the summer season thereby increasing growth and reproduction (Bale *et al.* 2002).

However, Deutsch *et al.* (2008) suggested that, in the absence of ameliorating factors such as migration and adaptation, the greatest extinction risks from global warming may be in the tropics. Warming in the tropics, though proportionately smaller in magnitude, could have the most deleterious impacts, because tropical insects have very narrow ranges of climatic suitability, compared to higher latitude species, and are already living very close to their optimal temperature.

Some important forest insect pests have critical associations with symbiotic fungi but limited information is available on how temperature changes may affect these symbionts and thus indirectly affect host population dynamics. In some cases, insect hosts and their symbionts may be similarly affected by climatic change, while in other cases, hosts and symbionts maybe affected asymmetrically, effectively decoupling the symbiosis (Six, 2007).

Species distribution**:** Climate plays a major role in defining the distribution limits of insect species. With changes in climate, these limits are shifting as species expand into higher latitudes and altitudes and disappear from areas that have become climatically unsuitable (Menéndez,2007). Such shifts are occurring in species whose distributions are limited by temperature such as many temperate and northern species. It is now clear that poleward and upward shifts of species ranges have occurred across many taxonomic groups and in a large diversity of geographical locations during the 20th century.

Parmesan and Yohe (2003) reported that more than 1700 Northern Hemisphere species have exhibited significant range shifts averaging 6.1 km per decade towards the poles (or 6.1 m per decade upward). Climate change may also weaken the association between climatic and habitat suitability. Forest pests are also occurring outside historic infestation ranges and at intensities not previously observed. There is increasing evidence in the literature that insect species are changing their genetic makeup in response to climate change.

Some examples of forest pest species that have responded or are predicted to respond to climate change by altering distribution include the following:

- The outbreak of *Leptocybe invasa*, the gall pest of eucalypts species in India is a befitting example of this.
- Climate change, which is clearly felt in the traditional rubber growing regions of India, may possibly alter the host-pathogen interactions leading to epidemics of otherwise minor diseases (Narayanan and Mydin, 2012).

- A major epidemic of the mountain pine beetle (*Dendroctonus ponderosae*) has been spreading northwards and upwards in altitude in western Canada (British Colombia andmore recently, Alberta) for several years.
- Jepsen *et al*. (2008) give ample evidence of northward outbreak range expansions of two geometrids (winter moth, *Operophtera brumata*, and autumnal moth, *Epirrita autumnata*) in Scandinavia.
- The pine caterpillar (*Thaumetopoea pityocampa*) has significantly expanded its latitudinal and altitudinal distribution in Europe.
- The European rust pathogen *Melampsora allii-populina* is likely to spread northwards with increased summer temperatures.

The ability of a species to respond to global warming and expand its range will depend on a number of life history characteristics, making the possible responses quite variable among species. Range-restricted species show more severe range contractions than other groups and are considered most at risk of extinction, due to recent climate change (Parmesan, 2007). Range shifts may be limited by factors such as day length or the presence of competitors, predators or parasitoids (Walther *et al.* 2002).

Phenology

Phenology is the timing of seasonal activities of plants and animals such as flowering or breeding. It is mostly temperature dependent; hence phenology can be expected to be influenced by climate change. It is one of the easiest impacts of climate change to monitor (Gordo and Sanz, 2005) and by far the most documented for a wide range of organisms (Root *et al.* 2003). Common activities to monitor include earlier breeding or first singing of birds, earlier arrival of migrant birds, earlier appearance of butterflies, earlier choruses and spawning in amphibians and earlier shooting and flowering of plants (Walther *et al.* 2002).Evidence of phenological changes in plants as a consequence of climate change is abundant and growing (Menzel *et al.* 2008).

In a review of phenological changes of interacting species, Visser and Both (2005) noted that insects have advanced their phenology faster (early eggs hatching and early migration return date) than their hosts (bud burst and flowering). They have also advanced their period of peak abundance more than their predators (laying date and migration arrival of birds). The disruption of synchrony between the winter moth (*Operophtera brumata*) hatching and bud burst of its host oak trees has in turn resulted in an asynchrony between the pest and one of its predators, the great tit (*Parus major*), which relies on the caterpillars to feed their young (van Asch and Visser, 2007). Such climate induced phenological changes are clearly resulting in a great deal of asynchrony between interacting species which will ultimately influence community structure, composition and diversity.

Where insect life cycle events are temperature-dependent, they may occur earlier and increased temperatures are likely to facilitate extended periods of activity (Harrington, *et al.* 2001). With increased temperatures, it is expected that insects will pass through their larval stages faster and become adults earlier. Therefore expected responses in insects could include an advance in the timing of larval and adult emergence and an increase in the length of the flight period (Menéndez, 2007). Members of the order Lepidoptera again provide the best examples of such phenological changes. Gordo and Sanz (2005) investigated climate impacts on four Mediterranean insect species (a butterfly, abee, a fly and a beetle) and noted that all species exhibited changes in their first appearance date over the last 50 years which was correlated with increases in spring temperature.

Parmesan and Yohe (2003) estimated that more than half (59 percent) of 1598 species investigated exhibited measurable changes in their phenologies and/or distributions over the past 20 to 140 years. They also estimated a mean advancement of spring events by 2.3 days/decade based on the quantitative analyses of phenological responses for these species. Root *et al.* (2003), in a similar quantitative study, estimated an advancement of 5.1 days per decade. Parmesan (2007) investigated the discrepancy between these two estimates and noted that once the differences between the studies in selection criteria for incorporating data was accounted for, the two studies supported each other, with an overall spring advancement of 2.3 to 2.8 days/decade found in the resulting analysis.

***Activity and abundance of natural enemies*:** Relationships between insect pests and their natural enemies will change as a result of global warming, resulting in both increases and decreases in the status of individual pest species. Changes in temperature will also alter the timing of diurnal activity patterns of different groups of insects, and changes in inter-specific interactions could also alter the effectiveness of natural enemies for pest management (Hill and Dymock 1989).

Quantifying the effect of climate change on the activity and effectiveness of natural enemies will be a major concern in future pest management programs. The majority of insects are benign to agro-ecosystems, and there is much evidence to suggest that it is due to population control through interspecific interactions among insect pests and their natural enemies (pathogens, parasites, and predators). Oriental armyworm, *Mythimna separata* (Walk.) populations increase during extended periods of drought (which is detrimental to the natural enemies), followed by heavy rainfall (Sharma *et al.* 2002). Aphid abundance increases with an increase in CO_2 and temperature, however, the parasitism rates remain unchanged in elevated CO_2.

Temperature not only affects the rate of insect development, but also has a profound effect on fecundity and sex ratio of parasitoids (Dhillon and Sharma 2009). The interactions between insect pests and their natural enemies need to be studied carefully to devise appropriate methods for using natural enemies in pest management.

Plant–pollinator interactions under climate change

Tree-pollinator interactions are important ecosystem services that are threatened by global warming and climate change. Pollinators such as birds, bees, butterflies, moths, flies, wasps, beetles, bats and even mosquitoes are essential for food production because they transfer pollen between seed plants impacting 35% of the world's crops. Among the pollinator groups, bees have been considered a priority group. Bees are synonymous with insect pollinators and they are publicly shared assets, most species and populations belonging to nobody, yet benefiting all of us through pollination – a perfect example of 'positive externality', in economic parlance (Batra, 1995). According to Gallai *et al*. (2009), more than 40 % of honey bees have been disappeared during last 25 years in India.Solitary bees and other insect pollinators play a great role in the pollination of wild plants. They also pollinate many cultivated plants. There is a lack of data on many invertebrate species that act as pollination agents. Many pollinator species that were relatively rare in the past are becoming rarer, while more common species have become widespread. The loss of bee pollinators is becoming a reality as reports all over the world have pointed out that most pollinator populations have declined to levels that cannot sustain their pollination services in both agro-ecosystems and natural habitats. European honeybees in North America have suffered dramatic declines (up to 50% of managed colonies) (Kraus and Page, 1995).

Research activities in India on bees or on other pollinators are in a state of neglect. Despite the global worry, no study had been done to assess directly the scale of the decline in natural pollinators. In India at present, one hundred and fifty million colonies are needed to meet the pollination requirement of around 50 million hectare bee dependant crops, but there are only 1.2 million colonies present (TNAU agritech portal). On a global level, the Convention on Biological Diversity has identified the importance of pollinators, with the establishment of the International Initiative for the Conservation and Sustainable Use of Pollinators (also known as the International Pollinators Initiative-IPI) in 2000, facilitated and coordinated by FAO. International Pollinators Initiative includes a project involving seven nations (including India) with the aim of identifying practices and building capacity in the management of pollination services.

Indirect impacts

Changes in temperature, precipitation, atmospheric CO_2 concentrations and other climatic factors can alter tree physiology in ways that affect their resistance to herbivores and pathogens (Ayres and Lombardero, 2000).

Elevated CO_2: Higher levels of CO_2 can also result in changed plant structure such as increased leaf area and thickness, greater numbers of leaves, higher total leaf area per plant, and larger diameter of stems and branches (Garrett *et al.* 2006). An increase in defensive chemicals may also result under such conditions (van Asch and Visser, 2007). Either of these changes to host physiology would influence palatability to insects, though the impacts on pests differ by species. Under increased CO_2 levels the winter moth (*Operophtera brumata*) consumes more oak (*Quercus robur*) leaves due to a reduction in leaf toughness, while the gypsy moth (*Lymantria dispar*) exhibits normal pupation weight but requires a longer time to develop as a result of an increase in tannin concentrations (van Asch and Visser, 2007).

Elevated levels of atmospheric carbon dioxide result in improved growth rates and water use efficiency of plants and trees. This increased productivity leads to lower nitrogen concentrations in trees and plants as carbon:nitrogen (C: N) ratio rise and thus reduces the nutritional value of vegetation to insects (Mortsch, 2006). In response, insects may increase their feeding (and consequently tree damage) in an attempt to compensate for the reduced quality and gain the necessary nitrogen (Ayres and Lombardero, 2000). In many cases the increased feeding does enable the insect to meet its nutritional needs, but most often it does not and results in poor performance, reduced growth rates and increased mortality (Harrington *et al.* 2001). Suchan effect, however, is not consistently observed, and increased growth due to enhanced CO_2 may in fact more than compensate for the defoliation in some cases (Kopper and Lindroth, 2003).

Drought: Drought is one of the most important climate-related events through which rapid ecosystem changes can occur, as it affects the very survival of existing tree populations. Long-term drought can result in reduced tree growth and health thereby increasing their susceptibility to insect pests and pathogens. A number of insect pests and pathogens are associated with stressed trees, such as *Agrilus* beetles and the common and widespread *Armillaria* species which have been linked to oak decline (Evans, 2008).

Drought can also elicit changes in plant and tree physiology, which will impact pest disturbance dynamics. Leaves may change colour or become thicker or waxier which could affect their palatability to insects (Harrington *et. al.* 2001). The concentration of a variety of secondary plant compounds tends to increase under drought stress, which would also lead to changes in the attraction of plants to insect pests. Moderate drought however may actually increase production of defense compounds in plants and trees, possibly providing increased protection against pests.

Sugar concentrations in foliage can increase under drought conditions making it more palatable to herbivores and therefore, resulting in increased levels of damage (Harrington *et. al.* 2001). Increases in the sugar content in drought-stressed balsam fir for example have been known to stimulate the feeding of certain stages of spruce bud worm(*Choristoneura fumiferana*) and accelerate their growth (Mortsch, 2006). Another advantage for forest pests is the increased temperature of drought-stressed trees, which can be 2 to 4 °C warmer, which can benefit the fecundity and survival of insects (Mortsch, 2006).

The impacts of such changes to host tree physiology and susceptibility provoke different responses from pest species. Rouault *et al.* (2006) investigated the impacts of drought and high temperatures on forest insects and noted that woodborers were positively influenced by the high temperatures which increased their development rates and the prolonged water stress that lowered host tree resistance while defoliators benefited from the increased nitrogen in plant tissues linked to moderate or intermittent water stress. The large natural spatial and temporal variability in forest processes makes it difficult to positively relate drought-related tree mortality to a greater incidence of insect pest or fungal pathogen damage.

***Extreme events*:** Besides drought, climate change may affect the frequency and intensity of other extreme climate-related events, with subsequent impacts on forest health. Direct damage to trees or alterations in the ecosystem may increase their susceptibility to pest outbreaks. Climate change also being associated with increased warm air mass movements towards high latitudes, the frequency and extent of long-distance windborne dispersal events are likely to increase, as was observed in a recent influx of diamondback moths on Svalbard Island in Norway, 800 km north of the likely source population in the Russian Federation (Coulson *et al.* 2002).

Impacts on community ecology: Distributional changes and range shifts interfere with community relationships as expanding species will begin to interact with other species in new environments with which previous interaction may have been limited or non-existent (Menéndez, 2007).Species capable of responding to climate change by increasing their range will also benefit from the lack of competitors and natural enemies in their new environment. Species expansions may not be promptly followed by that of its natural enemies (Battisti, 2004).Some pathogens may benefit from the improved survival and spread of their insect vectors.

Conclusion

It is likely that changing temperature and precipitation pattern due to climate change will produce a strong direct impact on the health of both natural and man modified forests. The climate change-induced modifications of frequency and intensity of forest wildfires, outbreaks of insects and pathogens, and extreme events such as high winds, may be more important than the direct impact of higher temperatures and elevated CO_2. Increased tree cultivation in private lands and development of urban forests are on the rise and therefore, there is a clear need for extensive research in India in the following line in future:

- Behavioural assessments of forest health agents (Insect pests and pathogens both native and invasive species, natural enemies, pollinators, litter inhabiting fauna and flora) in forests and plantations of economically important tress species.
- Development of pest management strategies for dealing with future pest adaptations to climate change.
- Strengthening plant quarantine to meet the new challenges emerging due to the increased risk and frequency of global trade-driven international pest movement with changing climatic situations.
- Development of pest/disease tolerant trees identified through breeding programmes as an alternative management practice to reduce subsequent vulnerability of plantation trees due to climate change.

Summary

The challenge to understanding climate change impacts is not just in obtaining information on the impacts of temperature, precipitation and other climatic factors on forests and pests but also acquiring knowledge on the interaction between the different climate change factors, and how climate change impacts disturbances and *vice versa*. Increased opportunities for pests to encounter new and suitable eco-climatic zones for establishment will result in many new infestations and challenges in forest pest management. The forest sector needs effective monitoring and detection activities to allow for quick action in the face of changing or increasing pest outbreaks including continual pest risk assessments. There is also a need for alternative practices to reduce subsequent vulnerability of forests, such as planting pest tolerant trees identified through breeding programmes; noting however that it is unlikely that such programmes can predict new pest risks in a timely fashion due to shifting species adapting to new environments. Comprehensive risk assessments as well as enhanced knowledge management systems using a variety of information technologies such as simulation models, geographic information systems (GIS) and remote sensing could also play a role in protecting forest health from the impacts of climate change and forest pests. More information is needed on the impacts on forests, forest pests and the complex relationships relating to climate change. Much of the information available comes from Europe and America. India is yet to generate reports on this aspect. There is also scant information available on the effect of climate change on symbionts and host dynamics. Further detailed studies of important forest pests would allow for the development of pest management strategies for the future and assist forest managers and policy-makers to better prepare for the challenge of dealing with climate change and provide insights into future pest adaptations to climate change.

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CLIMATE CHANGE AND FOREST GENETIC RESOURCES

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Introduction

Forest genetic resources (FGRs) refer to the heritable materials maintained within and among tree and other woody plant species that are of actual or potential economic, environmental, scientific or societal value. A population of a particular tree species comprises all the individuals of that species in the same geographical area and genetically isolated from other populations of the same species. Trees and other woody species differ from other organisms in several key respects. Forest tree species are generally perennial, long-lived and have developed natural mechanisms to maintain high levels of genetic variation within species. They include high rates of outcrossing and often long-distance dispersal of pollen and seed. These mechanisms, combined with native environments that are often variable, have enabled forest tree species to develop into some of the most genetically diverse organisms in existence. For long-term survival at a particular site, they need to capacity endure environmental extremes and changes and/or to persist in the soil seed bank or regrow from root suckers and coppice. The high genetic diversity that characterizes tree populations and individuals, and associated stress tolerance and disease resistance mechanisms, help explain their capacity to persist and thrive for long periods. Trees are notable for their diverse breeding and reproductive systems, which are in turn major determinants of spatial patterns of tree species genetic diversity. Most tree species reproduce sexually, although many have a combination of sexual and asexual reproductive means, while a few have lost the ability to reproduce sexually and are maintained as sterile, root-suckering clones in certain parts of their range. Climate change poses a major threat to forestry, biodiversity, agriculture and food security through extreme climatic events, droughts, increases in temperature, more frequent and intense wildfires, and increased activity of pests and alien invasive weeds. It will be increasingly vital to provide the deepest possible reservoir of genetic variability on which natural and artificial selection can act, facilitating adaptation to changed conditions.

Globally, deforestation has contributed significantly to climate change by releasing carbon dioxide into the atmosphere and reducing the production of oxygen. Several countries have taken significant steps in conserving the genetic resources of forest trees. However, they have rarely taken into account the implications of climate change for the conservation of forest genetic resources. Climate change poses unique conservation challenges that require specific responses. Globally forests have been expanding in terms of area and timber stock and subsequently they have acted as a carbon sink while they have been recovering from previous eras of deforestation. The impacts of climate change on forests, and especially on their genetic diversity have not been given proper consideration in forest management policies. Several recommendations for action have been put forth. These focus on establishing additional genetic conservation units specifically to respond to climate change, enhancing co-operation among countries and enlarging collaboration on the conservation of forest genetic resources, the need for continued and expanded monitoring and sharing of data, including the development of decision tools and red lists within each nation, and further research on aspects of assisted migration and on marginal and peripheral tree populations.

Genetic diversity is a key component of resilience and adaptability. Overall, forest tree populations are genetically very diverse, conferring them an enormous potential for genetic adaptation via the processes of gene flow and natural selection. Recent progress in genetics can contribute to the development of appropriate practical actions that forest managers and policy makers can adopt to promote forest resilience to climate change. Gaps in our knowledge remain, and we identify where additional information is needed (e.g. the adaptive value of peripheral populations or the genetic determinism of key adaptive traits) and the types of studies that are required to provide this key understanding.

No worthwhile paper could be seen on forest genetic resources in relation to climate change or resilience in the Indian context. Majority of papers involved assessment of climate change impacts or the sensitivity or vulnerability of forests to climate change and some considered adaptation. This paper attempts to focus on forest genetic resources (FGRs), and it does so in the context of trees in natural forests, plantations and agroforestry systems (Rodney, 2015).

The context

Forest trees are long-lived species that are genetically very diverse. Trees have developed natural mechanisms to maintain high levels of genetic variation and reduce inbreeding, e.g. through long-distance dispersal of pollen and reproduction among unrelated distant individuals. Because native tree individuals with a particular genetic make-up occupy very diverse environments, these mechanisms have maintained high levels of genetic variability within forest trees despite strong selection. Climate change is expected to have a significant impact on forests, causing changes in the geographic distribution of species, ecosystem functioning and interactions between species. Given the long lifespan of trees, fast local adaptation will largely depend on the genetic variability available within and among tree stands and populations. High levels of genetic diversity are thus beneficial as they allow individual trees and populations to adapt more easily to environmental changes.

Challenges facing Indian forests

Forests face major challenges from climate change and various native and exotic pests. In particular, it is the uncertainty in predicting the nature and impacts of these threats that is hampering efforts to plan mitigation. Despite a huge amount of modelling aimed at predicting the likely pattern, speed and intensity of climate change, there is still great uncertainty in forecasts of the magnitude of change at specific locations and the ability of our forest resources to cope with them. Similarly, whilst many new disease causing organisms have been identified as present in India, perhaps the greater threat lies in those that are present but have not yet been identified and those that have yet to arrive. There are numerous examples where introduced pathogens have led to mass destruction of tree species elsewhere in the world, e.g. chestnut blight (Jacobs *et al.* 2013) and white pine blister rust (Kinloch, 2003) in North America.

The interaction of virulent exotic pests with native trees coupled with climate change could operate in several ways. This can induce maladaptation to changing future conditions. Trees that are stressed may be more likely to succumb to both native and introduced pests and diseases. There will be altered balance between tree host and existing pests. For example, rising temperatures may affect the synchrony between herbivore emergence and bud burst. Changed climates cause species that were not previously damaging to develop into threats or facilitate the establishment of new species from other warmer countries.

Genetic variation and the phenotypic plasticity found in forest tree populations provide the means to cope with the new challenging conditions. Most genetic studies to date indicate that there is a large amount of heritable adaptive variation available in tree species on which natural selection can operate. Thus, the rather dramatic predictions made by climate envelope models of large-scale changes in forest distribution within the coming decades require reassessment and refinement to include genetic processes. However, adaptive potential depends on the species and local ecological conditions and demographic constraints could severely limit the capacity of populations to develop under the most severe climate changes. Thus, although usually appropriate, management scenarios based solely on locally existing forest material and genetic resources may be hazardous particularly at range and ecological edges (Bruno *et al.* 2015). The task of monitoring to determine whether the native species in natural woodlands are currently at risk under climate change is vital. A lack of genetic adaptation and demographic collapse can drive populations to extinction. Determining which genetic and demographic thresholds will lead to maladaptation is crucial to make informed management decisions, particularly in forests where, despite predictions, evidence of decline due to climate change is not yet strong. This can be achieved by genetic monitoring. Monitoring the potential of forests to adapt genetically under climate change is necessary over broad areas to inform management. Monitoring based on parameters used in classical forest management (such as adult age classes, seedling density and presence of pests) can now be coupled with molecular genetics assessment methods to provide early warning signs of maladaptation risks (Bruno *et al.* 2015).

Assisted migration can be the answer for managing forests and their habitats under climate change. When sound evidence suggests that current genetic resources at a site will cease to offer an appropriate option under future climate, introduction of non-local resources is being considered. One type of assisted migration concerns the sourcing of seed and planting stock and can take two forms: the use of exotic species (i.e. species that do not naturally occur at the planting location or, more generally, within the country) or the use of non-local genetic resources (i.e. populations of naturally occurring species which originate from other parts of the species distribution range). Assisted migration and assisted gene flow programs can disrupt local genetic adaptation and affect the present and future dynamics of forest genetic resources. We can take advantage of past experiences in the introduction of species and provenances, but these are not real experiments to test the effectiveness of present-day-assisted migration programs. Caution is needed in the use of extensive assisted migration as the responses will likely affect not only trees but also the whole forest community in which they are established (Bruno *et al*. 2015). Natural regeneration is the most appropriate management technique for promoting the adaptation of natural forests to climate change. Natural regeneration is being promoted in the context of close-to-nature forest management for several reasons including those that relate to cost reduction, decreased disturbance, better selection potential due to larger seedling density and conservation and continuous natural development of the local gene pool. To provide sufficient material on which natural selection can operate to bring about developmental change, the option of natural regeneration is likely to be the most appropriate as it typically provides a much larger base population than is the case for plantations.

Forestry need to rethink its strategies for long rotation species to make it possible for selection to occur in those areas where climate change is expected to have its strongest impacts (Bruno *et al*. 2015). The conservation of genetic diversity has to be included as a component of habitat and species conservation strategies. Foresters tend to give much less consideration to the conservation of genetic resources (gene conservation) than to that of species and habitats. Gene conservation of forest tree species should be viewed as an integral part of biodiversity conservation, alongside that for species and habitats. Protected forest areas in which there is little or no active management can sometimes directly contribute to the conservation of forest genetic resources, genetic diversity monitoring should become a priority concern there, for the most relevant species (Bruno *et al*. 2015).

Tree breeding involves selecting individuals that have particularly desirable traits and crossing these individuals to improve, particular trait or traits of interest within populations. Breeding programs can therefore produce genetic resources, which are valuable in enabling forests to adapt to climate change and to provide more and/or better ecosystem services. Whether based on a high- or a low-input strategy, breeding programs should include the assessment of phenotypic traits that are likely to be important in conferring genetic adaptation to climate change (which may well be found outside the usually investigated resources and will require well-organized international collaboration). Low-input breeding strategies represent an opportunity to do so for species that are traditionally under-represented in breeding programs because of their low market value. This may be useful, as in the future, such species (e.g. Mediterranean trees) may become increasingly important under climate change (Bruno *et al*. 2015).

In addition to changing perceptions of the importance of genetic resources for better coping with increased disturbances, the views of society are also shifting regarding the role of genetic resources in meeting the demands for forest goods and services. The two main current drivers of this shifting perception are climate change and expected future demands by end-users. Increasing the societal perception of the value of genetic diversity in managed forest ecosystems should be a priority. Raising awareness among forest managers, policy makers and conservationists of the essential role of genetic diversity on biodiversity dynamics and adaptability of forests to future conditions is urgently needed. Improvements in knowledge transfer beyond academia are required (Bruno *et al*. 2015).

Need for resilience

Recently, attention has begun to focus on identifying and quantifying ways to bolster the resilience of ecosystems (Folke *et al.* 2004; Batt *et al.*, 2013), in a move from prevention to mitigation of disturbances such as climate change. Now both climate change and globalized trade are realities and there is a need to find ways to ensure the persistence of essential ecosystems in the face of new conditions, in other words, to maximize their potential to adapt to a changed environment. All these aspects are difficult to measure and, even where clear negative effects are expected, results have, on occasions, been counterintuitive. For example, some systems have shown unexpected resilience, even in the face of pressures that had been expected to cause ecosystem change (Bestelmeyer *et al.* 2013; Ponce-Campos *et al.* 2013). The policy shift towards resilience appears to be emerging from a combination of increasingly visible change and the lack of progress in international efforts to address these issues. Therefore, to find ways to meet policy goals and to ensure the long-term persistence of the ecosystems we value, it is essential to reach a working understanding of what resilience means and how it can be optimized via appropriate management (Cavers and Cottrell, 2015).

Resilience in theory

Resilience is defined as the extent of perturbation that a system can experience before it undergoes a shift to an alternative state (Holling, 1973; Scheffer *et al.* 2001) or, more subtly, 'the capacity of a system to reorganize whilst undergoing change so as to retain the same function, structure, identity and feedbacks (Folke *et al.* 2004). Resilience can also be defined in the case of an ecological network as its 'capability to absorb, resist or recover from disturbances and damage at the same time continuing to meet its overall objectives of supporting biodiversity and providing ecosystem services'. Originating from engineering theory, these concepts of resilience developed for the purposes of predicting how and when systems shift from one stable state to another and are perhaps most advanced in the study of lakes, where the essentially closed nature of the system makes them more amenable to model development. State shifts may be complicated by hysteresis, where forward and reverse tipping points occur at different levels of pressure, such that restoring the original state is not simply a case of reversing the initial disturbance (Cote and Darling, 2010).

A key element in resilience theory is the relationship between diversity and resilience. Although positive relationships have been shown between biodiversity and stability of ecosystem function (Laliberte *et al.* 2010), in theory it is the functional redundancy associated with higher diversity that confers stability. However, measuring the extent of functional redundancy is difficult, and this becomes more complicated when applied to heterogeneous environments, where functional roles may alter with context (Wellnitz and LeRoy. Poff, 2001). Furthermore, depending on whether ecosystem resilience (resilience of the ecosystem as a whole) or species resilience (the resilience of individual species) or genotypic resilience is being considered, stability may depend on either species diversity or intraspecific genetic diversity, respectively, and the processes governing their maintenance. If one tree species within that forest becomes the focus of a severe threat, it might best be managed by complete removal of that species and replacement with an alternative species or with natural recruitment. In contrast, if the forest type is important, for example, if it is a priority habitat, then the resilience of particular tree species within that woodland is essential. Exposure of that key species to severe threat risks the delivery of the ecosystem service, and the internal diversity of the species consequently becomes important.

Direct evidence for the relationship between diversity and resilience is typically experimental but has been shown for ecosystem resilience in many systems (Norden *et al*. 2009; Batt *et al.* 2013; McGovern, 2013; Prober *et al.*, 2013). However, in the case of single species resilience, the evidence base is much poorer, with well cited studies of eelgrass (Reusch *et al.* 2005) and model organisms such as yeast (Bell and Gonzalez, 2009), *Drosophila* (Bakker *et al.* 2010) and *Daphnia* (Latta *et al.* 2010) providing the best demonstrations. Such studies indicate that the level of intraspecific genetic diversity, the integrity of gene flow mechanisms and population size all play key roles in delivering the potential for 'variability rescue'. The mechanism of variability rescue involves initial population decline, followed by recovery as genotypes adapted to the new conditions prosper via natural selection (Cavers and Cottrell, 2015).

Salt tolerance to survive sea water incursion into coastal terrestrial environments

One way to address impacts of sea-level rise on coastal forests is to identify salt tolerance in plants/trees. In Kiribati, a single king tide can kill established *Artocarpus altilis* (breadfruit) trees. As these trees harbour seabirds such as Terns which are used by local fishermen to locate schools of fish, their loss has a major impact on food security and livelihoods. Given the impacts of sea-level rise in Kiribati, Tuvalu, and other atoll island nations in Oceania, development of salt-tolerant breadfruit is an urgent task. Studies with salt-tolerant non-halophyte trees (Thomson *et al.* 1987; Marcar *et al.* 1999) have frequently demonstrated considerable genetically based resistance to salinity. Given the substantial genetic diversity in breadfruit, including putative salt tolerance in particular varieties and natural hybrids between *A. altilis* and *A. mariannensis* (Morton, 1987; Ragone, 1997), it is almost certain that salt-tolerant breadfruit can be selected and further developed, illustrating the need to conserve and make use of genetic diversity in multipurpose tree species.

Rapid transition from fire-sensitive to fire-resistant variability

Severe fire may have the same effect as clearing a forest, especially where fire creates large patchy openings. The pattern and size of such openings in relation to the forest cover influence genetic diversity. Where mortality among burnt species is heavy, it results in reduced population sizes and increased genetic drift. For isolated populations, the migration rates of seed and pollen exchange are therefore affected. Sources of migration could even be cut off, thus reducing the effectiveness of pollinators (Kigomo, 2001). Adverse fire may directly affect biotic dispersal agents, and this may decrease migration of genes between populations. Migration may increase if the migration vectors are abiotic. A devastating fire may affect traits that could have a direct bearing on fire-resistant species, resulting in direct selection that indiscriminately removes all such genotypes (FAO, 2010). The cumulative impact of interacting disturbances can increase fire risk. For example, drought often reduces tree vigour, increasing vulnerability to insect infestations and diseases. Insect infestations and diseases add to the fuel available and therefore increase the opportunity for forest fires, which in turn can support future infestations by weakening tree defence systems (Dale *et al.* 2001).

Invasive species

Invasive species, including plants, insect pests and microbial pathogens, are increasingly being identified and noted as major threats to ecosystem integrity and individual species, including trees. The main invasive plant threat comes from "transformer" plant species which have the capacity to invade natural or slightly disturbed forest associations, becoming the dominant canopy species and completely modifying or displacing entire ecosystems, with the loss of displacing entire ecosystems, with the loss of many of the existing species (trees and others). An example is the introduced tropical American tree *Prosopis juliflora* in East Africa, which is taking over large swathes of natural forest and woodlands, with considerable negative impacts on native tree populations (in terms of both species and genetic diversity). It is also damaging local livelihoods in the process (Mwangi and Swallow, 2005). In island countries and territories of Oceania, excessive opening of the forest canopy through intensive timber harvesting, coupled with major cyclones, has greatly favoured the spread of light-loving vines such as *Merremia peltata* and *Mikania scandens*; these vines and creepers have now taken over large swathes of forest ecosystems, thickly draping all trees and shrubs (Maturin, 2013; Kamusoko, 2014).

Drought and heat-induced tree mortality reveals emerging climate change risks for forests

Greenhouse gas emissions have significantly altered global climate, and will continue to do so in the future. Increases in the frequency, duration, and/or severity of drought and heat stress associated with climate change could fundamentally alter the composition, structure, and biogeography of forests in many regions including the forest genetic resources. Of particular concern are potential increases in tree mortality associated with climate-induced physiological stress and interactions with other climate-mediated processes such as insect outbreaks and wildfire. Episodic mortality occurs in the absence of climate change and studies suggest that at least some of the world's forested ecosystems already may be responding to climate change and raise concern that forests may become increasingly vulnerable to higher background tree mortality rates and die-off in response to future warming and drought, even in environments that are not normally considered water limited. This further suggests risks to ecosystem services, including the loss of sequestered forest carbon and associated atmospheric feedbacks. Key information gaps and scientific uncertainties that currently hinder our ability to predict tree mortality in response to climate change emphasise the need for a globally co-ordinated observation system. The potential for amplified tree mortality due to drought and heat in forests worldwide has been revealed (Allen *et al.* 2010).

Importance of forest genetic resources or intraspecific variability

Natural forests are reservoirs of genetic diversity for tree species or intraspecific variability within species, essential to the adaptation of forests, and thus of the forestry sector to climate change. Trees are long-lived, and maintaining resilient forest ecosystems requires more than planting new tree varieties and species. Persistence will largely depend on the ability of existing trees and populations to adapt locally. In particular, the existence of a high level of genetic diversity within stands is a key pre-requisite for forest trees to adapt and be resilient to the unpredictable effects of climate change. There is need to examine genetic variation within forest tree populations in India, and assess how this variability and its management could help forests to adapt to environmental changes. Tree species within (semi) natural forests contain significant genetic variation. Variable environmental conditions, such as temperature, light availability and drought intensity maintain and promote genetic diversity within and between (semi) natural forests, even at short spatial scales. High genetic variation in forest tree populations allows for more rapid adaptation to climate change. Genes associated with key adaptive traits (such as trees resistance to drought, cold or forest fires) can vary in their frequency spatially and geographically. This type of information is now easily accessible and should be included, along with neutral genetic diversity, in the adaptive forest management tool kit. Forestry practices can significantly modify the genetic composition and structure of forest trees and the development of their genetic diversity.

Genetic variability and adaptation to environmental changes at local spatial scales

Earlier research has confirmed that within-species genetic diversity can be very high with significant differentiation even among neighboring trees within the same forest. With sufficient genetic variation, trees in forests can adapt rapidly to environmental changes. Researchers identified genes associated with individual tree response to major environmental threats such as drought, cold, heat, and recurrent forest fires. Within populations, genes associated with the seasonality of new leaf emergence in spring, flowering time, and resistance to drought and cold varied significantly along environmental gradients at small spatial scales. Experimentally it is showed that the variability found for these genes is associated not just with migration and population foundation, but also with varying environmental conditions, such as altitudinal and latitudinal gradients, and is thus affected by natural selection. They also found that up to 80-90 percent of the genetic diversity underlying adaptive genes remains within populations, suggesting that local environmental conditions can promote and maintain genetic diversity within and among tree populations. They also found that genetic diversity for key traits can develop within just a few generations, allowing rapid adaptation to a changing environment. Knowledge of how genetic variability is partitioned in space for such important genes can thus help improve models of future range distributions, and better inform the choice of trees in reforestation projects.

Other results point to the existence of significant genetic variability affecting tree survival and reproductive output (fitness) in small forests. These studies revealed that the pollen output of male trees is highly dependent on the microenvironment in which each tree is growing (e.g. soil humidity, fertility and texture). Similarly, studies of three maritime pine forests located in the Mediterranean region indicate that altitude has a measurable effect on genetic diversity at the scale of a few hectares. They also showed that the local environment is very important for the survival of transplanted trees. Indigenous trees showed a higher fitness than transplanted trees, only under certain microenvironmental conditions. This suggests that the difference in fitness between populations depends strongly on the environmental context, and that it is affected not only by regional climate but also by the local environment at very small scales. Consequently, local genetic resources are not always best for all environmental conditions, such as in sites with full sun exposure.

Genetic resources for forest management in a changing environment

To make forests more resilient to an unpredictable future, development of highly efficient sequencing and genotyping methods previously restricted to model organisms only has added to our knowledge of this aspect. These methods provide better information on the genetic make-up of trees and their adaptative potential, thus helping them to sustainably manage forests in a changing environment. As a short term perspective, it is conceivable that foresters will target the collection of reproductive material for conservation, direct use and breeding programs for trees carrying particular gene variants of interest for managed forests. In the longer term, surveying changes in occurrence of different genotypes will considerably improve monitoring, allowing predictions of whether or not particular stands have a good ability to withstand strong environmental changes.

Water is a natural resource of vital importance in agriculture. This makes it also a limiting factor for growing sufficient crops or commercial plantations or agroforestry stands to ensure food and wood supplies for the world's growing population. For harnessing genetic resources for improving drought stress tolerance in crops, there is an urgent need for the genotyping of gene bank accessions to benefit from the genetic diversity of gene bank material worldwide, and the reliable phenotyping for drought stress tolerance. Thus, genotyping and phenotyping of forest genetic resources are vital. Adaptation to climate change involves monitoring and anticipating change and undertaking actions to avoid the negative consequences and to take advantage of potential benefits of those changes.

Managing climate change and forests in the face of uncertain future

Forest genetic resources managers will be challenged to integrate adaptation strategies (actions that help ecosystems accommodate changes adaptively) and mitigation strategies (actions that enable ecosystems to reduce anthropogenic influences on global climate) into overall plans. Adaptive strategies include resistance options (forestall impacts and protect highly valued resources), resilience options (improve the capacity of ecosystems to return to desired conditions after disturbance), and response options (facilitate transition of ecosystems from current to new conditions). Mitigation strategies include options to sequester carbon and reduce overall greenhouse gas emissions (Millar *et al.* 2007).

Climate change increases the drought risk

In the case of the projected drought exposure of various regions of India, the anticipated dynamics of the regional forests facilitate the adaptation of forests to climate change-induced drought risk. On the basis of an ensemble of climate change scenarios we expect substantial drying in various parts of India due to temperature rise, while such trends were found to be less pronounced during the past. In response to these climate trajectories, a change in species composition towards a higher share of drought tolerant species as well as the use of drought resistant provenances or variability are to be identified as paramount actions in forest adaptation in the drier warm regions. Adaptation to aggravating climate change may need to use artificial regeneration to enrich local gene pools and increase the drought tolerance of stands. Increasing risks from pests and other disturbances are expected as a result of more frequent and severe droughts, underlining the need to put a stronger focus on risk management principles rather than on indicators of productivity in silviculture and forest planning. A consolidation of disturbance monitoring systems and a broader use of pest dynamics and hazard rating models are paramount tools to facilitate this adaptation process in forest management. Systematic and long-term implementation of the presented measures should increase forest stability and resilience, and further secure the sustainable provision of ecosystem services under climate change.

In regions where climate change is expected to be extensive and rapid, many tree species are predicted to experience severe stress in their native ranges. Survival will then depend on the capacity to undertake at least one of the following: (1) quickly adapt genetically to new conditions at existing sites (2) survive changing conditions through a high degree of phenotypic plasticity without genetic change and/or (3) migrate rapidly to newly found suitable environments that match basic physiological requirements. The expected impacts of climate change and hence strategies for responding to it differ among these environments. Assisted migration and artificial selection for appropriate traits are approaches that can be applied to planted trees, whether in commercial plantations or farms, but are less appropriate for natural forests. Adapting to climate change poses a greater problem for naturally regenerating populations, where the potential for natural migration is hindered by forest fragmentation and agricultural expansion, and when confounding factors for adaption include pests and diseases, reduced population sizes, and simplified forest structures and species compositions. Lack of information on the following hinders our ability to manage climate change impacts better: (1) little is known about the sequences and functions of the genes conferring adaptation (2) the genetic and epigenetic basis of phenotypic plasticity and its role in producing responses to environmental alterations is unclear (3) the basic life-history characteristics, ecological determinants and geographic distributions of many trees are not well studied and (4) meaningful syntheses of such information into predictive models of change and response are poorly developed.

Trees harness the power of microbes to survive climate change

Microorganisms are the most abundant and diverse taxa on earth. They have the ability to tolerate extreme environments, catalyze a range of metabolic functions, and rapidly develop in response to changing environmental conditions. Imagine if plants and animals could harness these powers. In fact, microorganisms confer numerous benefits to plants and animals. For example, microorganisms in the mammalian gut improve nutrition, reduce susceptibility to disease, and even alter host behaviour (Diaz *et al.* 2011). Some of the most complex microbiomes are found in soils, where they are responsible for nutrient cycling, crop yield, and carbon sequestration (Bender *et al.* 2016). In some cases, soil microbes can even rescue plants from the negative consequences of climate change (Lau and Lennon, 2012). If plants and animals can build associations with specific microbial members that maximize benefits, then harnessing microbial powers may provide rapid and efficient solutions to the challenges resulting from global change.

Gehring *et al.* (2017) showed that the relationship between soil microbial communities and plants is not a fortunate coincidence. Instead, some pinyon pine genotypes form associations with different below ground ectomycorrhizal fungal (EMF) communities that help them contend with drought. These EMF communities were responsible for the observed difference in drought tolerance between host tree genotypes. Because these microbial communities are, at least partially, under plant genetic control, EMF community composition is an extended phenotype of the host tree and potentially a mode of adaptation to the increased drought stress pinyon pines face in a changing climate. Given the vast array of biogeochemical and metabolic functions in the microbial arsenal, if similarly tight linkages occur between diverse soil bacterial and fungal communities and host plant genotypes, then host plants may possess a powerful tactic for adapting to environmental change. Gehring *et al.* (2017) provide important advances for the idea that host-associated microbial communities may underlie adaptation (Zilber-Rosenberg and Rosenberg, 2008). They piece together evidence showing that the pinyon pine genotypes differ in their EMF microbial associates (even when they are grown in the same soil), and that these divergent EMF communities influence host performance and fitness in response to drought. Such findings support the view that plant-associated microbiomes represent a heritable extended phenotype of the host genome, that microbial communities influence fitness, and that the host traits controlling these associations can serve as adaptations to changing environments.

Although genetically based differences in plant colonization by microbial partners are well known in other symbioses (Heath and Tiffin, 2009; Grillo *et al.* 2016), rarely are connections between specific plant-controlled symbiotic associations and fitness made. This critical link is necessary to show that these associations are adaptive. Gehring *et al.* (2017) establish this link, between host-determined EMF communities and host fitness variation, by carefully building evidence from a combination of long-term observational field studies, manipulative greenhouse studies, and microbial community sequencing. They characterize EMF communities associated with drought-tolerant and drought-sensitive trees in both the field and greenhouse, while demonstrating how those microbial communities influence tree fitness responses to drought. The mutualistic association between plants and EMF communities is an ancient symbiosis in which hosts provide fixed carbon (from photosynthesis) to their root symbionts in exchange for increased nutrient acquisition via the fungus. However, EMF species can provide other benefits (e.g., stress tolerance) and can vary widely in the levels of host benefits provided (Pena and Polle, 2014).

Gehring *et al.* (2017) found that drought-tolerant genotypes were colonized by EMF species in the genus *Geospora* at much higher rates. Indeed, even drought-intolerant individuals that had higher colonization by *Geospora* showed higher drought tolerance compared with other drought-intolerant individuals that failed to form associations with *Geospora*. In the absence of EMF species (when soil was sterile), differences between tree genotypes in drought tolerance disappeared. Given that plant genotypes also influence diverse soil bacterial and fungal communities that perform a plethora of metabolic and biogeochemical functions (Wagner *et al.* 2016; Edwards *et al.* 2015), the adaptive potential of host traits underlying plant–microbe interactions could be extensive. Gehring *et al.* (2017) also stimulate many new questions at the intersection of emerging fields in the biological sciences. For example, perhaps the wealth of knowledge on plant–microbe interactions at the biochemical level and, more recently, at the genomic level can someday inform our understanding of global change ecology and lead to better models of plant community responses to climate change. Perhaps the recognition that genotypes vary in their associations with above ground and below ground microorganisms will change how we breed agronomic crops to feed the planet in the face of the global changes dominating us.

Recommendations for future forest managers and researchers

The nation would benefit from incorporating measures to maintain and if necessary increase genetic variation within tree populations and stands to ensure the ability of forests to adapt to climate change. The conservation of tree genetic resources should be promoted accordingly. Management of different ecosystems should take into account that protected forests can act as gene banks.

New knowledge from molecular genetics provides insights into the processes through which forests adapt to changing conditions. Such knowledge is important for guiding forest management decisions, and thus avoiding costly mistakes. The new knowledge highlights the key role of genetic diversity of trees in determining forest resilience. All stakeholders in the forestry sector should strengthen forest genetics conservation with support from ICFRE. However, the conservation of forest genetic resources currently does not seem sufficiently emphasized to ensure that agreed biodiversity targets are met.

Genetic adaptation of forest trees to climate change ultimately depends on specific genes, which underlines the importance of studying and valuing the genetic variability stored in trees and to identify genes involved in local adaptation. We can benefit from including such knowledge in models forecasting climate-induced range shifts. In fact, the inclusion of genetic diversity in such models may considerably modify the expected range shift of forest tree species.

The strategy should aim at increasing the contribution of agriculture and forestry to maintenance and enhancement of biodiversity, and it is expected that by 2030, State-wise Forest Genetic Resource Management Plans should be in place throughout India. Increasing the genetic diversity of trees increases the species diversity of the forest community they harbour.

The marketing of forest reproductive materials should be improved with requirements on how to maintain a high level of genetic diversity within traded seed lots. Requirements should address the minimum number of seed trees to collect from a natural stand (typically more than 100), the necessity to sample seed trees from ecologically variable microenvironments within stands, and the importance of mixing seed lots collected within a region of provenance. Traded seed lots should eventually be made of collections sampled from hundreds of seed trees. It is suggested that such recommendations go beyond reforestation and afforestation projects and address all ecological restoration efforts.

Forest management practices that maintain genetic developmental processes in naturally regenerated forests should be promoted. If needed, forest adaptation potential can be accelerated through tree breeding practices and transfer of suitable forest reproductive material.

Connectivity between protected areas facilitates gene flow and is important for the maintenance of genetic variation and adaptive potential of species.

Experimental work is needed to test the extent to which intraspecific genetic diversity underpins stability. This should encompass testing of multiple genotypes, but also multiple pressures. For this, a decision-making framework should be developed, to let forest policy makers identify the most appropriate action in specific pest threat situations. This should define a minimum set of parameters for a host tree species, such as its ecology, distribution and diversity; those of the threat organism(s) and likely future environments. Model-based testing could then be used first to evaluate potential developmental rates in tree populations, taking into account genetic diversity, adaptive potential and variations in demographic turnover, and secondly, to explore and prioritize different management scenarios using both idealized populations and spatially explicit simulations reflecting the known distribution of species in the Indian context.

New information on genetic and adaptive variation for tree species should be collected at a fine spatial scale. Detailed assessments of phenotypic variation in existing trials should be made, including development of high-throughput methods for gathering such data. New, large-scale trials should be established to test resistance related trait variation and to maximize the impact of advanced genomic approaches. The coordination and collation of existing data sets on intraspecific diversity in Indian tree species should be carried out as a priority, particularly for those species as yet unaffected but with imminent serious threats, and encompassing both molecular and phenotypic variation (Cavers and Cottrell, 2015).

Conclusion

Forests in India exist in many forms and composition, which include native woodlands with very low levels of intervention, low impact silviculture plantations and woodlands of native and exotic species in a mixture of man-made plantations composed of fast-growing exotic conifer species. All are subject to biotic and abiotic change in the form of pests, climate change and increasing frequency of weather extremes. Their ability to adapt to these challenges is dependent on a number of factors including inter- and intra-specific diversity. The main factor influencing adaptedness is the balance between natural selection and gene flow, and therefore, consideration needs to be given to the best means of conserving the developmental process rather than the genetic structure present at a given point in time. The importance of integrating developmental considerations into adaptive forestry is being stressed in cases, where, more extreme climate change is predicted (Lefe'vre *et al.* 2013).

Research to support adaptation to climate change is still heavily focused on assessing impacts and vulnerability. However, more refined impact assessments are not necessarily leading to better management decisions. Multi-disciplinary research approaches are emerging that integrate traditional forest ecosystem sciences with social, economic and behavioural sciences to improve decision making. Implementing adaptation options is best achieved by building a shared understanding of future challenges among different institutions, agencies, forest owners and stakeholders. Research-policy-practice partnerships that recognise local management needs and indigenous knowledge and integrate these with climate and ecosystem science can facilitate improved decision making (Rodney, 2015).

Summary

Forest ecosystems can face a range of challenges in the coming decades, of which climate change and pests are the most serious. These challenges will be overlaid on a background of historically modified and fragmented forests managed in a wide range of ways for different objectives over the years. As Indian forests are species rich in the global context, their resilience to these challenges is fundamentally dependent on the expression of resilience of the variability within individual species or their genetic resources. A better strategy for establishing long-term resilience would be to harness natural developmental processes, to maximize the capability of individuals of tree species to respond to new threats by the reorganization of populations via natural selection or in other words, to be resilient. Such processes depend on the internal variability of the species, their mechanisms of dispersal and their ability to recruit new genotypes to a population. A review of the theoretical concept of resilience is presented in this paper. In addition, it has also examined how resilience might be applied to tree populations comprising of intraspecific variability and assessed the state of knowledge of forests from this perspective.

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HARNESSING FOREST GENETIC RESOURCES FOR CLIMATE RESILIENCE AND FOREST HEALTH

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Forests are considered to be the richest storehouse of genetic resources which functions as the repository on which agriculture, medicine and diverse array of ecosystem services rely on. However, climate change has induced a myriad of direct and indirect challenges, which necessitates a relook at the function of forests and its ability to conserve genetic resources. This paper looks at the climate resilience of tropical forests in the context of forest health. Although forests have proved to be resilient to changes in the past, in recent times the quality of forests has deteriorated mainly due to degradation and fragmentation.

Large expanse of bamboo forests undergo mass flowering and perish at the same time with grave impact on the food availability of large mammals like elephants forcing them to move out of forests resulting in human-wildlife conflicts. We need to have a wider genetic pool for our bamboo forests to ensure that the flowering is evenly spaced and that the resources do not dwindle all at once. Teak is another species which needs urgent consideration from the point of view of genetic variability. Starting from the 1970s, the productivity of Teak is on a sharp decline, which has multiple reasons to it. Decline in soil fertility in subsequent rotations, absence of good quality planting stock, impact of pests like the Teak defoliator, which can substantially reduce the volume increment and the Teak trunk borer, which can kill older trees are of much concern. A recent study has demonstrated the possibility of increased outbreaks of the Teak defoliator, which can nullify the productivity enhancement predicted under higher CO_2 levels. Increased temperatures have also been correlated with the higher incidence of heart rot in young Teak stands.

From the forest health perspective a high impact problem and which is not well addressed is the impact of exotic species in the natural forests. For example, a total of 89 invasive alien species have been recorded in Kerala, many of which have gained entry into natural forests. In most invaded locations, the rich diversity of flora is brought down into a monoculture of the invading species. As these chosen examples show, assessing the diversity of forest genetic resources at the species, population and ecosystem levels is an immediate pre-requisite to evolve conservation strategies. Inventories on wild genetic resources of cultivated crops and medicinal plants whcih can resist extreme climatic variations from the Proteced Areas are lacking. One of the key interventions needed is to enhance the area of intact forests where evolutionary processes continue unimpacted with appropriate long-term management plans. However, this is an uphill task considering the increase in the area of open forests and the possibility of our intact forests getting more and more fragmented owing to development pressures. A multisectoral approach is required to address this grave problem.

IMPACT OF CLIMATE VARIABILITY ON BENEFICIAL SOIL MICROORGANISMS: NEED FOR HARNESSING THEM FOR FOREST ECOSYSTEM RESILIENCE

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Introduction

Global climatic variability due to anthropogenic influence, particularly the atmospheric warming with altered weather patterns has been much discernible in the recent past. Much of its effects on terrestrial above ground vegetation have been substantially investigated leaving little attention paid to the below-ground biota, especially the soil microbes such as Plant Growth Promoting Rhizosphere (PGPR) and mycorrhizal fungi, which perform many important ecological functions, including soil carbon and nutrient cycling and maintaining soil ecosystem health (Staddon, 2005; Staddon *et al*. 2002). They are considered to be very important in contributing to the carbon bio-geochemical cycle and therefore, they aid in carbon sequestration and thus, they become part of global carbon trade, besides their availability may determine the plant's response to climate change (Lewis *et al*. 2010; Tobita *et al*. 2011).

Microbes as the first colonizers on this planet influenced the life processes of all other living systems and have become an integral part of the entire biosphere and they play a key role in maintaining the biological equilibrium on the earth. The rhizosphere is a dynamic soil environment formed by living plant roots and their associated microorganisms. They are of both free living and symbiotic in nature, having beneficial relationships with the host plant. Root colonizing bacteria (rhizobacteria) such as *Azospirillum, Azotobacter, Pseudomonas* etc., that exert beneficial effects on plant development via direct or indirect mechanisms have been defined as Plant Growth Promoting Rhizobacteria (PGPR) and they augment plant productivity and immunity (Yang *et al.* 2009). The mechanisms by which PGPR promote plant growth, include the ability to produce phytohormones, asymbiotic N_2 fixation, production of siderophores, synthesis of antibiotics, enzymes and/or fungicidal compounds and solubilization of mineral phosphates and other nutrients (Gholami *et al*. 2009). The well known symbiotic relationships between plants and microbes are root nodule

Rhizobium on leguminous plants, *Frankia* on *Alnus* and Casuarinas and mycorrhizal fungi on different plants including tree species.

"Mycorrhiza", literally means "Fungus Root", is the association between specialized root-inhabiting fungi and the roots of living plants. In this mutually beneficial association, or symbiosis, each partner, or symbiont, receives essential nutrients and other benefits and also contributing to the other partner's survival. Among these symbiotic fungi, the endomycorrhizal fungi viz., Arbuscular Mycorrhizal (AM) are widely distributed in different ecosystems and associated with many plants including forest trees. Another important type of mycorrhizal fungi is the ectomycorrhizal (ECM) fungi. The ECM fungi occur in about 10% of the world's flora, include most of the gymnosperms, especially the conifers and certain angiosperm families such as Betulaceae, Casuarinaceae, Juglandaceae, Myrtaceae and so on.

This symbiotic group of mycorrhizal fungi improves seedling growth and survival by enhancing the uptake of nutrients and water and increases root life span. They also help to protect the roots against other pathogenic organisms and against environmental stresses, such as heavy metal toxicity or soil salinity etc. In the past few decades the extent of tropical forests has changed dramatically with the ever increasing demand for wood fibre. Because above and below ground organisms are tightly linked, such changes result in dramatic losses, which decreases hope for restoration of degraded sites through natural regeneration.

Both AM and ECM fungi play an important role in improving the nutrient uptake, especially phosphorous (P), increased water absorption and growth of plants (Fitter *et al*. 2000; Augé, 2001; Ezawa *et al*. 2002) and provide ecosystem-resilience from pathogenic as well as other potentially invasive mycorrhizal fungi (Desprez-Loustau *et al*. 2007). Vogt *et al.* (1982) have shown that the importance of mycorrhizal contribution in forested ecosystems and demonstrated that 14–15% of net primary production was contributed by mycorrhizal fungi. ECM have been shown to produce Nitrogen degrading protease enzymes and Phosphate solubilizing acid phosphatase enzymes, which enable them access to forest-floor nutrient pools (Dighton, 1991). They also enhance the plant performance by providing growth substances such as auxins, gibberellins, etc. and by increasing tolerance to adverse pH and temperatures. Hence, mycorrhizal fungi act as an interphase through which plants obtain nutrients and, as such, are critical for terrestrial ecosystem functioning.

Beneficial microorganisms are being utilized as bio-fertilizers for better quality seedling production and survival in many agriculture and forestry crops. They are also very important in shaping the vegetation community structure as they mediate competition between plants for their essential requirements. The success of reforestation programs may greatly depend on mycorrhizal root colonization of seedlings, which increases their competitiveness, due to increase in the initial growth rate and hence, the rehabilitation of tropical forests would greatly need AM and ECM bio-fertilizer inoculation.

The natural resources in India including the forest and forestry crop production are reported to be increasingly susceptible to climatic variability. As per an estimate, around 41% of forests in India have been already degraded and dense forests are slowly losing their crown density. More than 70% of the forests have problems with regeneration and 55% are prone to fire. As much as 78% of the forest area is subjected to heavy grazing and other unregulated use (NFC, 2006; FAO, 2009). As per ISFR (2017), 10.58% of the total geographical area of the country are open and scrub jungles. This opens up the increased activity of soil microbes to release the carbon that locked up in forested soil environment, which account for about 40% (787 pg carbon) of the global soil carbon pool (Solomon *et al*. 2007). The soil microbe mediated global annual carbon release is estimate to be 50-75 pg, which is nearly nine times than that of global anthropogenic origin (Crowther *et al*. 2015). Many attempts are being made to afforest/reforest the available land area as mitigating measure to manage the carbon sink and thus, the climatic variability.

In general, beneficial microbes especially the AM fungi as a negative feedback to the increasing atmospheric carbon dioxide play a key role in climate variability studies. The response of beneficial soil microbes to the environmental changes and the impacts of probable shifts in soil microbes and in colonization and conferring beneficial properties on their host plant species are poorly understood (Staddon *et al*. 2002; 2003; Compant *et al*. 2010 and Covacevich *et al*. 2010). Information on the mutualistic relationship in the plant microbe interaction, which enables the plants to grow well in the natural environment, is very essential to better predict with certainty how the ecosystem will respond to global climatic changes.

Arbuscular Mycorrhizal (AM) Fungi

AM fungi is the most common type of its kind, found on most of the terrestrial plants and is one of the widely studied plant symbiotic fungi (Smith and Read, 1997; Wilson, 2012; Giri and Saxena, 2017). The extensive fungal mycelial network in soil (can occupy over 100 $m.cm^{-3}$ in total soil volume) is believed to provide pathways for carbon flow from root to soil and thus in terms of global carbon cycle, perhaps mycorrhizas can account for upto 20% of the carbon fixed by plants (Jacobsen and Rosendahl, 1990; Miller *et al*. 1995; Bago *et al*. 2000; Manzoni *et al*. 2012; Zhang *et al*. 2016) and are considered to bridge the gap between the above-and below ground processes (Leake *et al*. 2004), thus they may be an important mediating factor between plants and climate change response (Compant *et al*. 2010). Climate change effects on AM fungi and the resulting plant responses is a crucial factor in predicting ecosystem responses on a global scale (Wilson, 2012). Fossil record evidence confirms that species' distribution ranges are influenced by climate change. In case of mycorrhizal fungi – an obligate biotrophs, changes in their viability, productivity, longevity and efficacy as a symbiotic partner are most likely with shift in abundance and distribution of their host-plant partners (Bellgard and Williams, 2011). As mycorrhizal fungi contribute to ecosystem productivity and resilience to perturbations, they play a key role in the successional positioning of plant species distributions and thereby the diversity of these beneficial fungi would be essential for ecosystem productivity and resilience of global ecosystem changes particularly in places like grass lands of high altitude and latitude, tropical regions etc., where rare and geographically restricted plant taxa are under threat due to rampant habitat fragmentation and ecosystem conversions to monoculture. As a major determinant for the phenology, physiology, distribution and interactions of plants largely by temperature, light, water availability, humidity, wind etc., the climate establishes strong relationship with plants and soil and this interactive relationship is the basis for anticipating changes in terrestrial biomes in response to climatic variability (Bellgard and Williams, 2011).

Both direct negative and positive impacts of increasing temperature on AM fungi have been reported (Getty, 2016). It was reported that many aspects of environmental change will impact on mycorrhizas, but the main changes to their community structure will result from changes in plant community structure (Staddon *et al*. 2002). Also, there was no evidence of elevated atmospheric CO_2 affects the mycorrhizal fungi, while there was increasing evidence that temperature can have directly effect on mycorrhizal fungi. However, Wolf *et al.* (2003) observed that under plant monocultures, only *Glomus clarum* responded significantly to CO_2 elevation out of 11 species present and this response was not detectable under poly culture and concluded that CO_2 enrichment and plant species richness impact AM fungal spore communities. Similarly, Chung *et al.* (2003) showed that increase in plant species richness fostered greater microbial biomass as well as the abundance of saprophytic and AM fungi and observed that the effect of plant species richness on microbial communities was significantly modified by elevated CO_2 and N deposition. Johnson *et al*. (2003) found that plant species responded individualistically to the presence of AM fungi and the availability of CO_2 and suggest that CO_2 enrichment ameliorates the carbon cost of some AM fungal symbioses.

AM fungi are reported to respond to long-term climatic manipulations including both soil temperature and moisture content in the field. Drought can severely affect soil microbial communities, leading to sudden declines in microbial biomass and activity. It is likely that drought and freezing might be more frequent and impact more severely on ecosystems and their functioning (Reichstein *et al*. 2013). In response to drought, they reported to develop increased proportion of root length colonized and decreased extraradical mycorrhizal hyphae density and the mycorrhizal response was directly related to vegetation changes (Staddon *et al*., 2003). In general, Compant *et al*. (2010) reported that in most of the studies AM fungal colonization tended to increase in response to experimental increase in CO_2 and temperature, which according to Fitter *et al.* (2000) and Zavalloni *et al.* (2012), is probably due to increased plant productivity that demands more nutrients and consequent enhanced production of root exudates. On the other hand, Wilson (2012; 2016) observed increasing temperatures tended to decrease AM fungal colonization. On an average based on various reviews, Staddon (2005) observed that carbon allocation patterns do not alter between mycorrhizal plant and fungal partners as a result of increased C availability at elevated CO_2.

Mixed responses have been reported to show by AM fungi towards altered precipitation due to drought or increased rainfall; however drought generally found to reduce AMF colonization (Compant *et al*. 2010) and as reported by Davies *et al*. (2002), the response can be strain specific. Walter *et al*. (2015) recorded increased AM fungal biomass due to drought condition in a grass land community of two species, while there was no impact on root colonization and plant biomass and an increase in abundance of hyphae on one species. However, reduced AM fungal growth with decrease in soil water content in tall prairie grasslands in Oklahoma (Sheik *et al*. 2012), and decreased hyphae abundance with increased root colonization in drought condition in a low land grassland in Argentina (Garcia *et al*. 2008) have been recorded. Augé (2001) highlights the influence of AM fungi and drought physiology that AM fungi influences on tissue hydration and foliar gas exchange are often subtle, transient and probably circumstance and symbiont specific and AM fungi influence on host water relations and drought physiology can be substantive, but only occasional. Seasonal and drought-related declines in the extraradical hyphae of AM fungi and percent root colonized have been observed in many, but not all studies (Clark *et al*. 2009). In general, among mycorrhizal groups arbuscular mycorrhizas (AM) associated with grassland ecosystems are least vulnerable under the influence of global climate change effects (Bellgard and Williams, 2011). Host plants derive several benefits from AM fungal association and these benefits are likely to confer the host plant resilience to the changing climate scenarios and thus the host plant – microbe interaction become much more economical and environmentally valuable.

Ectomycorrhizal Fungi (ECM)

The ECM fungi are common in both Gymnosperms (Pinaceae, Cupressaceae) and Angiosperms (Aceraceae, Betulaceae, Fagaceae, Juglandaceae, Leguminosae, Myrtaceae, Rosaceae, Salicaceae, Spindaceae and Ulmaceae) (Warcup, 1980; Molina and Trappe, 1984). The fungal partner in ectomycorrhizas, mostly belong to Basidiomycetes (families like Amanitaceae, Boletaceae, Cortinariaceae, Russulaceae, Trichlomataceae, Rhizopoganaceae and Sclerodermataceae) and some Ascomycetes

(Trappe, 1977) The Basidiomycetes consits of the Hymenomycetes such as *Amanita, Boletus, Cortinarius, Suillus, Leccinum, Laccaria, Lactarius* and *Tricholoma* and the Gasteromycetes include *Rhizopogon, Pisolithus* and *Scleroderma* (Smith, 1971). Molina and Trappe (1982) reported from Pacific North West of USA that *Pinus contorta, Pinus ponderosa* and *Pinus monticola* had similar mycorrhizal partners while some fungi were able to form ectomycorrhiza only *Pseudotsuga menziesii* and *Larix occidentalis.* In India, Bakshi (1974) reported the association of *Amanita hemibapha, A. verna, Astraeus, hygrometricus, Cantharellus cibarius, Cenococcum graniforme, Geastrum fimbriatum, Lactarius scrobiculatus, Pulveroboletus shoreae, Rhizopogon flavum, Russula delica, Scleroderma bovista, S. cepa, S. geaster, S. verrucosum, Xerocomus bakshii* with different species of *Pinus* and other trees of Dehra dun and Himalayan regions.

Mohan (1991) reported some of the ECM fungi viz., *Amanita muscaria, Laccaria laccata, Lycoperdon perlatum, Rhizopogon luteolus, Russlula* sp., *Scleroderma citrinum, Suillus brevipes, S. subluteus, Thelephora terrestris* and *Tricholoma* sp. in *Pinus patula* plantations in the Nilgiri Hills, Tamil Nadu. Vijayakumar *et al. (*1999) reported the ECM fungi, *Pisolithus tinctorius* and *Thelephora ramarioides* for the first time in association with *Acacia auriculiformis, Acacia holosericea* and *Acacia mangium* in Andhra Pradesh. Recently, Mohan (2002) reported the distribution of different ECM fungi viz., *Pisolithus tinctorius and Thelephora ramarioides* in association with economically important tree species such as Eucalypts, Casuarinas and Acacias in Southern India.

The appearance of basidiomata of the different ECM fungi in association with various tree species such as *Acacia mearnsii, A. melanoxylon, Cupressus macrocarpum, Eucalyptus globulus, E. grandis* and *Pinus patula* were found to be affected by the amount of rainfall. The number of basidiomata of different ECM fungi were found greater during monsoon seasons, especially July to October months as compared to summer months during the two year period of observations. This kind of response to rainfall on the basidiomata production on beech and pine woods over a period of time has been shown by Wilkins and Harris (1946). Last *et al*. (1981), while studying the basidiomata production of *Amanita muscaria* in *Pinus patula* plantations of different age groups also found a relationship between the rainfall and the total production of basidiomata of the fungus. Agerer (1985), while studying the production of basidiomata of mycorrhizal fungi in spruce plantations in West Germany over a period of 4 years found that the “culminated precipitations” i.e., the precipitation which have fallen for a certain number of weeks till any time is an important factor for the growth of basidiomata of different fungi. The results of the present study are in concordance with the investigation made by Natarajan and Mohan (1998). They found the effect of rainfall on the occurrence of basidiomata of different ECM fungi viz., *Amanita muscaria, Laccaria laccata, Lycoperdon perlatum, Rhizopogon luteolus, Russula parazurea, Scleroderma citrinum, Suillus brevipes, Suillus subluteus, Thelephora terrestris* and *Tricholoma* sp. in *P. patula* plantations in the Nilgiri Hills, Tamil Nadu.

Ectomycorrhizal (ECM) associations occurring at high latitudes and altitudes ecosystems are most likely to be impacted by short-term changes such as loss of habitat and host plants under global climate change effects, because of their susceptibility (low buffer capacity of soils) of many of the ECM systems and climate change impacts are more pronounced in these ecosystems, while highly specialized ECM species associated with forest ecosystems are reported as vulnerable mycorrhizal types that are subject to intermediate-term global climate change effects (Bellgard and Williams, 2011). Carbon is a limiting factor for the production of fungal biomass in soil. As mycorrhizal fungi directly depend on plants for most of their carbon requirement, increase in carbon allocation below-ground to roots lead to parallel increase in C-supply for all types of mycorrhizas (Norby *et al.* 1986; O'Neill, 1994). As like in AM fungi, increased CO_2 concentration has been reported to increase both percentage root colonization and growth of the external mycelial network in ECM fungi (Lukac *et al.* 2003).

In a much similar way like that of AMF, ECM fungi help the host plant access to important soil nutrients (Courty *et al*. 2010). It has been reported that as in the case of AMF, elevated CO_2 induce changes in ECM colonization. Fransson *et al*. (2005) reported significant mycelial biomass production in pine plant seedlings under elevated CO_2. Norby *et al.* (1987); Ineichen *et al*. (1995); Rouhier and Read (1998); Garcia *et al.* (2008) have also demonstrated the same kind of effect in different plants with different strains of ECM, while some other works reported only temporal increase in mycorrhizal formation (O'Neill *et al.* 1987; Lewis *et al.,* 1994), did not increase at all (Markkola *et al.* 1996), only negligible effect on mycorrhizal development and no change in colonization after 4 months, but increase after 1 year (Walker *et al.* 1995a). All these studies clearly show that both increase effect and varying interaction under elevated CO_2. However, altered CO_2 concentration can potentially induce shifts in species composition and structure in ECM communities and abundance of some speices (Courty *et al.* 2010). It has been reported that these beneficial effects can enhance water nutrient and water absorption by the host plants (Loewe *et al.* 2000).

Diversity of mycorrhizal fungi is reported to be influenced by temperature changes. This is possible in nature because of temperature tolerant seasonal host plant invasion will likely to precede invasions of warm-season-adapted ECM fungi (Johnson, 2009). Elevated temperature is also reported to induce changes in EM fungal colonization. Studies conducted elsewhere have demonstrated that respiration of some ECM strains reduced; some ECM morphotypes decreased colonization; increased the percentage of total ECM colonization and did not show changes in fungal biomass or ECM mycelial production under elevated temperature (Malcolm *et al.* 2008; Kasai *et al*. 2000; Swaty *et al.* 1998; Clemmensen *et al*. 2006).

Valdés *et al.* (2006) demonstrated that both total fine-root biomass and ECM-root biomass were strongly affected by severe drought in high elevation tropical plantation forests. Drought can significantly alter the ECM fungal colonization, however the effect in terms of their abundance and occurrence may be different with different taxa (Shi *et al.* 2002; Swaty *et al.* 2004). Community shift under reduced water availability due drought was also reported (Meier *et al.* 1990). Different mechanisms of drought tolerance like improved water uptake capacity of the colonized roots; efflux of hydraulic lift water from the external mycorrhizal mycelia of ECM; higher CO_2 fixation in inoculated plants, etc., have been reported in ECM colonized plants (Bogeat-Triboulot *et al.* 2004; Egerton-Warburton *et al.* 2008; Davies *et al.* 1996).

Ecosystem fragmentation, which may occur as a result of climate change impacts can have direct bearing on the dispersal and the dispersal agents of mycorrhizal fungi. For example, dispersal and colonization of conifer species can be profoundly affected by ECM fungi leading to limit their colonization in new areas (Thiet and Boerner, 2007).

Plant Growth Promoting Rhizobacteria (PGPR)

PGPR represent a wide range of rhizosphere bacteria with excellent root colonizing ability and capacity to produce a wide range of enzymes and metabolites that help plants tolerate both biotic and abiotic stresses. Changing climate scenarios have drastically affected the soil microbial community including PGPR and altered the soil rhizosphere dynamics.

Impact of climate change reported to have direct and indirect effects on the colonization of soil microbial communities. The direct effects on soil microbial communities like temperature, soil moisture content (Balser *et al*. 2010) altered plant activity, allocation, exudates, or community composition, etc., are if altered by climate change, the microbes may be indirectly effected via changing substrate availability and potentially microclimatic effects (Singh *et al.* 2010). Also, bacterial endophytes in different plant parts and the rhizosphere soil are likely to get affect by environmental changes associated with climate change (reviewed by Compant *et al.* 2010).

It has been noted that elevated CO_2 has effects on both rhizobacterial as well as endophytic communities and the experiments conducted elsewhere have demonstrated that the elevated CO^2 triggered the legumes interaction with the rhizobacteria as well as favoured some strains over the others in some plants. The above ground biomass production and consequent increase in net primary production directly under the effect of elevated CO_2 has been shown to increase C supply belowground and stimulate soil biological activity (Pan *et al.* 1998; Pendall *et al*. 2004). The effect of elevated CO_2 may be more pronounced when specific microbial groups are targeted. Significant effects of elevated CO_2 on *Pseudomonas* and *Rhizobium* populations were reported (Marilley *et al*. 1999; Drigo *et al.* 2009; Schortemeyer *et al.* 1996; Montealegre *et al.* 2000) and this response varied in trend among different plant hosts and among different soils. Rhizobia when used as microbial inoculants have shown many direct and indirect Plant Growth Promoting (PGP) properties. They are having a spectrum of tolerance mechanisms/pathways against biotic and abiotic stress factors with which the bacteria make use of their PGP traits under stress (Gopalakrishnan *et al.* 2015). Rhizobial response towards extreme temperature have been extensively studied under different environment and reported a spectrum of stress adaptive mechanisms, which involve the production of extracellular lipopolysaccharide, extracellular polysaccharide (Nandal *et al.* 2005) and heat shock proteins (Michiels *et al.* 1994; Mu¨nchbach *et al.* 1999; Han *et al.* 2008; Alexandre and Oliveira, 2011).

Drought is one of the major production-limiting factors to agriculture and it has been predicted to increase in frequency, duration and intensity due to global climate change. In recent years, efforts have been directed at harnessing these naturally occurring, beneficial soil microbes to improve crop production under a changing climate (Yang *et al.* 2009; Nadeem *et al.* 2014). However, the roles of PGPRs in the management of abiotic stress such as drought has more recently gained importance (Yang *et al.,* 2009; Dimpka *et al.* 2009; Grover *et al.* 2010). The drought tolerant ability of PGPR on many plant hosts related to agriculture (Sandhya *et al.* 2009; Kasim *et al.* 2013) and their ability to confer more than one type of biotic and/or abiotic stress tolerance (Mayak *et al.* 2004; Coleman-Derr and Tringe, 2014) have been investigated. Plant response to drought stress mechanisms involves multiple physiological, molecular and biochemical pathways and quantitative traits that control different metabolic processes, such as water and nutrient relations, carbohydrate metabolism, protein metabolism, hormone metabolism as well as antioxidant defences (Huang *et al.* 2014). These adaptations of plants to aid in survival during periods of drought stress have been comprehensively reviewed by Farooq *et al.* (2009) and Huang *et al.* (2014). The underlying mechanisms of plant adaptations to drought stress and bacterial mediated drought tolerance is very complex and understanding this is very crucial for the development of drought tolerance in plants and its mitigation and management practices. The proposed physiological mechanisms that have been evolved out of the studies conducted in PGPR mediated drought tolerance include alterations in root architecture which results in improved water and nutrient uptake, with positive effects on the overall plant growth, increase in relative water content, increase in several organic and inorganic solutes as well as an increase in the synthesis of osmolytes including proline, increase in antioxidant enzymes that scavenge for reactive oxygen species, and manipulation of phytohormones including IAA, ABA, and CK (Ngumbi and Kloepper, 2016).

Nevertheless, the effects of additional climatic drivers on soil and rhizosphere microbial communities such as UV-B radiation and Ozone and their interactions have been much less studied. Avery *et al.* (2003) demonstrated changes in UV-B irradiation level affected community-level physiological profiles (CLPP), but not the number of cultivable bacteria in an Antarctic plant. Rinan *et al*. (2008) showed shifts in Phospholipid Fatty Acids (PLFA) profiles and CLPP, with no effect on total microbial biomass due to increased UV-B irradiation over *Eriophorum russeolum* plants. Schloter *et al.* (2005) and Esperschu¨tz *et al.* (2009) studied and demonstrated significantly altered composition of rhizosphere bacterial communities of *Fagus sylvatica* trees following long-term exposure to ozone stress. Dohrmann and Tebbe (2005) pointed out that ozone-stressed grasses showed remarkable similarity in the composition of their associated rhizosphere bacterial communities compared to respective controls. The outcome of PGPR mediated stress tolerance studies points to more performance trials for evaluation of effective PGPR strains under field conditions and suggests that these studies with improved methods and techniques may help to resolve the complexity underlying the process and to devise suitable adaptive management strategies under continued climate change regime.

Conclusion

Climate change alters the interaction between plants and beneficial microorganisms in many ways. Studies have indicated that elevated CO_2 conditions will lead to increased colonization of PGPF, PGPB, induce positive responses in plant and mycorrhizal components to elevated CO_2. It is also important to note that elevated CO_2 concentrations may induce important beneficial AM and ECM fungal community composition, which help the host plant to perform better in the altered condition. The response of elevated CO_2, will also depend on the plant and the microbial genotype. The environmental scenario is rapidly changing under the global climatic variability. Microbes in the soil environment and ect-endophytic associates are known to regulate the plant microbe interaction by involving in various biogeochemical cycles. Different isolates of nitrogen fixers, phosphate solubilizers, phosphorus mobbilizers (mycorrhizal fungi), waste and dead organic matter decomposing microbes etc. are playing key roles in maintaining the soil equilibrium and thereby the soil ecosystem heath. The future research for ecosystem resilience to changing global climate should be focused on mycorrhizal symbionts and their metabolic products by which the host plant harness the resilience potential against changing environmental parameters and that act as a feed back to the growing climate change parameters.

Understanding and harnessing the plant-microbial interactions for the sustainable production of food, fuel and fiber to support a growing world population on a dwindling supply of arable land will be the challenge of generations to come. Climate change is likely to have significant impacts on soils that may affect all of the services provided by soil biodiversity and hence quantification of these impacts is very much needed. All mitigation and attenuation measures should be taken to limit global climate change, which are expected to have a beneficial impact on soil biodiversity preservation, soil functioning and associated services.

Summary

Climate variability and associated environmental changes have far reaching consequences in the biosphere. The beneficial soil microorganisms of both symbiotic and free living, growing in close conformity with the terrestrial plants have the remarkable ability to alter and survive in the extreme condition and thereby the host plants will be provided with a range of benefits for their survival. This paper highlights the importance of beneficial micro organisms like. Arbuscular Mycorrhizal (AM) fungi, Ectomycorrhizal (ECM) fungi and Plant Growth Promoting Rhizobacteria (PGPR) in the context of climate change scenario.

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ADAPTIVE FOREST MANAGEMENT IN INDIA IN THE CONTEXT OF CLIMATE CHANGE: ISSUES AND CHALLENGES

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Introduction

Global warming and climate variability that cause immense concern today are the consequences of human-induced rise in Green House Gas (GHGs) concentrations in the atmosphere, particularly after the onset of industrial revolution. According to fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2014), there had been an increase in atmospheric temperature of about 0.89°C and 0.72°C respectively over a period of more than 100 years and 50 years till 2012 and the predicted global temperature change at the end of the century is likely to be in the range between 1.5 and 4.5°C over the baseline period of 1986-2005 (IPCC, 2013). The report also states that globally there will be changes in rainfall pattern and increase in the frequency and intensity of extreme weather events associated with rise in atmospheric temperature. It is now realized that the impacts of climate change are no longer a distant conjured up problem. Rather it manifests as the most important environmental and developmental challenge globally and is an issue of great concern to all countries and regions irrespective of their size or level of development. Climate change is being experienced in various forms, particularly as rising temperature, erratic weather events, variable rainfall, frequent droughts, sea level rise and inundation of low lying areas, cyclones and similar other coastal and marine catastrophes (Auffhammer *et al*. 2011 and Lobell *et al*. 2012). Though several countries have taken cognizance of the effects of climate change and have adopted measures to reduce its impacts, there is a long way to go with regard to the efficacy of fruition of these initiatives in view of the impending crisis looming over the planet.

The forests in India are facing increasingly difficult challenges. The most obvious challenge is to meet the growing demand for forest products, while safeguarding the ability of forests to provide a range of environmental services including among others, conservation of biodiversity, regulate hydrological cycle, amelioration of climate and protection of soil and water resources. Considering the overall pressure on the forests in general and also that of climate change in particular, it is imperative to adopt management strategies for improving the management effectiveness and resilience of forest ecosystems for its continued and improved deliverance of ecosystem goods and services. Adaptive management of forest resources become relevant in this context.

This paper highlights the importance of adaptive forest management in the context of climate change and recommendations for managing India's forests as a bulwark against climate change.

Impacts of climate change on forest

Human existence is inextricably linked with the goods and services provided by forests. Being a developing country, located in the warmer, tropics, India is considered highly vulnerable to climate change. Betts *et al*. (2008) pointed out that tropical forests are vulnerable to climate change and its impacts could be so severe as to threaten their structure, functionality and services. This is probably because the developing countries have limited capacity to deal with the issues related to climate change. Although, the impacts of climate variability are wide and far reaching on all facets of the physical and biological world, its impacts on forest ecosystems are particularly relevant and crucial as forests is one of the prime source of carbon sink and an important agent for mitigating the problem.

The climate change impacts on forest ecosystem are found to manifest both on species level and ecosystem level. Species are becoming rare/endangered together with their range shifts and changes in life cycle pattern, genetic trait, growth pattern etc. In critical forest ecosystems like rain forests, mangroves etc., loss of biodiversity, changing boundaries of ecosystems and other biotic and abiotic responses/stresses are being increasingly noticed. Forecasts of future impacts due to climate change predict large-scale range reduction and extinction of most species (Moritz and Agudo, 2013). Variation in precipitation and temperature are reported to be one of the key factors of climate change that is likely to have significant impacts on biodiversity (Krishnan *et al*. 2012).

Several studies have been conducted (mostly in developed countries) regarding the impacts of climate change on natural resources and forest ecosystem (Lemmen *et al.* 2008; Lemprière *et al.* 2008; Williamson *et al*. 2009 and Johnston *et al*. 2010). However, such studies specific to Indian context are fragmentary and few, except a few studies like that of Ravindranath *et al*. (2006) and Gopalakrishnan *et al*. (2011) who predicted vegetation changes and vulnerability status of the forested ecosystems in the context of climate change (IGNFA, 2016). Climate change impact on alpine forests of Uttarakhand (*Betula utilis*) revealed clear shift of tree line over the period from 1970-2006 (Singh *et al*. 2012).

According to the latest India State of the Forest Report (FSI, 2017), there has been net increase in land area of 6778 km^2 under forest cover, however on the other hand, several studies show that the quality and quantity of the forests is not rosy everywhere as there has been reports of biome shifts under scenarios of future climate change (Rasquinha and Sankaran, 2016). The climate modelling and likely impacts of climate change on forests according to India's Second National Communication to UNFCC, states that 30.6% and 45.9% forested grids under study out of the total are to become vulnerable respectively by the end of 2035 and 2085 as per AIB SRES IPCC scenario (MoEF, 2012).

Adaptive forest management

Intense pressure on forests both due to climatic and anthropogenic factors have led us to make serious rethinking on what needs to done in the changing scenario, especially on devising suitable management measures on improving the resilience of forests and dependent communities, so as to circumvent or minimize the impacts of forest degradation, resource depletion and to ensure maximum sustainable utilization of the available resources. The increasing threat from climate change impacts on the productive capacity of tropical forests need to be addressed with the principles of adaptive forest management. In spite of various managerial initiatives, the advancement in this line is restricted largely due to poor resource information, reduced institutional capacity utilization, lack of foreseeing and innovative planning and policies. Adaptive forest management is relatively a new field and only very limited studies have been addressed this so far (Ray *et al*. 2015 and Yousefpour *et al*. 2017), however this at the core of the forest management research today (Yousefpour *et al*. 2012). From tropical countries, not much information is available with regard to implementation of adaptive forest management in response to climate change (Guariguata *et al*. 2012). In India, accurate projections of climate change impact on forest ecosystems at a scale which could be useful for developmental planning, livelihood and conservation strategies are largely lacking (Devi *et al*. 2018).

Stern (2009) defines adaptation as "development in a more hostile climate". Adaptation to climate change involves monitoring and anticipating change and undertaking actions to avoid the negative consequences and take advantage of potential benefits of those changes. For individual countries, reduction in GHGs emissions will demand major changes in energy policy as well as action to augment the process of carbon sink like forest cover increase. Effective management measures to combat the changes arising out of climate variability includes various policies and attitudes of the government towards understanding and devising strategies, more research oriented towards modelling and prediction, case studies of reference conditions with which the impacts are more pronounced in ecological and socio-economic aspects and party to consensus for global agreements to protect the atmosphere. Decision making in adapting forest management involves several crucial aspects. The three pillars of the suggested framework for adaptive forest management are: (i) the baseline understanding and knowledge of the decision makers, (ii) identification and selection of appropriate management options for both current and future changes in anticipation and (iii) analysis and implementation of the correct decision strategy (Yousefpour *et al*., 2017). According to World Bank (2010), more climate-resilient development is needed. Potential adaptive management and planning must be the solution for a way forward to curb the serious implications of climate variability and related issues. Mitigation response will not reduce adverse effects of GHGs that is already in the atmosphere, but would significantly reduce the rate of growth in global warming. Therefore, along with fast mitigation responses, we require adaptation to climate change. Forest management planning provides an excellent solution for considering climate change impacts and adaptations.

It is high time to start developing adaptive management strategies now, as far as the climate change related issues in India are concerned. These include vulnerability assessment of forests to climate change, revising expectations of forest use, determining research and educational needs, development of forest policies to facilitate adaptive management, and determining when to implement responses. Government agencies should take the lead in creating an environment to foster adaptive management in forestry and in developing the necessary information required to respond.

Adaptive management should be practiced at various levels, though more often local actors may have to play a major role, as they are the ones that bear the brunt of the problem. This process involves two steps, the first being correct perception to the climate change and associated risks and the second being appropriate steps to be taken to minimize the adverse effects of climate change. Assessment of adaptive capacity of forests and its components, its dependent communities and their economy will not only help us to identify and address sources of vulnerability areas, but also useful in helping us to develop policies to enhance the adaptive management capacity of various forestry stakeholders and to assist them in identifying realistic adaptation options.

Major issues and challenges ahead

The choice of adaptation measures require complete understanding of the micro-level changes happening in the system and particularly discretion of the local managers to select the most appropriate measure suitable for their condition (IUFRO, 2009). Some of the key adaptation measures suitable to manage the climate related issues on forest ecosystems in India are as follows:

Vulnerability Identification

India's forests are the lifeline of its rural population. Pressure from unsustainable development, declining availability of forest products, inadequate access to climate friendly energy sources and absence of viable economic and social alternatives drive the rural poor and tribal communities to intense dependence on forests that often transcend the thresholds of sustainable yield. It is very important to identify the critical ecosystems/areas/species that are likely to get impacted by climate change as well as factors/processes like forest fire, grazing, insect and pests, etc., that may become more deleterious under the influence of climate change and to adopt suitable management measures for the conservation, management and sustainable utilization of the same.

Improved forest productivity and ecological services

India's forest productivity is significantly below the global average. Rapid land-use changes occurring around the forests have, at several places, resulted in fragmentation and disjoints in habitat connectivity. This is impeding the genetic flow and crippling ecosystem functionality. Besides, deterioration in site quality and second rotation decline in forest plantations have started impacting the long term performance of forest production sector. Improvement of plantation forestry by adopting silvicultural practices and by employing improved planting materials raised through tree improvement programmes/clonal technology and micro-propagation techniques may be carried out for enhancing forest productivity. A major research need is to explore and identify climate resilient plantation species and perform their new provenance trials. Identification of the tangible and intangible services provided by the forest is very important to suitably manage the forest, so that the same can continue to be ensured to its dependents in the wake of the climate change problems. Also, this will ensure to reduce the over-exploitation of forests by bringing improvement in the livelihoods of forest dependent communities.

Reclamation and rehabilitation of degraded lands by afforestation

As per an estimate, around 41 percent of India's forests have been already degraded and dense forests are slowly losing their crown density. More than 70 percent of the forests have problems in regeneration and 55 percent prone to fire. As much as 78 percent of the forest area is subjected to heavy grazing and other unregulated use (NFC, 2006; FAO, 2009). Climate change and proliferation of invasive species compound this situation. The forest land under degradation is to be reclaimed and rehabilitated under green cover to ensure its sustainable utility for future. As per ISFR (2017), 10.58% of the total geographical area of the country is open and scrub jungle, which needs suitable management measures like plantation, afforestation, assisted natural regeneration, eco-restoration, etc., to make them more productive. Strong initiatives with surplus funding needs to be ensured under various plans/from alternate sources like, Green India Mission, Clean Development Mechanism, REDD-plus etc. and the government machineries of forest management can better play a vital role in this.

Capacity building of the personnel

Capacity building related challenges include insufficient financial investment; inadequate knowledge base and technology; absence of incentive structure and extension support to farmers for agro/farm forestry etc. The capacities of field staff working at the cutting edge of the forest management require significant up-scaling to effectively manage the impacts of climate change. It is also necessary to strengthen the forest knowledge management system and use of technology, which will help in informed decision making.

Institutional factors

Current policies and practices adopted by Forest Department have its origins in the colonial era and premised largely on production forestry. This is amply reflected in the content of Working Plans too. In view of the far reaching and rapid changes occurring with regard to natural resource management, adequate and appropriate changes need to be there in forest management also. In other words, amendment to forest policy and legislation is a pre-requisite for employing adaptive forest management.

Knowledge factors

Though there is general understanding and realization on the impending impacts of climate change, there are very few specific studies on this aspect. Even when such studies are available they may not be in a user-friendly and retrievable format for the field managers for taking informed decisions. Sufficient research, especially to know the resource base and its implication in the wake of climate change scenario with clear cut objective and goals need to be planned and accomplished.

Reinvigorating livelihoods

Resilience of forest dependent communities is a critical aspect of the adaptive forest management. This is particularly relevant in India, where still a very large population reliant on forest resources for livelihoods. Unless understood and addressed the impacts of climate change could very well adversely affect the very fabric of local livelihoods and induce poverty and thus deepen the already existing vulnerability of the local communities and thereby the dependency on forestry resources.

Conclusion

Forests in India are already at stake, due to multitude of disturbances, Climate change impacts are relatively new addition to it that are likely to cause severe uncertainty in future forest ecosystem services and productivity. It is important to note that informed forest management planning in the physical and biological aspects of the forest and socio-economic aspects of the forest dependent communities for the current level of issues and future issues in anticipation, as well as development of resilient forest to climate change can only yield better results in combating the problem. Decision making in adapting forest management involves several crucial aspects. Adaptive forest management is considered to be a relatively new subject in Indian context. Our forest managers and forest management policy makers are yet to conceive the very basic idea of the principle of adaptive forest management. Moreover, the reflection of the same in national and State level forest policies require a great level of effort in terms of information, manpower and monetary resources such as grass root level understanding of the intricacies of both the magnitude and dimension of the problem, taking the appropriate decision at the correct point of time, by anticipating the future changes, capacity building of the personnel involved in decision making, developing information of the resources, which include everything related to forest and forest produce and its monitoring and evaluation, identifying the vulnerability sectors, giving timely warning of the extreme events etc. Better adaptive forest management plan and implementation of the same by the informed decision makers at the correct point of time may ensure the future sustainability of the forests and their goods and services to the people.

Summary

Climate change has become a reality and its impacts on all spheres of life, especially resilience of the forest and its products and services are far reaching. Studies conducted elsewhere have pointed out categorically that range shifts of disturbance agents both across latitude and altitude are the early warning signals and mark the onset of considerably more severe changes in future. Apart from mitigation measures, effective adaptive management strategies together with improved adaptation capacity of the forests will conjure up the aftermaths sustainably over a quite long period of time. The increasing threat from climate change impacts on the productive capacity of tropical forests need to be addressed with the principles of adaptive forest management. In spite of various managerial initiatives, the advancement in this line is restricted largely due to poor resource information, reduced institutional capacity utilization and lack of foreseeing and innovative planning and policies. Adaptive forest management is relatively a new field and only very limited study have been undertaken on this aspect so far. From tropical countries, not much information is available with regard to implementation of adaptive forest management in response to climate change. In India, accurate projections of climate change impact on forest ecosystems at a scale which could be useful for developmental planning, livelihood and conservation strategies are largely lacking. Decision making in adapting forest management involves several crucial aspects. The three pillars of the suggested framework for adaptive forest management are the baseline understanding and knowledge of the decision makers; identification and selection of appropriate

management options for both current and future changes in anticipation and analysis and implementation of the correct decision strategy. This paper highlights the importance of adaptive forest management in the context of climate change and recommendations for managing India's forests as a bulwark against climate change.

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ISSUES AND CHALLENGES IN ADAPTIVE FOREST MANAGEMENT

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Introduction

Commanding seven per cent of world's biodiversity, India is one of the 17 mega diversity countries. It supports 16 major forest types, varying from alpine pastures in the Himalayas to temperate, sub-tropical and tropical forests and mangroves of the coastal regions, having a vast variety of flora and fauna. The country's forest cover is 70.82 million ha, constituting 21.54 per cent of its geographical land area. In the history of human civilization, build-up of Green House Gases (GHGs) in the atmosphere has been phenomenal in the last century due to the very rapid pace of human development, including industrialization. The cumulative effect in the form of warming of earth and its associated fall outs will have far reaching impacts on the entire humanity.

CO_2 is among the chief constituents of the GHGs. Over the past 150 years, deforestation has contributed to an estimated 30 percent of the atmospheric build-up of CO_2 and is responsible for about 20 percent of green house gases. The redeeming feature of the forests is that as a whole, they absorb more carbon than they emit as of now. FAO estimated that the world's forests and forest soils store more than 652 giga tons of carbon – many times more than the amount found floating free in the atmosphere. It has been estimated that carbon stock of India's forests as in 2017 is 7,083 million tons. Therefore, forest has immense potential to capture atmospheric carbon and it functions as store house or carbon reservoir.

However, the problem is that, this critical carbon-regulating service of forests could be lost entirely, if the earth heats up 2.5 degree celsius or more relative to pre-industrial levels, which is expected to occur if emissions are not substantially reduced. Further, higher temperatures, along with the prolonged droughts, more intense pest invasions, and other environmental stresses that could accompany climate change, would lead to considerable forest destruction and degradation.

Vulnerability of Indian Forests

Study of climate change modeling for the period 2020-2050 and its impact on forest types of India has been undertaken by Indian Institute of Science in the four eco-sensitive regions of the country viz. the Himalayas, the Western Ghats, the Coastal region and the North-Eastern States, accounting for more than half of the country's forests. The study predicts that only one fourth of the forest grids (69 out of the total 285 studied) falling in these four regions will be vulnerable to changes in the mid period, namely by 2035 and vegetation in those grids would change type. CO^2 concentration by that period is estimated to be around 490 ppm. While the Himalayas would be more vulnerable, the Western Ghats and the Coasts are moderately vulnerable, the North Eastern states would be impacted the least. However, in the long term, it is expected that there would be large scale shifting of forest biomes throughout India. The highest impact is expected on the Teak and Sal forests of central and eastern regions and the temperate Himalayas.

Some broader and general predictions on the shift of vegetation from the current forms to entirely altered vegetation mix in various forest types across the regions of India are available. Broadly, the tropical dry forest, dry and moist savannas are projected to change to tropical dry forest and tropical moist forest. Xeric scrubland, to a smaller extent, is set to decrease in area and xeric woodland is expected to increase in the drier regions. In the colder regions, Boreal and temperate conifer coverage will decrease, while temperate deciduous and temperate evergreen coverage increases.

Mitigation and adaptation strategies in Forest management

The key issue that the forest planners and managers will face is the direction in which they have to focus their management attention. Achievement of the societal goal of sustainable forest management that aims to maintain and enhance the economic, social and environmental value of all types of forests for the benefit of present and future generations will continue to be the nation's forest sectors' primary agenda. This will call for continuous effort in minimizing the impacts of global climate change on forest ecosystems. Foresters need to focus on the climate change mitigation as a first step to minimize its impacts on forests. Hard woods particularly serve as carbon blocks, helping to lock up carbon on a permanent basis. India, having over 100 million hectares of wasteland and degraded forests, mitigation through the forest sector and afforestation seems like an attractive solution. Use of such woods is seen as an option to substitute more emission-intensive, maximum carbon foot print resources. The priority before the forest managers would be to plan and implement afforestation, reforestation and assisted natural regeneration of the forests, besides building tree assets on private lands with a view to create additional carbon sink. In this regard, research on enhancing the capacity of the forest ecosystems for carbon sequestration needs to be taken up on priority. However, using forests as carbon sinks has been a contentious issue. The fear is that it legitimize the continued destruction of old-growth and pristine forests which are rich ecosystems and have an established biodiversity base, that naturally maintains the environment.

Integrating the climate change concerns into the forest management will be the key driver in our adaptive forest management strategy. Adaptive forest management is "a forest management approach that expressly tackles the uncertainty and dynamism of complex systems". Given the prevailing uncertainty regarding ecosystem structure, function, and inter-specific interactions in a climate change scenario, precaution demands an ecosystem approach rather than single-species approach to management. This approach includes the recognition that adaptation occurs through a process of 'plan-do-review-act'. In practice, adaptive management also recognizes seven key components that should be considered for quality natural resource management practice viz. 1) Determination of scale, 2) Collection and use of knowledge, 3) Information management, 4) Monitoring and evaluation, 5) Risk management, 6) Community engagement, and 7) Opportunities for collaboration.

Adaptive forest management will be essential to address arising challenges and reduce forest vulnerability. Adaptation measures might include, for example, selection of pest-resistant or drought-tolerant varieties, use of stocks from a range of provenances, under planting of genotypes of species adapted to expected new climate conditions, or assisted natural regeneration of functional species. The measures need to be adapted to forest condition and the specific site. Forestry research will have to address these challenges.

Challenges ahead

The most important challenge to the forest managers will be to track the precise movement of vegetation in a given forest area, with reference to short term and long term time frames. As the level of GHGs is likely to gradually move up, the predicted changes with the passage of time are bound to be dynamic in nature. Such shifts in vegetation including trees would have influence on the associated lesser flora and the dependent faunal species. As these changes will occur in a more subtle manner in the larger landscapes bearing a specific forest type, the projected shift in vegetation may lead to large-scale forest dieback and loss of biodiversity, especially in the transition zones between forest types. The current temporal prescriptions in form of Working Plans for managed forests and the Management Plans for the protected areas are made for a brief tenure ranging from five to ten years with no credible weightage given to climate change forecasts. In the absence of reliable and accurate assessment of anticipated change events consequent to global warming in the spatial scale for specific forest management units like a forest division or a protected area, it would be rather difficult to suggest the most appropriate management prescriptions for the area. In this context, forest working plans, management plans and practices need to be adapted to modifications caused by climate change, both gradual and abrupt.

Conclusion

The forest management in the context of climate change has to be based on solid scientific data and reliable prediction models. It needs sound backing from research inputs. It is heartening to note that the draft National Forest Policy, 2018 lays focus on factoring in climate change concerns in all the forests/ wildlife areas working/ management plans and forward looking.

STATUS PAPER ON CLIMATE-SMART FORESTRY: RESEARCH AND MANAGEMENT

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Introduction

Forests play an important role in the economic development of a country. They provide a large variety of tangible and intangible benefits for the people at large and are prime source of livelihood for millions of poor people. Forests have close link with climatic condition of a given area. Climatic variation influence vegetation types and a changing climate over very long period had been the major reason for the present scenario of forest type distribution on earth (Oliver and Larsen, 1996). However, anthropogenic activities are causing an accelerated change in climate at present (Santer *et al.* 1996) affecting the forest vegetation, especially its structure, functions and services around the world.

While forests themselves are affected by climate change, the solution for its adverse impacts also lies in forests. Hence, over the past two decades, the mitigation potential of forests and the forest sector has been progressively included in the international climate regime. Forests, when cleared, overused, degraded or unsustainably managed, contribute to the one-sixth of global carbon emissions, while a properly managed forest sequesters and store carbon thereby mitigating the effect of greenhouse gases. Forests have the potential to absorb about one-tenth of the carbon projected to be emitted globally in the first half of this century into their biomass, soils and products and in principle, to store this carbon in perpetuity. For example, it is estimated that European Union (EU) forests and the forest sector currently produce an overall climate mitigation impact that amounts to about 13 percent of the total EU emissions. This includes both the forests and harvested wood products as a carbon sink, as well as the substitution effect of forest products for materials and bio-energy (Nabuurs *et.al.* 2015). As per estimates, the annual CO_2 removals by India's forests and tree cover is enough to neutralize 11.25 per cent of India's total GHG emissions (CO_2 equivalent) at 1994 levels and therefore, India's forests and tree cover serve as a major sink of CO_2 and a major mode of carbon mitigation (MoEF, 2009).

India is a large developing economy with 1/6th of the world population and the resource requirement of such a large population, including the fossil fuel requirement is quite substantial. Hence it is inevitable to have emission of green house gases to some extent to keep pace with development. In future, fossil fuels will remain the predominant fuel for India in 2030s, with more than 70 percent of primary energy coming from fossil based fuels (TERI, 2015). India's energy sector accounts for 71 percent of total green house gas emissions in the country. In 2013, India figured in the top three countries affected by climate risk. The country with only 2.4 percent of the world's land area, is also the home to 7-8 percent of all recorded species (UN,2018) and it has given us the onerous responsibility of biodiversity conservation in a mega-diverse country.

Climate smart forestry

Climate-smart approaches in forestry are connected with most major cross-sectoral themes of development and environment and it is expected that 'climate-smart' will become the default development approach. India has adopted a climate smart approach through its National Action Plan on Climate Change (NAPCC) which is a directional shift in the development pathway. NAPCC identified eight missions to address climate change mitigation, adaptation and knowledge management. The focus of these missions is on "promoting understanding of climate change, adaptation and mitigation, energy efficiency, and natural resource conservation". The NAPCC provides a comprehensive policy framework to address the relevant issues to tackle climate change in India, including the creation of strategic knowledge mission. It provides the framework for the various stakeholders and States to engage with the respective missions to build on, develop, expand, enable and implement the required regional and sectoral programs and strategies. This requires tremendous effort from all concerned - public sector, private sector, knowledge leaders, non-governmental organizations (NGOs), civil society and local communities, to consolidate and collaborate to enable the implementation of these Missions (Kattumuri and Ravindranath, 2016). Following NAPCC, the State level Action Plan on Climate Change (SAPCC) are being implemented by the Indian States. FAO (2018) has outlined certain key considerations for implementing a climate-smart approach to development in the forest sector and its important points are the following:

- Respond to considerable increases in global demand for wood and NWFPs in the face of climate change and other factors.
- Address specific issues related to food access and the livelihoods of forest-dependent people across the supply, value and benefit chains.
- Interact effectively with emerging technological, commercial and socially driven changes in, or associated with, the forest sector.

- Identify gaps in capacity, efficiency and system resilience in the forest sector, particularly those gaps that are likely to increase under climate stress, and develop generic or specific actions to address them.
- Identify options for strengthening the coordination of activities within the forest sector to improve, for example, the flow of goods and services, ensure efficient resource use and enhance functional resilience.
- Connect activities in the forest sector in a coherent manner with other development objectives, including hunger eradication, poverty alleviation, natural resource protection and rehabilitation, nutritional safety and health, personal and community empowerment, self-determination and vulnerability reduction.
- Ensure that responses are clearly recognizable and actionable by policy agents working effectively with practitioners and beneficiaries at all levels and are based on clear evidence of functionality and effectiveness.
- Sustainably manage forests to increase forest growth and carbon storage.
- Use forest raw materials to manufacture products as a way of storing carbon.
- Conserve forests to protect standing trees; provide ecosystem services, such as water replenishment and shelter for fauna; and sustain the livelihoods of forest-dependent indigenous peoples and local communities.
- Use forests and trees to reduce reliance on oil, coal and gas by delivering more raw materials for climate-smart products, such as bio-based fuels and timber products.

Climate smart approaches in forestry have certain distinct characteristics, particularly the significant level of socio-economic dependence of many poor and marginalized people on forests and trees. Integration of climate-smart approaches in forestry needs research on : (1) assessing the risk the climate change poses to the objectives of forest management (2) identifying the most vulnerable forest-dependent people and forest areas (3) develop management measures that would reduce their vulnerability (4) finding out source of availability of financial and technical support for undertaking adaptation measures (5) Identifying options available in the forest management unit for mitigating climate change, including cost-benefit assessment and (6) evolve management practices to achieve the specified mitigation and adaptation goals (FAO,2013).

Some of the practices suggested for adapting to the changing climate are anticipatory plantations, sanitary harvest, linking fragmented forests, planting mixed species and pest and fire management, conservation of biodiversity hotspots, managing man-animal conflict, *in situ* and *ex situ* conservation of genetic resources, adopting long term and short term adaptation policies, promoting community forestry and capacity building to develop adaptation strategies (Chaturvedi *et al.* 2010; Gupta *et al*. 2017). Management intervention might focus on strengthening adaptive capacity that enable forest ecosystem to adapt to future changes. On social front, increased resource conflict makes women and children vulnerable to changing climate. In spite of various efforts to uplift women, changing climate might put the women and weaker section of the society at a disadvantage (Nelson and Stathers, 2009).

The significance of climate variability for agricultural production indicates that the impact of variations in temperature and precipitation on Indian agriculture is an important source of information for coping with the impact of climate change on agriculture in the future (Jayaraman and Murari,2014). In this scenario, agroforestry as an alternative livelihood to the climate stressed agriculture is being seen as a viable adaptation model.

Green India Mission – opportunities for research and management

The National Mission for Green India was launched in February 2010, which is one of the eight missions under the National Action Plan on Climate Change. It was initiated to safeguard the country's biological resources and associated livelihoods against the perils of climate change recognising significant impacts of forestry on ecological sustainability, biodiversity conservation as well as food, water and livelihood security to the nation. Apart from carbon sequestration through tree planting, it envisages to achieve biodiversity enhancement, ecosystem restoration and economic security of local communities at landscape level in the context of climate change adaptation and mitigation. The mission has an objective to increase forest / tree cover in 5m ha of land and improve quality of forest cover in another 5m ha of lands. Apart from enhancing ecosystem services from 10m ha of land it also aims at improving livelihood of 3 million forest dependent households and enhances CO_2 sequestration by 50 to 60 MT in the year 2020, through a decentralized participatory approach (MoEF, 2010).

Under one of its sub mission viz. Agro-forestry and Social Forestry (increasing biomass and creating carbon sink), the mission supports participatory mode of raising quality seedlings and addressing the socio economic livelihood of the rural poor. The mission supports technology for value-added products, certification and marketing of NTFP, which would support bridging the knowledge gap. As a climate smart approach the mission allows identification of vulnerable hill slopes and to take up protection and soil/water conservation measures backed up with plantation of suitable indigenous species. The mission promotes research to understand the linkage between vegetation, groundwater and surface flows, and encourage the identifying and protecting areas of hydrological importance within the various sub-missions. Some of the key research areas includes long-term research to study vegetation response to climate change; silvicultural and management response to achieve the mission objectives; pilot adaptation projects to develop adaptation options, strategies and practices; benchmarking carbon capture potential of ecosystems and economic evaluation of ecosystem goods and services; measuring degradation within density class ranges; social and economic research etc. The scientific and technical capability of forestry research institutions including Indian Council of Forestry Research and Education (ICFRE) would be significantly enhanced for ecological research and modelling of climate change impacts, mitigation and adaptation aspects. The mission supports the strengthening of the research institutes under ICFRE and the State Forest Departments, including financial supporting for increased strength of scientists and their support staff, better infrastructure, equipment, etc.

Many of the proposed interventions are innovative and it would require collaboration of research institutions and the implementation agencies. ICFRE collaboration with academic scientific institutions of repute, both in country and overseas, joint research programs, exchange visits; capacity building etc would be strongly supported under the Mission.

The mission has setup REDD-plus cell which will have the task of creating awareness/capacity building on the REDD-plus process for all stakeholders, including the community institutions. The Cell will have multiple role in designing, formulating appropriate REDD-plus projects/strategy, propose for implementing /funding support to the designated bodies , provide technical advice on development and implementation of Monitoring Reporting and Verification (MRV) protocols and fair benefit-sharing mechanisms in the forestry sector through improved capacity and comprehensive methodology design for forest carbon inventory as per internationally and domestically agreed rules for MRV. The Mission will improve capacity of multiple stakeholders, particularly forest-dependant communities, to implement REDD Plus at decentralized levels. A majority of interventions under the Mission have potential to qualify under REDD-plus.

The mission has also endeavoured to provide innovation funds at national, State and district level Mission organizations for cross-cutting research/action research studies and initiatives by the local-level organization to try out things in consonance with the overall Mission goals and objectives. Green India Mission has landscape based approach for implementation of activities on forest and non-forest land. The criteria for identification of the landscapes include vulnerability of forests to climate change, status of forest cover, biodiversity, critical habitats, corridors, potential of area for carbon sink and socio economic criteria like poverty and ethnicity (tribal /non-tribal) etc. Green India Mission (GIM) is being implemented in some states at present namely Andhra Pradesh, Chhattisgarh, Karnataka, Kerala, Manipur, Mizoram, Odisha, Punjab and Uttrakhand. The Government has received Perspective Plans from the other States namely: Bihar, Madhya Pradesh, Jammu & Kashmir, Maharashtra, Meghalaya and Himachal Pradesh. Fresh Proposals are taken up for funding approvals subject to availability of resources and progress of previous works. The Green India Mission includes a sub-mission to enhance tree cover in 0.20 million hectare of urban and peri-Urban areas, including institutional lands. This includes support for urban greening on various categories of land including open spaces/green spaces like parks/wood lots, avenues and in households and Institutional lands belonging/allotted to business/industrial houses and educational institutions, etc. through afforestation (Rajya Sabha, 2017). Further, MoEF & CC (2014) implements an urban forestry scheme namely "Nagar Van-Udyan Yojana - *Ek Kadam Hariyaliki Or*" a programme for climate smart green cities on pilot basis to create 200 city forests in the country.

REDD-plus

Reducing emissions from deforestation and forest degradation (REDD) and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries (REDD plus) was first negotiated under the United Nations Framework Convention on Climate Change (UNFCCC) in 2005, with the objective of mitigating climate change through reducing net emissions of greenhouse gases through enhanced forest management in developing countries. At the twenty-ninth meeting of the UNFCCC Subsidiary Body for Scientific and Technological Advice in Poznan, Poland in 2008, the avoided carbon emissions from conservation of forest carbon stocks, sustainable management of forests and the enhancement of forest carbon stocks were given the same level of priority as deforestation and forest degradation and since has been referred to as REDD-plus (IGNFA, 2013).

REDD-plus is a mechanism developed by Parties to the United Nations Framework Convention on Climate Change (UNFCCC). It will become a comprehensive climate change mitigation solution, helping to reduce up to 20 percent of global carbon emissions. REDD plus creates a financial value for the carbon stored in forests by offering incentives for developing countries to reduce emissions from forested lands and invest in low-carbon paths to sustainable development. Developing countries would receive results-based payments for results-based actions. REDD+ goes beyond simply reducing deforestation and forest degradation, and includes the role of conservation, sustainable management of forests and enhancement of forest carbon.

In addition to addressing capacity building, REDD plus will identify gaps under the present forest management system. The financial incentives generated through carbon added or carbon saved will support the livelihood of communities and contribute to overall socio-economic development. The incentives received from REDD plus are to be passed on to local communities involved in protection and management of forests to ensure sustained protection of India's forests. India's submission to UNFCC (2011) states its commitment to transfer REDD plus benefits to the local, forest dependent, forest dwelling and tribal communities who are contributing towards forest conservation and enhancement of forest carbon stocks (TERI, 2013).

India's first REDD-plus pilot project by Plan Vivo in the East Khasi Hills district (Mawphlang) in Meghalaya, has been initiated in 2010. Some other pilot projects have been concluded with the help of institutions such as TERI, which carried out pilot studies in Uttarakhand, U.P., M.P., Orissa, West Bengal, Nagaland, Gujarat, and Rajasthan. ICFRE is involved in 'REDD-plus pilot project in Van Panchayats of Uttarakhand and IGNFA has also carried out a 'Pilot study on REDD-plus' in the same state. Another project on 'Partnership for Land Use Science (Forest-PLUS) funded by USAID under bilateral agreement with MoEF&CC has been implemented in four locations in H.P., Karnataka, M.P. and Sikkim in collaboration with FRI with the aim to explore methods and approaches to REDD-plus implementation.

Oppurtunities under REDD Plus

Ministry of Environment, Forest and Climate Change, Government of India has drafted a National policy on REDD-plus to provide roadmap for India's REDD-plus preparedness and lays down the broad principles for developing and implementing REDD-plus programmes in the country to enable India to gain from international REDD-plus mechanism for its pro-conservation policies and efforts and at the same time create financial incentives to local communities which are in the forefront of conservation of forests. The draft identifies that India has considerable advantage in view of scientific and technical capacity and institutional strength in respect of the 3 phases of REDD-plus, i.e. (i) Strategy Development (Readiness), (ii) Implementation and Results Based Demonstration Activities and (iii) Fully measured, reported and verified emissions reductions. India has strong forest conservation policies including progressive policies and arrangements for community participation and benefit sharing. India has robust remote sensing and forest area monitoring and reporting institutions and arrangements. Among the strategy to carryout REDD-plus, the scope of various proposed programmes viz. developing a national forest monitoring system, setting up of national REDD-plus architecture and governance, creation of a platform for stakeholder engagement, national REDD-plus information system including national Forest Carbon Accounting And Monitoring System (NFCAMS), system for managing data on valuation and equitable sharing of multiple benefits of forests. capacity building, developing institutions and technical capacity for modeling landuse change, deforestation rates, carbon stock changes and carbon sequestration rates requires consistent research input. ICFRE along with other scientific institutions and State Forest Departments have been identified to take up capacity building activities of various stakeholders (MoEF&CC, 2016).

Forest investment programme

India and five other developing countries - Brazil, the Democratic Republic of Congo, Morocco, Nepal, and Romania have joined five contributor countries Viz. Australia, Denmark, Norway, the United Kingdom, and the United States embarked on Forest Investment Programme (FIP) in a unique partnership to combat climate change through forest management. The FIP is one of the three specialized programmes of the Strategic Climate Fund under the Climate Investment Funds, which is being implemented jointly through the multilateral development banks in close collaboration with other development partners such as the United Nations and bilateral agencies. It is considered as first in a new generation of partnerships among developing and developed countries and other stakeholders which takes in to account of the need for a level playing field in addressing climate change situation (FIP,2017).

National Working Plan Code - 2014

The National Working Plan Code formulated by the MoEF&CC, Govt. of India has recognized that climate change phenomenon seriously affects and alters the distribution, type, composition, quality and mitigation potential of forests of the country, especially in the realm of anthropogenic stressors. The Working Plan Code states that, "since forest ecosystems operate on large temporal scales, long observational studies are necessary to identify the key changes". Therefore, grid based sampling has been designed to capture relevant information to cover the characteristic time scales to fully understand the impact of climate change on forests of India, so as to undertake appropriate managerial interventions.

In this context, the following research aspects need immediate attention:

Research needs

- Long term research to study response of vegetation to climate change.
- Formulating pilot projects for developing adaptation options.
- Study carbon capturing potential of various ecosystems and economic evaluation of goods and services of ecosystems.
- Understanding impact of climate change on forest degradation.
- Influence of climate change on flowering phenology, reproductive biology and pollination ecology.
- Changes in behaviour pattern of pollinators in response to climate change situation.
- Studies on social and economic impact of climate change, especially on forest dependent communities and weaker sections of the society.

- Changes in distribution pattern of endemic and threatened species in climate change scenario.
- Inter-relationship of climate change with forest fire and invasive alien species and their impact on forest ecosystem.
- Influence of climate change on forest health- epidemics caused by insect pests and diseases.
- Conventional breeding and biotechnological interventions to develop drought, salt, pest and disease tolerant trees.
- *In-situ* and *ex-situ* conservation of forest genetic resources, including RET species.

Capacity building

It is an accepted fact that forestry can play a pivotal role in modulating the climate change scenario. But, the forest managers and forest scientists in developing countries are not fully equipped with the technical knowhow to meet this challenge, so as to combat the impact of climate change on forests very effectively. Therefore, the skill up gradation of the forest managers and scientists in various aspects of climate change including practical mitigation and adaptation strategies is the need of the hour.

Infrastructural development

Action to combat climate change is directly linked to pooling of accurate meteorological data and its analysis. Most of the developing countries including India lack the state-of-the art facilities for collecting, collating and analyzing meteorological data. Therefore, it is essential that more meteorological observatories are established at strategic locations to collect climatological data and required computer facilities established for data analysis and interpretation.

Forest fire is the major cause of forest degradation in climate change situation. But, most of the State Forest Departments in India lack infrastructure and trained manpower to manage the fire incidence in the forests. So, it is high time we develop the infrastructure to combat fire and train the frontline forest staff in fire management.

Summary

Climate change has posed newer challenges in the management of forests and prioritising forest research to cater to the emerging scenario. Forests are resilient to the ever changing climate. The present day forests had been shaped over millions of years. But, the present day accelerated climate change due to anthropogenic activity does not provide sufficient time for the forests to co-evolve. World has come to understand the danger posed by the accelerated climate change the ecosystem and various efforts had been taken to mitigate and adapt to the changing climate. India has started implementing various climate smart policies and programmes like the action plans on climate change, green india mission, policy on REDD plus etc. adhering to the commitment it has provided to the international communities. The National working plan code, 2014 has incorporated the climate smart forest management to address the climate change issues. Forestry research need to respond to the challenges in implementing these policies and programmes. Capacity building, developing criteria and indicators to monitor the impact of implementation of the forests, long term observation of forest health, co-evolving mitigation and adaptation strategies are some of the research priorities. The success of the policies and the programmes shall depend on how fast we understand them and how practically we implement them. It has thrown up numerous opportunities for the forest managers and the researchers to gear up to meet the nation's commitment.

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CLIMATE SMART FORESTRY : RESEARCH AND MANAGEMENT IMPERATIVES

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Introduction

Climate Smart Forestry (CSF) is the most recent concept in the forestry lexicon. It is hardly a few years old idea (less than five years). CSF is basically an approach to support adaptation and mitigation at the regional level. It seeks to introduce climate change as a pressing issue in forest management. But, what constitutes CSF can be different for different regions. Nabuurs *et al.* (2018) contend that forests and forest sector role could be significantly strengthened through CSF. Their study builds CSF for Europe on three pillars namely reducing and / or removing greenhouse gas emissions to mitigate climate change; adapting forest management to build resilient forests; and active forest management aiming to sustainably increase the productivity and the benefits from forests. These objectives, they contend, can be achieved by tailoring policy measures and actions on the ground specific to European circumstances. Echoing slightly different concerns, FAO (2018) contends that at the global level CSF should aim at enhancing the contributions of forests and trees to food security and livelihoods; reducing the vulnerablility and increasing the resilience of forests and people; and addressing deforestation and forest degradation to help safeguard food security. FAO sees the protection of livelihoods and ensuring food security as the key constituent of CSF. The USDA (2016) treats CSF as an integral part of Climate Smart Agriculture. Their implementation plan for CSF inter alia includes extending forests by including sensitive and environmentally important private lands, expanding protected area network, planting more trees on private lands and urban areas, constructing wooden buildings etc. Their objective is to reduce national GHG emissions. Thus, CSF is different for different regions, countries and agencies depending upon their overall objectives and outlook.

What can be CSF for India?

It depends on how important are the forests for India, how vulnerable they are to the impacts of climate change and how well the forest sector can be integrated with other important sectors (say agriculture, rural development or urban development). According to the recent estimates of FSI (2018), India has about 70 million ha of forest of which about 30 million ha is of scrub land. About one fifth of India's 1.3 billion people live in or around forests and depend on forests for their livelihood. About half of this number of cattle also depend on forests for grazing. In spite of such immense biotic pressure, India has been able to manage its forests reasonably well. There has not been much forest loss in the last twently years or so. On the other hand, there has been some marginal gain in the forest and tree cover in the country. Claims and counter-claims apart about qualitative change in the forest cover. Forest sector, unlike in many other countries is not a net GHG emitter. Forest in India harour mega biodiversity. Per unit diversity of flora and fauna is much higher in tropics. The country derives immense benefits from its forests. Total annual rainfall and the lean season river flows are extremely important for agriculture, hydel power and drinking water supply to major cities. Forests also provide vast environmental and socioeconomic benefits.

Rise in temperature induced by GHG accumulated in the outer atmosphere, based on global models, is expected to be in the range of 2-3 degrees centigrade in the long run for India. There is huge uncertainty about regional climate models. As a result, we are unable to predict the impacts of climate change across the country with any degree of certainty. But, inter-annular variations in precipitation, temperature and the number of extreme events are rising. It is not uncommon to see that some parts of the country are reeling under severe drought, while other parts are experiencing heavy floods. Droughts and floods have become more frequent. Fall in winter temperature and rise in summer temperature and the resulting human deaths are on the rise. The overall trend is in line with the findings published in the IPCC reports. What impacts such weather patterns will have on the biodiversity rich tropical forest in India is not clear yet.

How vulnerable are the forests of India to climate change? In general, relative to the temperate and boreal forests, tropical forests are less vulnerable due to their rich biodiversity. Species rich ness contributes the stability of the ecosystems. Secondly, rise in the mean annual temperature due to climate change is also expected to be relatively small in the tropical regions. Obviously, there are no alarm bells ringing about the adverse impacts of climate change on Indian forests as of now. But the situation could change. A number of scholars have studied the vulnerability of Indian forests (Ravindranath *et al.* 2006; INCCA, 2010; Sharma. *et al.* 2017). Findings indicate the Himalayan forests could be most vulnerable; Western Ghats and coastal forests moderately vulnerable; and the north-eastern forests are less vulnerable. INCCA contends that climate change signatures have already begun to appear in the Indian Himalayan Region in the form of shift in the arrival of monsoon, long winter dry spells (5-6 months), increased frequency of forest fires etc. Report of the National Intelligence Council (Anon, 2009) predicts that by 2030 increased precipitation in India including monsoonal rains is likely to come in the form of fewer rainy days of extreme rainfall. Drizzle-type precipitation that replenishes soil moisture is likely to decrease. The timing may also shift, causing a drying during the late summer. Global climate change is expected to increase the likelihood of higher temperatures, reduced precipitation, and prolonged drought conditions, which exacerbate the risk of catastrophic wildfire and increased tree mortality (Chow *et al.* 2013). Such predictions are coming true.

Such impacts have implications for the forests. Moist deciduous and dry deciduous forests are already facing increased heat and moisture stress for a large part of the year. Weeds are invading forests. The number of forest fires and their intensity are increasing every year. Monsoon as well as summer flows in the rivers are declining. Forest vegetation may be already responding to such changes by way of altering their phenology, which is temperature dependent. Asynchronous changes in phenology may negatively impact some migratory species and pollinators (Horton *et al.* 2015). But it is not being monitored and therefore we have no knowledge about it. It is projected that by 2050most of the forest biomes in India will be highly vulnerable to the climate change. Changes in species-assemblage or forest types, changes in net primary productivity, possible forest die-back in the transient phase, and potential loss or change in biodiversity are expected. A clear possibility of a large-scale shift in forest types in India is protected for the period 2070 to 2100, with adverse implications for biodiversity (INCCA).

Given the present knowledge, understanding and actual experience on the ground, CSF for India could include a set of short, medium and long term measures. Short term measures should aim to reduce the climate related stress and therefore the vulnerability of forests. Medium term measure, should increase the resilience and long term measures should convert the forests into carbon sinks that can mitigate the national level GHG emissions. All of them have to be started simultaneously and must be taken to their logical conclusion in a phased manner. Short term measure should be fully in practice and must be working effectively by 2030. Thereafter, they will become a part of the forest management routine. Medium term measures should be accomplished by 2050. Long term measures should be in practice by 2100. Both forestry and climate change time lines demand such long timelines.

Over all, our approach to CSF should aim to achieve the following objectives:

i. Manage the climatic vulnerability and have the forests stocked fully to the site quality and capactiy.

ii. Conserve the local biodiversiy to the maximum extent possible.

iii. Meet the public demand for forest products, ecosystem services and protect the livelihoods of forest dependent people.

iv. Ensure sustainable forest management, and

v. Sequester the carbon emitted by other sectors in India.

The short term, medium term and long term measures are described hereunder as a set of SMART (specific, measurable, achievable, relevant and time bound) management and research imperatives for CSF:

Short term management measures

Short term measures are the urgent steps that should be taken to reduce the vulnerability of forests to the impacts of climate change and help us to conserve the forests in their present state. This is a set of 'no-regret' measure and include the following:

i. Reducing the number and intensity of forest fires.

ii. Contain the invasive alien weeds and protect the natural biodiversity.

iii. Reducing the moisture stress on dry and moist deciduous forests.

iv. Protect ecologically sensitive categories like riparian forests, mangroves, sholas, swamps, meadows etc., from any biotic interference, and

v. Establish essential infrastructure for forest management, monitoring and research.

Forest fires are common in tropical forests, particularly in the dry and moist forests. The impact of fire depends on its intensity and frequency (Ajee and Skinner, 2005; Stevens - Rumann *et al.* 2017). Climate change is exacerbating the forest fires. Traditional system of managing the forest fires is no longer adequate. It requires special fire protection plans, equipments and management arrangements (Fernandes, 2010; Chow. *et al.* 2013; Collin *et al.* 2014). An elaborate system for fire protection like permanent watch towers, forest roads, communication equipments, setting up fire protection teams etc., are required urgently. It should enable fire detection within half an hour of kindling fire and help in putting it out in the next half an hour. If not controlled within one hour, forest fires tend to become infernos leading to tremendous damage to the flora and fauna. Forest survey of India has set up a system of observing the forest fires based on satellite images and conveying the information on real time basis to the field executives. Whether this information is put to effective use needs to be verified. Weeds and forest fires are somewhat interconnected. Forest fires may bring in weeds and in turn weeds could lead to more forest fires. In the absence of natural predators, competitors and pathogens, weeds prosper and spread at the expense of native species. Dense invasive weeds diminish the seepage of rainwater into the deeper layers of the soil on one hand and reduce the fodder availability to herbivores on the other hand. It is affecting the regeneration of native trees and shrubs. Together, forest fires and weeds can deliver a body blow to the natural forests. They need to be kept under control if not eliminated altogether.

Moisture stress in dry and moist forests could be partially mitigated by systematically treating the forest lands on watershed principles. Till now, much of the watershed works were executed outside the forests. They now need to be extended the forests, which are the catchment areas for most of the rivers in the country. MGNRES could be used for this purpose. However, relaxation of rules may become necessary to implement the watershed works in interior forest areas, where there are very few habitations. Massive resources required for treating large forest areas will otherwise difficult to come by. Response of tropical forests to drought depends on crop diversity and age (Bretfeld, 2018). Younger and uniform forest crops are more susceptible because of their shallow root system. Mixed uneven aged forests are more drought tolerant because they tap sub-soil moisture in different strata of the soil. Reducing stand density (thinning the number of trees on an acre), adjusting species composition (altering the species of trees and other vegetation growing on a site), and creating mosaic forest patterns also improves forest resilience. These are some of the management options which can be exercised.

Protection of ecologically sensitive areas like mangroves, sholas, swamps, meadows etc., from any biotic interference needs no explanation. These are highly evolved ecosystems and once damaged, can't recover. They act as indicators of climate changes and biotic interference. We can't afford to lose them. They have to be given special protection. Similarly, we need considerable infrastructure like permanent weather monitoring stations, permanent preservation plots, river and stream flow gauges, a good network of roads for easy access to forest, communication towers etc. inside the forests areas without which we can't really say what has been the change in climatic parameters and what has been the impact. They have to be set up immediately. The infrastructure created should withstand future weather conditions (Horton, 2015).

Medium term management measures

Under the medium range, steps must be taken to improve the adaptive capacity and resilience of forests. These are somewhat difficult and long drawn measures. They also entail working with other stakeholders. Medium term measures include the following:

i. Converting the monoculture plantations into natural forests.

ii. Restoring degraded forests using native species.

iii. Consolidating the forest estates and minimising human interference

iv. Building resilience at landscape level, including rural and urban areas

v. Shifting the demands for forest products to private sector.

vi. Improving the livelihoods of people, and

vii. Strengthening the institutions for adaptive co-management.

Monoculture plantations may be more productive, but highly susceptible to climate change impacts, compared to the biodiversity rich native vegitation. Over the last 150 years of managed forestry in India, about 1.5 million hectares of native forests were scarified for raising plantations of exotic species. Teak is the major Indian forest plantation species. Fast growing exotics like eucalyptus, tropical pines etc., consume more resources including ground water and affect the summer discharge in the water courses. Exotics often fail to reproduce on their own, if the ecological conditions are adverse. In contrast, if the habitat is suitable, some exotics proliferate like weeds and grab the entire space for themselves (e.g. *Acacia mearnsii* in Ooty, *Acacia auriculiformis* in coastal Karnataka). Some species have adverse allelopathic effects and don't allow other species to grow underneath. Ecologically, plantations of exotics are not very desirable in the forest areas. They need to be replaced by native vegetation. About 30 million ha of open forests and 4.5 million ha of scrub forests are also available in India. These forests need to be stocked to their full capacity with native trees and shrubs. To avoid excessive cost and have better biodiversity, they can be regenerated by dibbling seed. Restoration of degraded forest has been receiving increased attention worldwide, for its low costs and ecological benefits. It is rated as far better than planting poly bagged seedlings in the long term. But, this technique is not yet standardised in India. It involves quite many nuances (Holl, 2017; Bozzano *et al,* 2014; Jalonen, 2017). Considerable research work is required on seed collection, processing, sowing and regeneration of open areas or degraded forests; if done successfully and scientifically, this single measure can hugely improve the forest in India. Although slow initially, the saplings from direct seed sowing match the growth rate of planted seedling in about a couple of decades and offer many advantages compared to planting of bagged seedlings.

Forests in India are often found as small mosaics with other land uses. It is rare to find big parcels of forest land free from biotic pressures. All available big forest areas are generally honey combed by human habitations. This problem has become very acute after the Forest Rights Act has been implemented. Human presence and anthropogenic activities have become ubiquitous inside the forest areas. Only in protected areas, particularly the tiger reserves, where people have been rehabilitated, one could see large forest areas without human presence. Resilience is influenced by the size of forest ecosystems (generally, the larger and less fragmented, the better), and by the condition and character of the surrounding landscape. (Resilience of the forest, when it is honey combed, comes down dramatically). Grazing of cattle, fire, NTFP collections and traffic flows interfere with nature. Conversely, the social cost of maintaining such remote human habitations is also quite high, but it is never aggregated and examined as the sum total. Providing basic infrastructure or delivering social services to the interior areas has never been easy. As a result, young people lose the opportunity for growth and development. They remain perpetually backward.

Slowly some people have been realising this problem and are seeking relocation. Both the forests and the forest dwellers benefit, if such people are provided acceptable level of relocation and rehabilitation facilities outside the forests. Left free from human interference, forest regenerate very quickly and will be in position of provide ecosystem services on a bigger scale in a decade or two.

Consolidating the forests alone may not be sufficient for the ecological and environmental security of all the people in the country, because the distribution of forests is quite uneven. There are many districts in the country, which hardly have any forests. But they also need ecosystem services, which can be provided by integrated development of people and their natural resources at the landscape level. Substantial green cover has to be built up on agricultural lands and in urban and peri-urban areas. Agroforestry as a sustainable land-use system is receiving wider recognition, not only in terms of agricultural sustainability, but also in issues related to biodiversity, soil and water conservation and ultimately to the climate change adaptation and mitigation (Bijalwan *et al.* 2016). We need to develop multi-functional landscapes based on adaptive co-management principles which are based on the principle of 'learning by doing' (Minang *et al.* 2015). Developing tree cover outside the forest is much more challenging than doing it inside. It needs constant interaction and support from a wide range of stakeholders who need to be convinced by way of knowledge sharing, participation and/or incentivising. Institutional mechanisms, legal instrumentalities and elaborate administrative arrangements are necessary, if developing adequate green cover outside the forests has to become a reality. It is still worth the effort, because like in the paper or plywood industry today, private sources can meet all the material requirements of wood and other forest products and leave the government forests to provide the larger ecosystem services required for the country.

Ultimately all the efforts are aimed at strengthening and improving the livelihoods of people and sustainability of institutions. Climate-smart initiatives are connected with most major crosscutting themes of development and environment. Key consideration for implementing a climate-smart approach to development in the forest sector include the neeed to connect activities in the forest sector in a coherent manner with other development objectives, vulnerability reduction, diversification of rural incomes, strengthening of local governance including participatory and community-based governance. Forest sector should work with numerous stakeholders and strengthen the livelihood of people living inside and outside the forests. Institutional mechanisms should be in place for frequent interactions, sharing the information available from different sources and co-ordinated working to ensure the well being of all.

Long term management measures

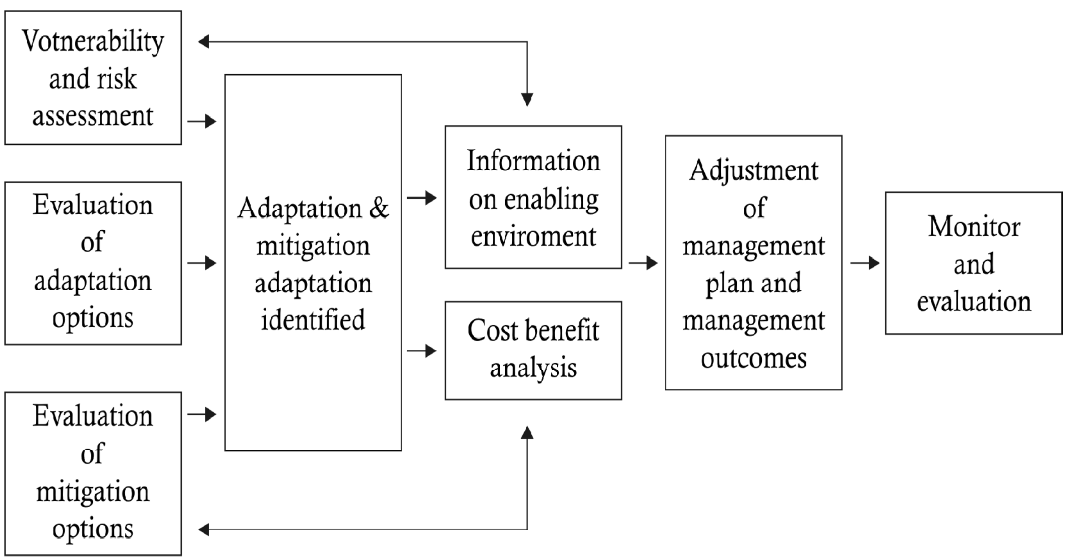
Whatever we do, it may still be inadequate to meet the CSF requirements. By the turn of this century, lot of adverse impacts are likely, which may be difficult to prevent. During this timescale, forests should be climate proofed and their potential to act as national level carbon sinks need to be explored fully. The following management activities would be necessary for this :

i. Assisted migration of flora and fauna, and

ii. Introducing payment for ecosystem services.

Left to themselves several species may go extinct due to climate change impacts. It is expected that in the decades to come, flora and fauna will shift northwards by a few kilometers and also move up in the altitude to find their new niches as an adaptation measure. This movement can be aided by human efforts while selecting the seed sources while regenerating the forests using seed zones and more hospitable climate. Considerable modelling and simulation is involved in doing this. Innovative measures like payment for ecosystems services may attract new investment and greater interest in developing, protecting and preserving green landscapes. When strictly implemented, payment for ecosystem service can generate enough revenue, not only for maintaining the forested landscapes, but also for supporting green cover outside forests.

Adaptation to climate change is an iterative process with virtually no end. FAO has captured this complex process and suggested the folowing pathways to accomplish CSF. It has to go on in endless number of cycles till the ecosystems and human societies learn to live with the changing climate.



Research needs

There are many research requirements for implementing CSF. Following are the most import research needs :

i. Establishing automatic weather stations in forest areas, collecting data regularly and analysing the climate trends.

ii. Establishing permanent preservation plots and monitoring the growth, recruitment, mortality and faunal changes.

iii. Monitoring forest fires, their frequency, intensity and studying post-fire impacts.

iv. Observe phenological changes in the forests and assessing its impact on the fauna.

v. Seed collection, processing, storage and distribution.

vi. Evolving restoration and regeneration techniques and monitoring the results, and

vii. Assessing the institutional dimensions for CSF.

It is better, if the research works are entrusted to independent third parties like ISRO, IMD, local university etc., so that the research work proceeds independently without any interruption for years and decades and statistically valid inferences become available.

Conclusion

Well-managed forests have an important role to play in realizing "Zero Net Deforestation and Forest Degradation" (ZNDD). Practices and policies needed to enhance the mitigation and adaptation potential of forests are largely encapsulated within the concept of Sustainable Forest Management (SFM). They are justified regardless of scale and size of climate change. Quite a few management practices like fire protection, weed control, improving forest cover etc., are routine. They are "no regret" options and worthy of implementation under any circumstances. Climate specific reforms like replacing monoculture plantations, change over to restoration practices, consolidating the forests, developing tree cover outside and shifting the demands to private sector require decades of efforts. Observing changes in weather patterns, assisting in the migration of flora and fauna, introducting payment of ecosystem services and strengthening the institutions and livelihoods of people require still longer time scales. Collectively, they constitute the CSF measures. Implementing them with zeal can take us to a stage where our national GHG emissions can be sequestered by our forests and no one else is required to bear that burden. That is the epitome of CSF. Tropical forests have high carbon sequestration potential and it may well be possible to accomplish this. Maintaining nature's capacity to buffer the impacts of climate change is often less costly than having to replace lost ecosystem functions by heavy infrastructure or technology. Ecological infrastructure can often be more adaptive than engineered infrastructure. Therefore, we should take the easy and more friendly CSF approach to manage theclimate change related risks.

Summary

This article examines the origin of the concept of "Climate Smart Forestry" and examines its scope in the Indian context. It briefly dwells on the vulnerability of Indian forests to climate change. The scope of CSF is examined in the Indian context. A three-pronged approach to CSF is suggested. In the first phase, vulnerability of the forests is to be contained. In the second phase, forests should be enabled to adapt and become resilient to the impacts of climate change. In the last and final phase, permanent measures to climate proof forests is suggested. All the phases can start as soon as possible, but should be in place and working effectively. Time line suggested for first phase is 2030, second phase is 2050 and the last phase is 2100. Most of the measures suggested broadly fall into the concept of Sustainable Forest Management. The ultimate objective to achieve is zero net degradation and deforestation and forest being able to sequester the carbon emitted by other sectors at the national level. That is stated as the final goal of CSF.

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SMART FORESTS: RESEARCH AND MANAGEMENT

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Introduction

Smart Forests are those that are managed on sound principles of silvilcultural management tools and techniques to promote biodiversity and ecological stability of a given landscape, which are highly resistant to climate change impacts. This concept is developed and implemented to promote the best forest management practices to insulate forests from climate change impacts.

The climate change projections carried out by different agencies under different scenarios of GHG emission have shown that, the forests will be impacted considerably due to rise in temperature and consequent changes in the rainfall pattern in India. The forests in India are highly vulnerable for the changes in the climate, in the regions that are projected to experience either excess or deficit rainfall.

High-resolution climate change scenarios for India using PRECIS , has shown that, there will be 20% increase in the south west and north-east rainfall in future scenarios. The model also predicts increase in rainfall in all the States, except Rajasthan, Punjab and Tamil Nadu.

The excess rainfall in Southern part of India will impact the Teak forests in Kerala and Tamil Nadu affecting growth, regeneration and other associated ecological functions.

Similarly, it is also projected that Central India may experience deficit rainfall affecting the Sal regeneration and associated bamboo growth and regeneration.

Himalayan regions are projected to experience again rise in temperature, which will make the lower elevation species to migrate upwards towards cooler regions. Some studies have indicated that, the Sal forests are expanding towards higher elevation due to change in the temperature and rainfall regimes in the north-eastern states of India.

Similarly, it is reported that the lower elevation Himalayan species like *Abies pindrow* and *Pinus walichiana,* changing their ecological niche and moving upwards into higher elevation. The species *Pinus gerardiana* is also found occupying higher elevations.

Shola forests are enlarging. Due to change in the rainfall pattern and temperature regimes, it is found that Shola forests of the Western Ghats getting expanded towards lower elevations.

In view of these projections, the Foresters have to initiate smart actions to insulate these forests from climate change impacts. Some of the measures include, anticipatory planting, silvicultural interventions to promote the species mix that withstand the climate change impacts and host of other such measures.

The following are some of the strategies to be adopted to develop forests that are resistant to impacts of climate change and make them more adaptive through enhanced plasticity of biological response:

Strategies to develop Smart Forests

i) **Reduction of emission from the forest ecosystem**: Forests are considered as the source of GHG emissions, due to decaying, fire and other biotic interferences which need to be reduced with better management strategies.

ii) **Fire control and fire resistant species planting**: Fire is a major disturbance factor that damages the forest structure and functions, depending on the intensity of fire occurrence. The fire affected forests fail to maintain the normal ecological services and contribute for higher emission rates, leading to global warming.

iii) **Assisted migration of species to higher elevations**: The climate change in the temperate forests is found to promote the migration of species to higher elevations. The forest managers can assist the migration of species in higher elevations by taking appropriate silviculural decisions.

iv) **Assisted anticipatory regeneration**: At landscape level, in order to accomplish the species movement across different elevations and micro-climatic conditions, the forest managers can identify the suitable sites for the threatened species and accordingly promote the regeneration across the landscapes so as to balance the population size.

v) **Harvesting cycles of NTFP:** In Tropical forests, where the community dependency is large on the non-timber forest products, the forest managers can develop sustainable forest management and harvesting practices, that can support the communities.

vi) **Innovative approach:** To ensure smart forest management, the innovative management approaches are to be found through long term and short term research programs to implement best management practices, that enhances the multi=function capability of smart forests.

vii) **Ecosystem service based management:** Most of the forest ecosystems are managed for single or few management objectives. However, we must develop multifunctional and multiple objectives based management systems to safeguard and enhance the ecosystem services.

viii) **Smart forest inventory tools and methods:** Using the advanced technology, the forest inventory including boundary fixing, monitoring crown density, canopy monitoring and individual trees management can be done, to ensure the forest are best managed to provide the highest ecosystem services.

Research areas for smart forest management

Some of the research areas indentified for smart forest management are as follows:

1. *Canopy research of high forests*: We do not have any research data or information on the canopy ecosystem interactions and associations of plant and animal community.

2. *Inventory of trees and stand structure*: Information on the stand models, tree growth, regeneration and mortality of the stand can be measured and models can be developed to predict the performance of smart forests under different scenarios.

3. Ecosystem value, and ecosystem services are to be modeled and projected for multifunction's under different scenarios.

4. Fire impact studies and fire management models are to developed and fire management maps are to be prepared.

5. Carbon flux monitoring and other gaseous exchange related studies are to be initiated.

6. Genome mapping, genetic frequency, and other reproductive biology studies are to be initiated in the climate change context.

7. Research programs to monitor changes in the vegetation, in context of climate change.

8. Studies on water regime in different projected climate change impacted areas in both scenarios to be undertaken and appropriate mitigation measures to be developed.

9. Studies on the impact of climate change on livelihood especially that of forest dependent communities.

PROMOTING GREEN COVER THROUGH VALUE ADDITION TECHNOLOGIES FOR NON-TRADITIONAL MATERIALS FOR WOOD BASED INDUSTRIES

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Introduction

After cement and steel, plywood panel and wood processing industries are the third most important contributors to the housing sector. According to FIPPI, there are about 62 large and medium size plywood mills and over 2500 SSI units, out of which more than 1000 of these are located in States of Haryana, Punjab, Uttaranchal and Western part of the Uttar Pradesh, which operate based on the plantation wood like poplar, and eucalyptus grown by the farmers under agroforestry system. With the R&D backup received from IPIRTI and other Institutes, wood based industries are now in a position to produce speciality value added panel products such as shuttering and marine plywood, pre-laminated particle board and Medium Density Fibreboard (MDF), laminated veneer lumber, moulded skin doors, bamboo composites, finger jointed and edge laminated timber, in addition to general purpose plywood, block board and flush door as per national and international standards.

However, the plywood and panel industry, which is by and large an agroforestry based industry, have been totally deprived of Government support. The main problem faced by the industry is raw material availability. The gap between demand and supply is also widening.

Indian wood processing industry is currently undergoing major structural changes with a gradual switch from the production of timber products using large diameter trees to those utilizing smaller diameter from second cuts, as well as moving towards plantations and the estate sector. Product diversity has increased. Rubber wood, poplar, eucalyptus and silver oak are used as raw material in wood-based panel industry. With the technological advancement in finger jointing and edge lamination techniques short length plantation timbers are finding extensive use in making joinery and furniture.

While India's use of particle board and MDF board still remains modest by Asian standards, a recent upswing in the economy and Govt. forecasts, predicted economic growth would bring about changes in future. There is 7% growth annually in utilization of particle board and MDF and likely to rise as Indian architects and furniture manufacturers has to choose more modern materials rather than to stick to their traditional material like plywood.

MDF has emerged as price competitive alternatives to the more traditional products such as plywood, particleboard and hardboard for certain applications. Their greatest advantage is that low quality and low value raw materials (including non-wood fibres) can be turned into high value and high quality wood-panels. Because of the desirable and user-friendly physical properties and favourable machining properties, MDF has a variety of end-uses and can replace tropical hardwood timbers for furniture. In addition, it is marketed as an environmentally friendly product, which relies on sustainable resources. Technologies for manufacture of panel products from Agro/ forest residues like baggase, rice husk, bamboo, coir, cotton stalk, etc. are available from reputed Institutes like IPIRTI, ICFRE and other similar organizations. Bamboo mat board is becoming an alternative to plywood, especially in the lower thickness range. Bamboo mat corrugated sheet has become an alternative to asbestos, cement sheet for roofing.

Another composite wood technology which has recently emerged has opened up opportunities for the production of high quality stable wooden sections from relatively inferior quality wood raw material. Laminated Veneer Lumbar (LVL) described as glued laminated veneer, similar to solid wood sections. Most of the plantation species can be converted to reasonably good quality veneer, which can be further converted into LVL suitable for applications like structural components (I &WEB Girders), door and window frames, rails and stiles in flush door manufacture, bent wood furniture components and many other uses. LVL from rubber wood is being produced in the country on a limited scale.

Alternative raw material sources

The option left for wood based industries for sustainable supply of wood raw material are (i). Raising of the plantations in areas outside forest which facilitates reduction of pressure on natural forest. Hence plantation forestry should be considered as a major option for sustained availability of timber. In this context, wood based industry should join hands with Govt of India to encourage agro/farm forestry which will not only help in increasing forest / tree cover but also enable to get required raw material on a sustainable basis. (ii). Utilization of agro / forest residues as wood substitutes. India is rich in agro / forest residues, which are not put in to proper use. Conversion of these residues in to panel products will not only help in value addition but also keep environment clean. Technological intervention with regard to its economic viability and commercial adoption is the need of hour .

India is a vast country with large stretches fertile area under agricultural and forests to generate enough lignocellulosic materials, which can be processed to panel and other component for substitution of wood and wood products. The main source of these materials is non timber forest products.

Agricultural residues

The range of wood based panels produced in the country has grown considerably during the last two decades of which plywood and particle/fibre boards constitute the major share. Various strategies identified to meet raw material shortfall for wood panel industries are improvements in conversion techniques, worker training, and utilization of non-wood raw materials and in the long term plantation of fast growing timber species. In the above context, utilization of forest and agro-residues for manufacturing particle board suitable for use under tropical climates assumes significance.

The greatest obstacle to increase the utilization of non-wood fibres is the problem of the collection and storage and lack of suitable equipments for the purpose. There are also problem with materials, which are available in sufficient quantities on site, but not used because of technical instability for alternative use consideration or both. Table-1 gives estimated availability of some non –wood lignocellulosic material in India.

Table 1. Availability of Non-Wood Lignocellulosic Material

Sl. No.	Particulars	Tones / annum (in millions)
1.	Bamboo	4.5
2.	Rice Straw	18.0
3.	Wheat Strew	73.5
4.	Rice Husk	20.0
5.	Coconut Husk	37.5
6.	Cotton Stalk	4.4
7.	Bagasse	6.0
8.	Pine Needles	2.7
9.	Non edible gras	170.0

Major non-timber forest products/agricultural products and their industrial processing

a. **Bamboo:** Bamboo is rightly called the “Green Gold” as it has immense potential for large scale value additions into plethora of panel, products, which can become game-changer for challenged and backward economies. In this direction, significant Research & Development (R&D) efforts have already been made at the Indian Plywood Industry Research & Training Institute (IPIRTI), Bangalore, which led to innovation of several bamboo composite products which can be broadly categorized into (1) Bamboo mat based products; (2) bamboo strip based products; (3) bamboo lumber-based products, apart from primary bamboo processing and bamboo housing and other applications.

1. A range of bamboo mat based products are developed, which are mainly Bamboo Mat Board (BMB), Bamboo Mat Veneer Composite (BMVC), Bamboo Mat Corrugated Sheet (BMCS), Bamboo Mat Ridge Cap (BMRC), Bamboo Mat Moulded Skin Board (BMMSB) etc. The Bamboo Mat Board (BMB) technology was commercialised in the 1985 in Angamally, Kerala, which is still under manufacture. Subsequently, the BMCS technology was commercialised in the year 2002 in Byrnihat Megahlaya. Such value added bamboo products can contribute significantly in reducing energy consumption and carbon footprints by cutting down on non-renewable building materials viz. steel, concrete, aluminium etc.

2. Bamboo strip based products are so designed to behave like solid wood in properties and applications. The products have applications as flooring material as well as in furniture manufacture. IPIRTI has innovated several strip based bamboo products such as Bamboo Vertical Laminate; Bamboo Horizontal Laminate; Bamboo Floor Tiles and Bamboo Flattened Board. Commercial production of bamboo strip based products started in 2011 in Kozhikode, Kerala.

3. Bamboo lumber based products are the third generation advance bamboo composites with potential to replace costly tropical hardwood such as teak for flooring and other applications. Commercial production of bamboo lumber started in 2015 in Agartala, Tripura.

4. Primary processing mainly includes cross cutting, knot removal, splitting, strip making, sliver making, besides seasoning and chemical preservative treatment. These processes have been done by hand for many generations. However, for making quality bamboo mat and for further processing into industrial products, one of the important concerns is the uniform thickness of slivers and the thickness at the knot portions. To get good quality, sliver process has been streamlined at IPIRTI.

5. IPIRTI has the expertise for the use of bamboo composites in prefabricated structures as well as developing low-cost earth quake resistant Bamboo-based IPIRTI-TRADA houses. Technologies are also available for bamboo particleboards, bamboo veneers etc.

It may be argued that bamboo is no longer a poor man's timber due to its versatility and scope of utilization. India has started changing this concept by utilizing bamboo as raw material for value added products, like replacing timber with bamboo products for industrial use and floor boards etc. which has great demand as a substitute for timber. On a commercial scale, these products can cater to the growing markets of India and rest of the globe and have the potential to play a stellar role of game-changer for the challenged and backward economy of Bamboo-rich areas - especially the North East Region (NER) of India.

b. **Rice husk*:*** Among all the agricultural residues, the most abundantly available material is rice husk. It is the by product of the most important agro-based industry in the country, namely paddy milling. Rice husk is available in the country to the extent of 20 million tons per annum. With increasing population and more improved methods of cultivation, still larger quantities of rice husk will become available. Research work to find ways and means to utilize rice husk for the production of useful materials has been underway for the past three decades or so. However, because of its unique chemical composition, not many successful methods have been evolved. Of all the methods of utilization of rice husk developed so far, manufacture of boards by the admixture of suitable binding agents is undoubtedly the best method from the point of view of both value added and the complete utilization of the husk without any further secondary by-products.

c. **Coconut husk:** India is one of the largest coconut growing countries with an annual production of about 6000 million nuts. The husk of a coconut weighs about 0.3 kg. The coarse and fine fibres are 30-43% by weight of the husk and the dust 57-70%. Out of the total husk available from coconuts only 50% is being utilized by the coir industry. Even if 10% of the remaining husk is converted into particle board, the production would be around 7 million sq/cm/yr of density 640 kg/m3 (19 mm thickness).

d. **Coconut coir wastes:** The coir fibre is extracted from coconut husk by the natural retting process and by mechanical decortications. It is a tough, strong, resilient and durable material. The bulk density of the fibre is between 0.25-0.5 g/cm 3 depending on the compactness. The use of these waste materials for building boards has been investigated by several researchers.

e. **Coconut coir pith:** The husk of mature coconut consists of numerous fibres embedded, in a soft cork like ground tissue usually referred to as pith. The bulk density of air dried pith is about 11042 kg/m 3. It is made up of pectins, tannins and other water soluble substances and hemi cellulose. Particle boards, insulation boards and hard boards have been successfully made with and without the use of binders.

f. **Arecanut husk:** Boards are made using the Asplund process and treating them with an alkali prior to forming to reduce moisture absorption and swelling. Asplund process consists of pre-disintegration of the material - soaking in cold water screening and washing of the pulp-formation, felt like sheets-pressing at 1000°C and 35 to 70 kg/m^2 pressure-driving and conditioning. The amount of husk available in country is roughly 75,000 tons per annum.

g. **Cotton stalks:** India has the largest area under cotton, accounting for one fourth of world's area under cotton cultivation. The estimated yield of residue is 4.4 million tones per annum. The stalks are cellulose: 42.7%, lignin: 25.1%, pentosans: 12.3%, moisture: 13.7%, benzene alcohol: 3.4%, and ash: 2.3%. The first cotton stalk based MDF plant in the world with an installed capacity of 39000 tones/ annum was established in India. However, due to poor market acceptance, high cost harvesting and transport and little technology back up, this product could not stand in the market.

h. **Bagasse:** This waste in sugarcane processing consists partly of delignified cells and partly parenchymatic pith. The presence of pith as an unfavorable effect, because it contains 33-38% pith. Since the pith is hygroscopic, the panels made out of it will acquire high thickness swelling absorb water and also decreases values of mechanical properties. To eliminate the pith, the diffusion process is adopted in which a large part of the pith gets separated from the fibre through disintegration process. After depithing, it is advisable to add fungicide and termiticide. The technology for manufacture of panel product from bagasse is well established in India and FRI has done commendable work in this line. Even a particle board factory had been established in UP, based on bagasse as raw material and was producing excellent product, but could not sustain for a longer period. Some of the problems faced by the industry are: The duration of sugar crushing season varies from year to year and therefore availability of mill run bagasse drops to 4-5 months in a year. Total area required for storage of mill run bagasse, depithed bagasse and pith at the peak loading level for 1100 TPA factory is 12,000 sq.m. Such a large storage area and subsequent movement of material is a serious problem. There is significant quality variation in respect of moisture content, silica content and fibre structure between materials obtained from different mills. Maintenance of consistent quality of the product is therefore difficult.

Technological Innovations

R.& D efforts should be made in selecting genetically screened and siliviculturally managed tree species, which can produce more volume of wood with desired properties. Technology should develop to reduce wastage of wood and process parameters should be the top priority for getting required inputs. Technology should be developed which are economically and commercially viable.

With the technological innovation, the constraints mentioned above have been addressed with respect to both technology and machineries, based on the new findings i.e. Eco-board in Maharastra has been successful in producing particle board from bagasse and market acceptance of the product is encouraging. In addition, Bajaj Eco-Tech Products Limited [BEPL], and other companies has planned to produce Medium Density Fibre Board [MDF], High Density Fibre Board [HDF] and Particle Board [PB] based on agro-residues. One company in Madhya Pradesh and Centrury Plywood Industries Ltd. are also planning to set up MDF plants based on bamboo.

Conclusion

- More use of non-traditional resources and application of green technologies will go a long way in tackling the problems of global warming and climate change mitigation.
- Importance of development of high value added products from low value resources (planation wood, agro-residues and bamboo) is increasing due to dwindling wood resources and increasing demand for the wood products.
- Development of indigenous technologies may reduce import of similar products and minimizes the production cost.
- Utilization of agro-wastes/forest residues not only have potential to generate additional income to farmers, but also reduces pressure on national forests and minimize air-pollution due to burning of crop-residues.
- Bamboo cultivation outside forest and application of value added technologies for bamboo may be a game changer to transform socio-economically challenged areas of the country such as NER, Chattisgarh, Orissa etc.

USING RESILIENCE CONCEPTS TO INVESTIGATE AND MITIGATE THE IMPACTS OF LINEAR INFRASTRUCTURES ON FORESTS

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Introduction

The tropical dry deciduous forests and associated sub-types of the Peninsular India were inscribed by Meher-Homji (1977) on the basis of structure, composition, floristic elements, bio-climatic conditions and palaeoecology. The tropical dry deciduous forests of the Peninsula are divided predominantly into three sub types such as, teak (*Tectona grandis*), sal (*Shorea robusta*) and the miscellaneous containing neither of teak or sal as dominants. The miscellaneous forests constitute species such as *Anogeissus latifolia*, *Terminalia tomentosa* and *Cleistanthus collinus*. The dry deciduous teak forest occurs within the limit of 700 mm to 2000 mm of annual average precipitation with a dry season of 8 months. The sal type extends from 1200 mm to over 2000 mm with a dry season of 6-7 months.

Railway corridors

Government of India has signed a Memorandum of Understanding (MoU) with the State of Chhattisgarh for improving critical freight and passenger transportation. Two railway lines of approximately 234 km is proposed under a joint venture of Chhattisgarh State Government (CERL and CEWRL), South East Central Railway (SECR) and South Eastern Coalfields Limited (SECL).

East Corridor - *Chhattisgarh East Railway Limited (CERL)*

The east corridor rail project connecting Kharsia to Dharamjaigarh is 102 Km long with a spur between Gharghora to Dhange Mahua. The corridor passes through several patches of revenue forest and Protected forest/Reserve forest/Orange forest area of Raigarh and Dharamjaigarh Forest Divisions of Chhattisgarh. There are records of presence of animals like sloth bear, spotted deer, wild pigs, elephants, common langurs, various species of birds and butterflies in the proposed forest area. An important aspect of this project is about an elephant migration route, which is adjacent to the proposed rail line towards Dharamjaigarh.

East-West Corridor *- Chhattisgarh East West Railway Limited (CEWRL)*

The east-west corridor rail project connecting Gevra road to Pendra road is about 134 Km long. The forest areas falling in both projects are mainly revenue forest along with patches of Protected, Reserved and Village forest. The projects will involve diversion of 535 ha of forest land. The corridor between Gevra road and Pendra road too passes through several patches of revenue forest and reserved forest area of Katghora and Pendra road Forest Divisions. There are records of presence of animals like sloth bear, spotted deer, wild pigs, common langurs, various species of birds and butterflies in the proposed forest area.

Impacts of linear clearings

Forest fragmentation caused by clearing for rural and urban purposes is recognised globally as one of the major threats to tropical forests (Laurance *et al.* 1998). Ecological impacts of roads, railways and other linear clearings have been identified in habitats ranging from temperate forests through grassland to desert (Trombulak and Frissell 2000; Spellerberg 2002; Forman et al. 2003). This paper discusses their applicability to tropical deciduous forests and the potential of several measures designed to investigate and mitigate the impacts. Although Winter (1991) pointed out that clearings for linear infrastructure are relatively minor in the context of clear-felling for forestry or rural or urban usage, often the extent of the linear clearing network results in relatively large areas of habitat being lost within, otherwise natural areas.

For example, in the two railway corridor projects of the State of Chhattisgarh i.e. CERL (Chhattisgarh East Railway Limited) and CEWRL (Chhattisgarh East West Railway Limited), approximately 535 ha of forest area has been identified for diversion

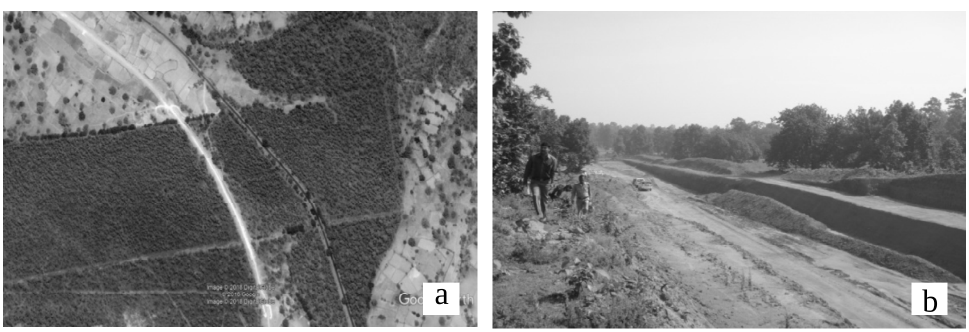

Fig. 1. (a) Google image of a continuous patch of forest dissected by road and railway lines in Dharamjaigarh, Chhatisgarh. (b) Linear clearings: as evident in case of a proposed railway line in Dharamjaigarh, Chhattisgarh

in 236 km of railway line. However, the area of forest habitat in its 10 km buffer affected by linear clearings may be much larger than the actual clearing footprint due to edge effects and other disturbance impacts that penetrate the forest to varying distances.

Vegetation and faunal communities

Alterations in microclimate, vegetation structure and floristics lead to changes in habitats for both flora and fauna. Forest canopies closer to linear clearing are disturbed leading to increases in species linked with disturbance, including weeds and invasive. Linear clearings also lead to edge effects that comprise biophysical changes between natural habitat and clearings. The type of surrounding habitat influence changes in faunal community composition. Newly regenerating species next to the edge will provide greater potential for generalist species to colonise and may also reduce edge avoidance by specialists. Changes in species composition due to these habitat alterations may also have consequences for ecological services and processes such as pollination, dispersal, competition or predation (Murcia 1995).

Here, in the case of railway projects of Chhattisgarh, majority of forest areas are of moderately dense with small patches of scrub and very dense forest. The forest type prevailing in the area as per the Champion and Seth Classification (1968) is of Northern Dry Mixed Deciduous Forest (5B/C2), Southern Moist Mixed Deciduous Forest(3B/C2), Dry Peninsular Sal Forest (5B/C1c), Dry Bamboo Brakes (5/E9) and a few patches of Dry Deciduous Scrub Forest (5/DS1) types.

Shorea robusta dominates the tree layer and has access to majority of the available resources. The other associates are sparsely distributed in the community. It can be said that the distribution of other species in the community is largely regulated by

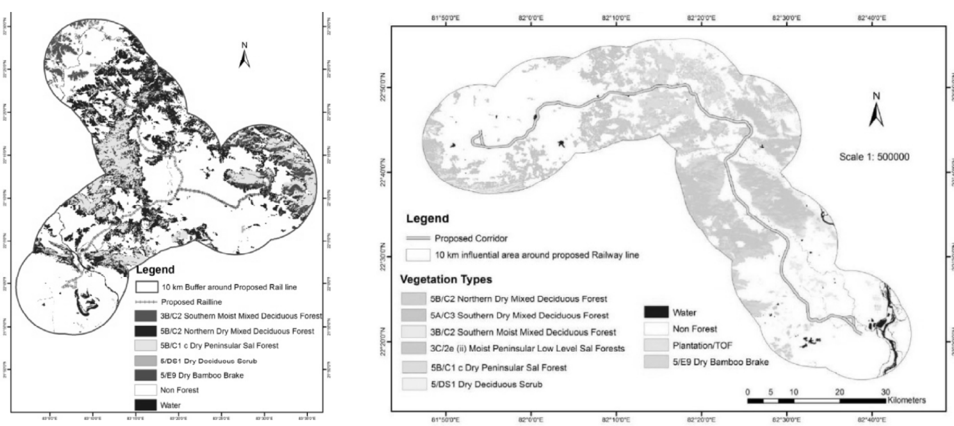

Fig. 2. Vegetation types within 10 Km buffer zone of influence of the proposed railway lines as per Champion & Seth, 1968

the density of dominant species. The phytosociological studies conducted in the project areas show that the community has *Buchanania lanzan* and *Madhuca indica* as codominants. *Terminalia tomentosa*, *Pterocarpus marsupium*, *Tectona grandis* and *Anogeissus latifolia* were the common tree associates in the community, while *Butea monosperma, Schleichera oleosa* and *Diospyros melanoxylon* were encountered occasionally. The forest community showed a typical composition of Central Indian Sal Forest.

Linear clearings have an impact on faunal composition at the edges as well as forest interior. Changes in small mammal community composition at the edge have been demonstrated in some of the studies. It also affects large mammals such as elephants. The project area of East Corridor has been mapped as moderately suitable to highly suitable for elephant (Fig. 3) based on Elephant Habitat Suitability (Areendran *et al*. 2011). The proposed elephant corridor and migration route based on the Elephant Habitat Suitability falls in the project area.

The flora and fauna of the surrounding area will be disturbed due to fragmentation caused by the rail line and more damages to fauna of the area could be witnessed, once the rail line becomes operational. It could create barriers to elephant movement that will subdivide its populations. Linear infrastructure such as railways reduces access to vital habitats for a variety of wildlife species, including elephants.

Aquatic life

The impact of altered habitat can extend well beyond the cleared areas, if the railway tracks are constructed near streams. It can lead to erosion, sedimentation, altered flow patterns and channelisation, with consequent upstream and downstream

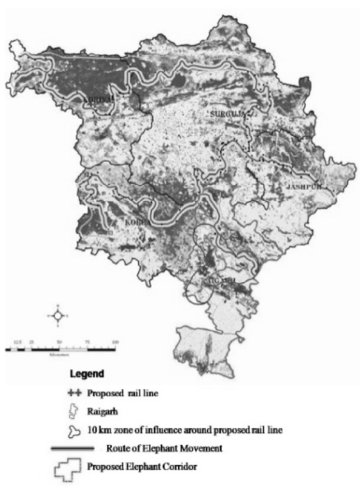

Fig. 3. Proposed elephant corridors based on Elephant Habitat Suitability (Areendran *et al.* 2011) near Kharsia - Dharamjaigarh Railway lines

impacts on aquatic life. Streams may also be polluted during the construction stage, due to contaminants from vehicle emissions, lubricants, trucks and bulldozers. The degree to which these contaminants enter streams may or may not be low, but it remains currently unexamined.

In case of the two proposed railway corridors of Chhattisgarh, the Maand River and the Hasdeo River constitute the main drainage systems of the Kharsia - Dharamjaigarh (East Corridor) and Gevra – Pendra (East-West Corridor) respectively. The drainage pattern existing in the area is mostly dendritic in nature. The streams and channels within 10 Km of the proposed railway line is shown in Fig. 4.

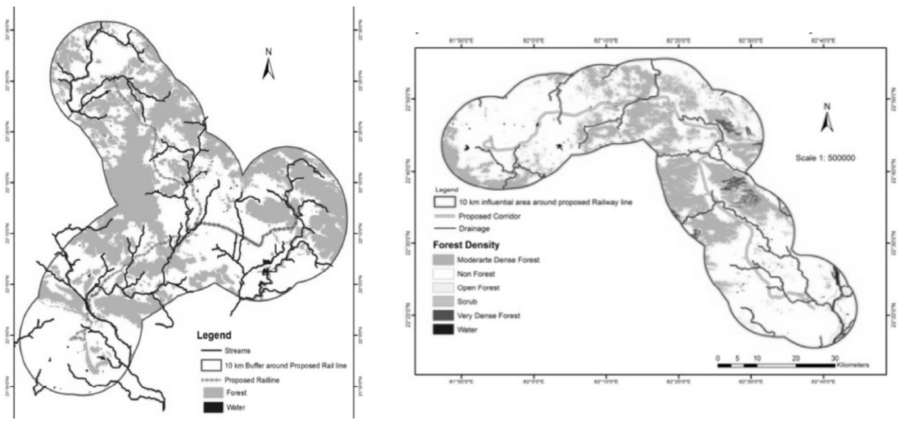

Fig. 4. Map showing important streams and channels within the 10 km zone of influence in both railway corridors

In order to ensure water availability to flora and fauna during scarcity, soil and moisture conservation measures were recommended in channels most affected with the erosion and gullies formation. For habitat improvement from water availability perspective, around 536 locations in both corridors have been identified by CG Forest Department.

Table 1. Number of identified locations for catchment area treatment

East Corridor		East West Corridor	
Forest Divisions	Locations	Forest Divisions	Locations
Dharamjaigarh	135	Karghora	135
Korba	95	Marwahi	85
Raigarh	86		
Total	316	Total	220

Linear barrier effects

Linear clearings create substantial barriers to many wildlife species. Physical barriers such as fences and concrete structures also prevent animals crossing linear clearings and may increase this barrier effect. If such barriers result in complete subdivision of animal populations, demographic and genetic problems for the species may arise. If individuals are unable to cross the barrier, populations on either side tend to reduce to smaller size, less viable and therefore more likely to become locally extinct from reproductive failure, predation, disease or an unexpected catastrophe (Shaffer, 1981).

There is less opportunity for individuals from a population on the other side of the linear clearing to recolonise the area after a population decline. Long-term isolation can also result in the negative effects of inbreeding. Overall, linear clearings reduce landscape connectivity through restricting movements of many animal species.

Mitigation and management of linear clearing impacts for fauna

This section discusses about some of the mitigation strategies that we suggested within the ambit of wildlife conservation plans that fall in line with the key principles of resilience concept.

Reducing habitat loss and managing connectivity

The first principle to mitigate impacts of linear clearings through forested areas would be to simply avoid sensitive habitat at the planning stage. Ideally, some routes could be re-routed or not built. Unfortunately, in many cases this solution is impractical. Due to the need for infrastructural, economic and social development, many such projects are fast tracked and implementation is ensured. The upcoming railway corridor projects of Chhattisgarh are meant to boost the industrial infrastructure in Chhattisgarh, a State with large tribal population and infested with left wing insurgents. Therefore, such projects often cannot avoid sensitive forest habitats. Continuing expansion of human populations and increasing requirements for transport and energy infrastructure are the driving forces behind infrastructure upgradation of the State and are only likely to escalate.

In these railway projects, environmental protection in terms of protection of forests and landscape connectivity emerges as one of the major design principles that could only be addressed with engineering options.

Connectivity can be both a good and a bad thing. Well-connected systems can recover from disturbances more quickly, but overly connected systems may lead to rapid spread of disturbances. Perhaps the most positive effect of landscape connectivity is that it can contribute to the maintenance of biodiversity.

Over passes and under passes

Managing forest connectivity under or above railway tracks can be aided by fauna-sensitive engineering designs. Bridges over creeks and gullies at heights that allow canopy to remain under the bridge will allow movements of canopy, understorey and ground-dwelling fauna.

Fig. 5. (a) A over pass designed for wildlife crossing in the Pench-Kanha Corridor
(b) A culvert designed for movement of smaller fauna

In case of these railway projects, we recommended construction of over and under passes for facilitating wildlife movements. The guidelines formulated by Wildlife Institute of India (WIF 2016) titled "Eco-friendly measures to mitigate impacts of linear infrastructure on wildlife was referred for the technical specifications of size and dimensions for under/over passes. A total of 6 over/under passes are planned in East Corridor and 8 underpasses are going to come up in East West Corridor. This would be in addition to many land bridges that are already designed.

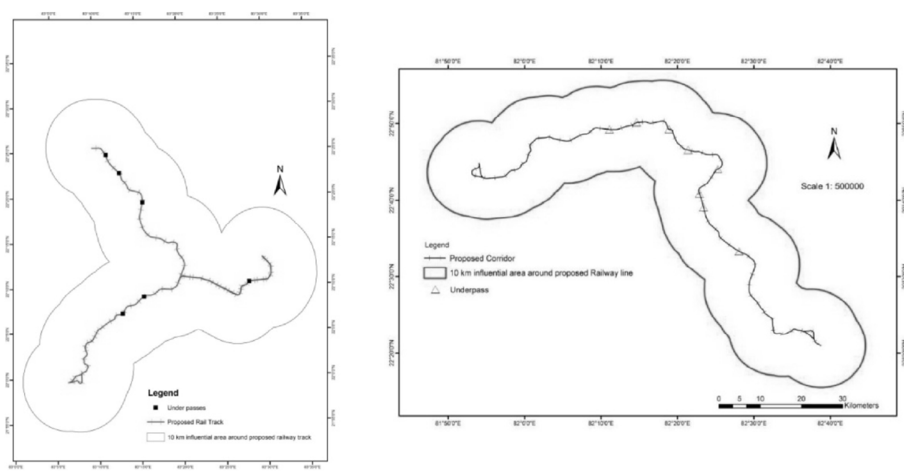

Fig. 6. Proposed locations for over/under passes in East and East West Railway Corridors

Conservation and future for green infrastructure in India

Linear infrastructure such as roads and railways do form a barrier to movements of wildlife. In the case of small mammals, even narrow clearings inhibit crossings but do not completely restrict movements.

Both underpasses and overpasses elsewhere have found to be effective for many forest ground-dwelling and arboreal species. However, it appears unlikely that species that are badly affected by disturbances such as noise, headlights and movement, will use these engineering solutions, unless they become habituated.

Green infrastructure may sound like a new term, but it is certainly not a new concept. It has its roots in the basic principle of conservation planning that emphasises preserving and linking natural areas to benefit biodiversity. This approach helps to counter the negative impacts of habitat fragmentation. It also aims to maintain diversity, manage connectivity, strengthen adaptability and restore ecosystems at all spatial scales.

Summary

The paper discusses about the impacts of linear infrastructure on forests, with an example of two ongoing railway projects in Chhattisgarh. The State of Chhattisgarh is primarily rich in forests, especially tropical deciduous and mixed forests types with dominant species such as *Shorea robusta* and *Tectona grandis.* The linear clearings during the construction of railway lines have various degrees of impact to the forests, wildlife and people living in and around. This paper is an extract of an Integrated Wildlife Conservation Plan that the authors prepared for the upcoming railway projects of Chhatisgarh. While investigating the impacts of forest diversion and suggesting mitigative measures, an effort has been made to keep in mind some of the principles of resilience concepts.

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NATIONAL CONFERENCE ON TOWARDS RESILIENT ECOSYSTEMS: THE ROLE OF FORESTRY RESEARCH

8th -9th May, 2018

Institute of Forest Genetics and Tree Breeding, Coimbatore

PROCEEDINGS AND RECOMMENDATIONS

I. PROCEEDINGS

Inaugural Session

The Chief Guest of the function Shri. Siddhanta Das, IFS, Director General of Forests & Special Secretary to GoI, MoEF & CC inaugurated the exhibition showcasing ICFRE Technologies**.** The Directors of ICFRE Institutes briefed the Chief Guest about the technologies developed by the respective Institutes. The inaugural function commenced with the prayer and invocation on Nature by Dr. Kannan C. S. Warrier, Scientict, IFGTB. Dr. Mohit Gera, IFS, Director, IFGTB welcomed the dignitaries and the participants. An overview of the conference was also presented by him which covered the evidences of climate change and its impact on forests in the country as well as in other regions of the world. The presentation also covered the objectives of the conference and brief introduction of all the technical sessions.

Shri S.D. Sharma, IFS, Dy. Director General (Research), ICFRE in his address mentioned that forestry research is confronted with biggest challenge of the age - the climate change. He added that the major forests of India, ranging from coastal belts to Alpine areas and desert areas, with its characteristic species are likely to be impacted by the projected climate change. He observed that long term and irreversible impacts are further expected to have adverse socio-economic implications for the forest based communities and the economy of the country. He said that ICFRE is taking it as a challenge to shoulder the national responsibility to undertake research in this area of contemporary importance.

Dr. S. C. Gairola, Director General, ICFRE, delivered the key note address and informed that deforestation, is one of the main sources of CO_2 emissions and resustant climate change related issues. He emphasized the need to have a road map to honour the international commitments of our country to manage the increasing temperature. He opined that NDC commitment is large as India is committed to cover 13 million ha in 2020 and 21 million ha in 2030. He opined that involvement all the concerned sectors and organizations is required to honour the international commitments to achieve such targets. He suggested that the recommendations from this conference should focus more on ‘what is to be done’ and ‘how it can be done’ involving various stakeholders with back up fo sufficient intellectual, administrative and financial support.

Shri. Siddhanta Das, IFS, Director General of Forests & Special Secretary, MoEF & CC the Chief Guest of the function released the Conference Compendium. Followed by this, Certificates of appreciation were presented by the Chief Guest to Scientists who have got patents for their inventions at IFGTB. In the inaugural address Shri. Siddhanta Das, underlined the need to identify the vulnerabilities leading to the climate change disaster.. He reminded that the country is going to face a climate induced disaster. It is the vulnerability of the system that makes the hazard a disaster. He called up on to identify measures that make the ecosystems less vulnerable to prevent the disaster. He highlighted the importance of forests as carbon sink and emphasized the role of forestry in reducing impacts of climate change. He made a presentation on “Strategy for sequestering additional 2.5 to 3.0 billion tones of CO_2 in forests by 2030” and informed that India is committed to enhance the carbon stock in the existing forests. He under scored the need for developing landscape based catchment area treatment plan and enhancing tree cover outside forests. He informed that MoEF&CC has already taken actions in this direction with catchment areas of river Ganga in Uttar Pradesh, Uttarkahnad and Bihar. He added that other rivers in the country will also be worked up on the same way later. He reminded that forestry is one of the major biological systems which can directly trap CO_2 and future research should help to tend the ecosystem as resilient. He opined that the present national conference have immense importance and will come out with practical recommendations. Dr. S. Murugesan, Scientist – G, Group Coordinator (Research) and Convener of the Conference proposed vote of thanks.

The technical issues of the conference were deliberated in five sessions namely (i) Vulnerability Assessment, (ii) Tree Improvement and Biotechnological Strategies for Climate Resilience, (iii) Harnessing Forest Genetic Resources For Climate Resilience and Forest Health, (iv) Adaptive Forest Management: Issues and Challenges and (v) Climate-Smart Forestry: Research and Management. Altogether there were 5 lead presentations and 10 invited talks delivered and discussed during the conference. The session wise proceedings of different technical sessions are as follows:

Session I: Vulnerability Assessment

Chairman : Shri. Siddhanta Das, IFS, DGF & SS, MoEF&CC
Co-chairman : Dr. R.S.C. Jayaraj, IFS, Director, RFRI

Invited Presentations were on:

1. *Vulnerability of Indian forests to climate change* - by Dr. Rajiv Kumar Chaturvedi, Senior Researcher, IISc, Bangalore.

2. *Climate change impact on forestry* - by Dr. A. Ramachandran, IFS, Professor – Emeritus, Anna University, Chennai.

Dr. R.K Chaturvedi, made a presentation on ‘Vulnerability of Indian forests to climate change’. In his presentation he gave an overview of the effect of climate change on temperature and rainfall pattern in India, especially in the Western Ghats, Himalayas, north-eastern and coastal region. He also gave a global picture of climate predictions and country status on carbon sequestration potential. From his studies, he concluded that, the undisturbed forests are less vulnerable to climate change risk. He observed that current forest vulnerabilities arise from structure and composition of forests – increased disturbance, declining biodiversity and loss in canopy cover. He opined that the current vulnerability can be minimized by addressing the structural and compositional aspects of the forests. He recommended two pronged strategy to deal with the challenge: i) integration of climate change impact and vulnerabilities in the forest working plans and including of afforestation and forest conservation programmes in the current management practices and ii) initiating long term monitoring for assessment of structure and composition of forest through cost effective new technologies like satellite and UAVs.

Dr. A. Ramachandran made a presentation on ‘climate change impact on forestry’. He gave an overview on climate change with particular reference to carbon sequestration in Indian forests particularly in soil organic carbon. He mentioned different methods to improve soil organic carbon and stressed that, the soil organic carbon plays a major role in improving the productivity of the forests. Further he emphasized that the success of the forest plantations are mainly dependent on the plant growth promoting bacteria and soil fertility. He emphasized accurate field level assessment of degradation of forests through proper studies based on soil carbon analysis. He also gave various steps to improve productivity by appropriate amendments of soil organic carbon, micro and macro nutrients and plant growth promoting bacteria (PGPB).

The Chairman commented that, instead of assessment of vulnerability, we need to predict the anticipated changes and act to address the issues. He also said that the assessment pattern of the forest cover should be modified to include correlation of ground cover with canopy cover. The Co-Chairman stressed the need for micro level, studies to be taken up along with macro-level for addressing the climate change vulnerability. He also pointed out that, the studies happening in China on resilience mapping/indexing needs to be taken up in Indian context.

Session II: Tree Improvement and Biotechnological Strategies for Climate Resilience

Chairman : Dr. C. T. S. Nair, Former Chief Economist, FAO Forestry Department
Co-chairman : Dr. B. Gurudev Singh, Scientist-G (Retd.) & Former GCR, IFGTB.

Invited Presentations were on:

1. *Tree Improvement and Biotechnological Strategies for Climate Resilience:The Case of Natural Rubber* - by Dr. James Jacob, Director, Rubber Research Institute, Kottayam, Kerala

2. *Tree Improvement and Biotechnological Options to Build Climate Resilience* - by Dr. A. Nicodemus, Scientist-F & Head, Genetics & Tree Breeding Division, IFGTB, Coimbatore

In his presentation, Dr. James Jacob explained the importance of rubber in the national scenario in relation to its contribution in GDP and the carbon sequestration potential. Rubber plantations have been reported to sequester 15-20 MT CO_2 per ha per year. The environmental and physiological impact on the carbon sequestration potential was also presented. He also covered breeding and biotechnological strategies adopted in this species, along with successful genetic transformation. However, due to the policy issues, the biotechnological tools without genetic modification have to be used for identification of resilient genotypes, he added. He also suggested that open pollinated breeding strategy need to be adopted to create new progenies and molecular markers to be used for selection.

Dr. A. Nicodemus presented the importance of genetic diversity to support the breeding for resilience. The importance of genotype and environment interaction as a key factor for breeding for adaptation traits was explained. The status of teak germplasm in the entire world for climate resilience was presented. The need for detailed studies on the breeding zones of native tree species was also discussed. He emphasized the need for concerted effort for establishing forest genetic resource network and synergy between the different sectors of forestry, including agriculture for strengthening the efforts towards climate resilience.

During the discussion, Dr. M. H. Swaminath, opined that classical breeding strategies have solutions for the climate resilience and suggested that the institutions must work on existing data on the breeding values of the species. Dr. K. Gurumurthi, said that the ecosystem resilience and breeding for climate resilience are two separate topics, mutually exclusive and operate on different directions. Dr. Mohit Gera, replied that efforts have been taken to bring climate resilience through conventional breeding programmes with broad genetic base available with IFGTB. In long rotation crops, the efforts will be highly relevant for climate resilience. Dr. I. D. Arya, said that biotechnological interventions such as somaclonal variations may be used to increase the genetic variability and simultaneously to produce pure lines and used for the breeding programmes. Dr. V.P. Tewari, also informed that natural selection is the best tool for selection of climate resilient genotypes. Dr. Shakti Singh Chauhan, opined the sequestration in timber of long gestation tree species has greater meaning than the pulpwood and short rotation tree species.

Dr. Rajiv Kumar Chaturvedi pointed that carbon sequestration by the trees has greater relevance for climate mitigation. Dr. James Jacob remarked that although planting more trees would reduce the climate change effect, the better strategy would be to reduce the emission. Dr. B. Gurudev Singh informed that studies on the epigenetics have a great relevance, when it comes to climate resilience.

Session III: Harnessing Forest Genetic Resources for Climate Resilience and Forest Health

Chairman : Dr. Neelu Gera, IFS, DDG (Education) & Director (IC), ICFRE
Co-chairman : Dr. V.P .Tewari, Director, HFRI, Shimla.

Invited Presentations were on:

1. *Climate change and Forest Genetic Resources* - by Dr. Z. Abraham, Principal Scientist (Retd.), National Bureau for Plant Genetic Resources (NBPGR), Thrissur, Kerala

2. *Harnessing Forest Genetic Resourses for Climate Resilience and forest Health* - by Dr. R. V. Varma, Former Chairman, Kerala State Biodiversity Board, Thiruvanandhapuram

Dr. Z. Abraham highlighted on maximizing capability of trees to respond to new threats related to climate change by reorganization of population via natural selection. He stressed the need for regular monitoring to determine native species in natural populations which are currently at risk. He highlighted the need for evaluating intra-specific variation within the populations, which is essential for the adaptation of forests, and thus of the forestry sector to climate change. He pointed out that microbial association of the trees has to be studied for adaptation to climate change. He underscored the need to find ways and means to ensure persistence of essential ecosystems by natural regeneration and understanding role of microbes in rescuing genotypes from climate variations The potential or capability to adapt to the changed environment is to be maximized, through research and management interventions.

Dr. R. V. Varma, highlighted the need for a multi-sectoral approach to deal with climate change issues. He cited the changes in phenological events of prominent tree species due to climate change. He mentioned about the gregarious flowering and perishing of bamboos which resulted in man-animal conflicts due to shortage of food source for wild animals and need for tackling such issues. Necessity to identify and appropriately utilize species, which help in pollination by serving as good hosts was highlighted as in the case of invasives like *senna* sp. having abundant sweet nectar attracting more pollinators. Regarding transgenic approach in teak, he opined that transgenic in teak to manage teak defoliator was a failure, he said and suggested to conduct in-depth studies for practical application.

Session IV: Adaptive Forest Management: Issues and Challenges

Chairman : Dr. Savita, IFS, Director, FRI, Dehradun
Co-chairman : Dr. Jagmohan Sharma, IFS, APCCF, Karnataka State Forest Department.

Invited Presentations were on:

1. *Is there anything new in adaptive forest management?* - by Dr. C.T.S. Nair, Former Chief Economist and FAO Forestry Department
2. *Adaptive Forest Management: Issues and Challenges* - by Dr. T. Sekar, IFS, Former PCCF, Tamil Nadu State Forest Department.
3. *Adaptive Forest Management: Issues and Challenges* - by Shri. T. Rabikumar, IFS, Secretary, National Biodiversity Authority, Govt. of India
4. *Studies on Ecological Potential of Land Use sectors for Climate Change Mitigation and Enhancing Livelihood Opportunities(Adaptation) in Kurnool District, Andhra Pradesh* - by Dr. Ratnakar Jauhari, IFS, Conservator of Forests, IFB, Hyderabad.
5. *Enhancing Climatic Resilience for Hyderabad Metropolitan area by Sustainable Management of Urban Forest Ecosystems* - by Dr. Chandrasekhar Reddy, IFS, Addl. PPCF, Telangana State Forest Department.

Dr. C.T.S. Nair informed that in 1970s practices of adaptive management had been initiated and by definition this adaptive management is based on experimental and scientific learning. He mentioned about adaptive management put forward as the way of managing natural resources and stated that science has potential for addressing uncertainties. He also pointed that fragmented good research has to be continued for achieving results and traditional management of timber trees in forestry has to be updated. However, he suggested that increasingly more research is managed through networks operating in a “collaborate, coordinate, communicate” framework. He talked about intensive research undertaken on adaptive forest management and climate change. He correlated heavy wind with low latex production in rubber tree. He impressed upon the need for strong linkage between research and practice to address the uncertainties on the ground and also mentioned about involvement of all stakeholders in adaptive forest management.

Dr. T. Sekar talked about key strategy and pointed out that climate change mitigation is first step to minimize its impacts on forest and our priority would be to plan and implement afforestation, reforestation and assisting natural regeneration of the forests besides building tree assets on private lands with a view to create additional carbon sink. He emphasized that given the prevailing uncertainty regarding ecosystem structure, function, and inter-species interactions in a climate change scenario, ecosystem approach rather than single-species approach to management is very important.

Through his presentation, Shri. T. Rabikumar emphasized on developing well defined management objective (preferably on ecological functions of the forests) and also on identification of indicators of forest condition. Further to this, there is a need for creating baselines on those identified indicators and then studying the impact of climate change on the forests based on identified indicators. He highlighted the need to integrate the knowledge emanating from such studies in management options. While discussing on challenges in adaptive forest management, he added that the major challenge will be maintenance of desired forest structure for various ecological functions under future climate conditions. The second big challenge according to him is monitoring the implementation of working plan prescriptions and corrective measures thereof, as there is lack of resources to implement working plan prescriptions and also working plan is not linked with budgetary planning process. He opined that the opportunities before us are i) Research on phenology, reproductive biology, tree-pollinator interactions, ii) Identification of climate resilient population (Intra - species diversity from natural variability), and iii) Reorientation on the implementation of working plan prescriptions and monitoring thereof. He suggested to conduct Pilot study for developing framework for Adaptive Forest Management.

Dr. Ratnakar Jauhari made a presentation on discussed about ecological potential of land in adaptive management. He mentioned that the forest dependent communities will have to adopt to the changes broght about by climate change. He discussed about the potential land for carbon stocking at Kurnool area and mentioned that rural people are taking care of forest there. While covering species composition, he informed that forest cover was low due to the indicators such as low level of species. He suggested that forest degradation could be tackled by cultivating more plants and increasing soil fertility.

Dr. Chandrasekar Reddy while presenting his paper, mentioned about importance of ecosystem services and urban forest block management. He discussed about adaptive management and urban forest block conservation zone and informed that urban forest blocks management efforts made in Hyderabad metropolitan area proved that forest area is protected and there is an increase in dense forest area, increased soil and water conservation through reduction in land degradation, increased carbon sequestration and increased availability of fodder and grasses besides aiding in environmental education among children.

Session V: Climate-smart Forestry: Research and Management

Chairmen : 1) Dr Subhash Ashutosh IFS, PCCF, Meghalaya.
2) Shri. Surendra Kumar, Director, IWST, Bangalore.

Invited Presentations were on:

1. *Smart Forests: Research and Management* - by Dr. M.H.Swaminath, IFS, PCCF (Retd.), SFD Karnataka
2. *Climate Smart Forestry Research and Management Imperatives* - by Dr. K. N. Murthy, IFS, PCCF & MD, Karnataka State Forest Industries Corporation Ltd.
3. *Reducing Vulnerability is a Climate-Smart approach to deal with the risks to forests under Climate Change* - by Dr Jagmohan Sharma, IFS, APCCF, Karnataka State Forest Department

Dr. M. H. Swaminath, spoke about the past management practices and their impact on forests. He spelled out strategies to develop smart forests such as: i) Reduction of emission from the forest ecosystem, ii) Fire control and fire resistant species planting, iii) Assisted anticipatory regeneration and iv) Sustainable harvesting cycles of NTFP. He recommended key areas in forestry research in the context of climate change like i) Canopy research of high forests, ii) Ecosystem value and ecosystem services, iii) Carbon flux monitoring and other gaseous exchange related studies, iv) Genome mapping, genetic frequency and other reproductive biology studies are to be initiated in the climate change context, v) Research programs to monitor changes in the vegetation in the context of climate change and vi) Water regime changes in different projected climate change impacted areas, in both scenarios and developing appropriate mitigation measures.

Dr. K. N. Murty, IFS spoke on how to work in a phased manner (short, medium, long) with SMART objectives. He suggested short term measures to reduce the vulnerability of forests and contain the stress by 2030 and medium term measures to improve the adaptive capacity and resilience of forests, which has to be accomplished by 2050 and long term measures to climate proof the forests and make forests as the national carbon sinks by 2100.

Dr Jagmohan Sharma informed that 91% (29 of 32) of the ecological processes are impacted in case of terrestrial ecosystems (i.e. forests). Hence, evidence for climate change impacts on natural ecosystems is unequivocal. He presented on studies confirming the displacement of species in India and mentioned about geographical range shifts in response to observed warming for 87% of 124 endemic species in Sikkim (India) with a mean upward displacement rate of 27.53 ± 22.04 meters per decade over the period 1849-50 to 2007-10. He opined that the major challenges in forestry due to climate change will be: i) Adaptation to climate change, ii) Contribution to climate change mitigation, iii) Remaining resilient, iv) Producing ecosystem services for sustainable livelihoods, v) Dealing with non-climatic externalities (competing demand for forestland, biomass harvesting, pests and diseases, forest fires) and vi) Ensuring environmental stability. Dr Jagmohan Sharma emphasized on vulnerability assessment at local scale, as it will be useful for identification of drivers of vulnerability. He suggested that Climate-Smart Forestry Management approach to reduce the risk under climate change should be i) "Preservation" for primary forests (that are largely undisturbed and do not show signs of degradation), ii) "Restoration" for primary forests (that are disturbed and show signs of degradation) and "Naturalization" for secondary forests (plantations). He concluded that forests are vulnerable and the vulnerability is likely to exacerbate under future climate. Further, vulnerability reduction is a robust strategy to deal with the risks from committed as well as future climate change. Hence, restoration of forests by adopting climate-smart forest management practices is an urgent need, he opined.

Session VI: Wrap-up: Drafting of Recommendations

Chairman : Dr. S. C. Gairola, IFS, Director General, ICFRE, Dehra Dun.
Co-Chairman: Dr. Mohit Gera, IFS, Director, IFGTB, Coimbatore.
Panelists : Dr. C. T. S. Nair, Former Chief Economist, FAO Forestry Department.
Dr. R. V. Varma, Former Chairman, Kerala State Biodiversity Board, Thiruvananthapuram.

Dr. S. C. Gairola, IFS, Director General, ICFRE, Dehra Dun and Chairman of this session welcomed the gathering and suggested to categorize the recommendations of each technical sessions into three *viz.* Recommendations for i) Research, ii) Management and iii) Policy. Chairman also emphasized the need to have "Proposed Actions" for implementing of recommendations. Accordingly, the recommendations of all the five sessions were categorized into Research, Management and Policy Recommendations and proposed actions were also drawn for implementing of recommendations. Dr. Mohit Gera, IFS, Director, IFGTB, Coimbatore and Co-Chairman of the session invited Dr. A. Balu, Scientist-G to present he recommendations along with the proposed actions session-wise. Co-Chairman also invited the discussions and deliberations on each recommendations. The recommendations were presented and discussed. The Panelists and the participants made their comments and suggested modifications were made in the proposed recommendations.

II. RECOMMENDATIONS

SESSION - I: Vulnerability Assessment

Research

1. Vulnerability assessment of forest ecosystems based on the likely impacts of climate change on forests and biodiversity at national, regional, sub-regional and local levels, using high resolution data.

Proposed Actions

a. Development of vulnerability indices for forest fire hazards, Alien Invasive Species (AIS), pest / disease outbreak, soil characteristics, water resource systems/ hydrologic vulnerability including risk analysis matrices at the national, regional and local levels, and regular monitoring at five year interval.

b. Generation of vulnerability maps / atlas to identify most vulnerable areas and species, and prioritise actions.

c. Delineation of fragile ecosystems and planning recovery programmes.

2. Eco-physiological assessment and genecological studies within and between species.

   Proposed Action: Assess distribution or persistence of priority species under different environments and correlate with morphological, physiological and molecular data.

3. Monitoring and assessment of vulnerability of endemic and endangered taxa of flora and fauna in different forest ecosystems.

   Proposed Action: Prioritize species and development of spatial and temporal models to conserve specialised habitats of endemic and endangered taxa of flora and fauna.

4. Understanding the co-evolutionary interactions between flora and fauna and potential impact of their decoupling.

   Proposed Actions: Document climate-related traits, such as the timing of bud break, leader shoot growth cessation, behavioural assessments of forest health agents - insect pests, pathogens both native and invasive species, natural enemies, pollinators, litter inhabiting fauna and flora and their interactive effects.

5. Genetic resource survey and development of conservation strategies for prioritised tree species

   Proposed Actions: Prioritize conservation of populations on the basis of importance to people, diversity and significant threat. Develop effective mix of *in situ, circa situ* and *ex situ* approaches to ensure conservation and maintain evolutionary processes; Increase population representation and genetic diversity of important and threatened species in conservation areas, and in seed collections; Document seed storage behaviour and germination requirements for prioritised species.

6. Improvement of plantation forestry by adopting silvicultural practices and by employing improved quality and healthy planting materials raised through tree improvement programmes/clonal/micro-propagation technology as well as use of bio-fertilizers for enhancing forest productivity.

   Proposed Actions: New varieties that are climate change ready, i.e., adapted to the changes foreseen with wider tolerance of climate variability to be developed through conventional breeding or molecular breeding; Breeding for increased tolerance to water stress, improved nutrient use efficiency.

Management

1. National forest monitoring and assessment programme needs to be prepared, to assess vulnerability periodically employing latest technology

   Proposed Actions: Improved resource inventory and evolve appropriate methodologies to assess vulnerability, on the lines of FSI's periodic observations on forest health including natural regeneration, fire incidences, soil erosion, AIS, insect / pest attack, biotic interferences etc.

2. Vulnerability assessment should be incorporated in working plans / management plans.

   Proposed Actions: Incorporate climate change concerns into working plans, afforestation and conservation programmes and forest management.

3. Maintaining of proper health and hygiene of the forest ecosystems and reduce vulnerability to pests and diseases.

   Proposed Actions: Regular and long term monitoring with emphasis on forest soil quality, soil organic carbon, microbes and microfauna.

Policy

1. A systematic long term National forest monitoring and assessment programme including forest and tree cover,soil assessment, forest health, etc.

SESSION – II

Tree Improvement and Biotechnological Strategies for Climate Resilience

Research

1. Investigations on eco-physiology of selected tree species.

   Proposed Actions: Field and nursery experiments to understand patterns of variation; physiological and biochemical studies in field tested material designed to understand impacts and responses to climatic changes; Transfer of knowledge obtained from model species in temperate regions to tropical species.

2. Genome sequencing for better understanding of genetic variations and developing climate change resilience.

   Proposed Actions: Harness genomic tools to improve understanding of genes that are important in salt and drought tolerance/ resistance, flood tolerance, phenophases, response to elevated CO_2 levels.

3. Integration of marker-assisted selection to accelerate improvement of adaptive traits in tree species.

   Proposed Actions: Marker assisted selection for adaptive traits such as biotic and abiotic stress tolerance and growth through phenotype-environment associations and phenotype-genotype-environment associations; Quantitative Trait Loci (QTL) analysis to hasten the development stress tolerant genotypes.

4. Assess the potential impacts of climate change on priority species to capture maximum genetic diversity within the resilient varieties.

   Proposed Actions: Identify the extent of climatic variability a species can withstand, possibilities to continue with the existing species in these agroclimatic conditions and the vulnerability of the existing tree species in the changed climatic scenario using fine scale mapping.

Management

1. Delineation of seed zones and breeding zones for priority species for generation of climate resilient populations.

Proposed Actions: Based on research inputs, seed zones and tree breeding regions to be delineated to translocate the propagules of pre-adapted populations to assist migration and gene flow within populations. Composite seed sources from multiple provenances to be deployed to increase diversity and buffer against future climate uncertainty.

Policy

1. A directive from MoEF&CC to all States to augment the use of genetically improved planting material in the departments' plantation programs.

   Proposed Actions: SFDs to strengthen planting stock improvement programmes with the involvement of communities or private participation including industries.

SESSION - III

Harnessing Forest Genetic Resources for climate resilience and Forest Health

Research

1. Delineation of populations of prioritized species for *in situ* and *ex situ* conservation.

   Proposed Actions: Assess distribution or persistence of prioritized species under climate change using morphological, physiological and molecular tools; Prioritize conservation of populations on the basis of importance to people, diversity and significant threat. Also establish *ex situ* conservation stands for prioritized species.

2. Studies on reproductive biology and regeneration of FGRMN prioritized species

   Proposed Actions Long term studies on reproductive biology, pollinators, seed dispersal, regeneration, fragmentation and soil characteristics of FGRMN prioritized species, and develop modelling and identify threats to FGR.

3. "Intact forest ecosystems" of larger magnitudes to be delineated in different forest types as long term observation plots along with the existing permanent preservation plots.

   Proposed Actions: Forest fire hazards, soil characteristics, water resource systems/ hydrological functions to be assessed in "Intact forest ecosystems" for adaptation and mitigation measures for climate change.

4. Develop spatially explicit and species-specific threat modelling framework to guide *in-situ/ex-situ* conservation, active regeneration and tree planting.

Proposed Actions: Prioritize species and develop spatial and temporal models to conserve specialised habitats of endemic and endangered taxa to guide in-situ/ex-situ conservation.

5. Strengthen International collaborations in areas of FGR Research.

   Proposed Actions: Active collaboration projects with involvement and funding support from APFORGEN, EUFORGEN, FAO and Biodiversity Internationalon FGR Research in relation to climate change.

Management

1. Support "Planned" or "Assisted" adaptation by redefining forestry goals and practices. The role of local populations / species / varieties is important as they have already undergone the process.

   Proposed Actions: Develop effective mix of *in situ, circa situ* and *ex situ* approaches to ensure conservation and maintain evolutionary processes; Increase population representation and genetic diversity of important and threatened species in conservation areas, and in seed collections; Document seed storage behaviour and germination requirements for prioritised species.

2. Implement Forest Genetic Resource Management Network (FGRMN) programme in the country involving all ICFRE Institutes, SFD, and Agricultural Universities.

Policy

1. Establishment of a National Bureau on Forest Genetic Resources.

SESSION – IV

Adaptive forest management: Issues and Challenges

Research

1. Explore and identify climate resilient species (natural/plantation)specific to regions and climatic zone.

   Proposed Actions: High-quality site-matched planting material of priority species, with a broad genetic base to ensure adaptive potential; Assessment of existing trials, and testing through new trials.

2. Evaluation of existing silvicultural systems and modifications to address climate change

Proposed Actions: Analyse past and current management practices including origin of material, movement of germplasm, and survival to enhance adaptive capacities of forests; Develop effective carbon management strategies.

3. Understand reproductive fitness of tree species

   Proposed Actions: Long term studies on the phenology, reproductive biology, tree-pollinator interactions etc for keystone species.

4. Research on forest types dynamics in view of pressures on forests and their vulnerability to changing climate.

   Proposed Actions: Develop vulnerability indices for different forest types of the country.

Management

1. Forest fire hazards, soil characteristics, water resource systems/ hydrological functions to be considered for adaptation and mitigation measures of climate change.

   Proposed Actions: Development of vulnerability indices for forest fire hazards, soil characteristics, water resource systems/ hydrologic vulnerability including risk analysis matrices at the national, regional and local levels

2. Novel approaches in sustainable forest management practices through partnership and participatory approaches in fringe forest areas.

   Proposed Actions: To mainstream climate change adaptation into SFM, information on composition of the forest, net productivity, disturbances affecting the ecosystem, adoption of advanced tools that allow foresters operating at various levels to understand climate change, mechanisms for sharing knowledge about impacts and adaptation and knowledge exchange.

3. Reduce the extent of reliance of local forest dependent communities on forests.

   Proposed Actions: Alternative employment, alternative energy sources, Sustainable harvesting, value addition and marketing of NTFP.

4. Productivity improvement initiatives outside forest land.

   Proposed Actions: Identify requirements for maximizing productivity of trees in agricultural landscapes under changing climate; Develop a portfolio of clones / species that have phenotypic plasticity and that perform well across a range of environments (national/regional/local level)

5. Capacity building of forestry personnel on the need for adaptive management in forestry.

   Proposed Actions: State level capacity building programmes focussing on vulnerability assessment to address mitigation and enhance adaptiveness of forest ecosystems.

Policy

1. Climate change considerations to be the essential component of planning for forest management.

   Proposed Actions: State level capacity building programmes focussing on vulnerability assessment to address mitigation and enhance adaptiveness of forest ecosystems.

2. A policy directive on incentives for agroforestry to ensure "produce more wood, use more wood".

   Proposed Actions: Transit and market reforms, minimum support prices, reconsideration on OGL, synergy with Bamboo Mission objectives, dedicated funding for R&D for increasing productivity of indigenous species.

SESSION – V

Climate – Smart Forestry: Research and Management

Research

1. In production forestry, climate resilient phenotypes need to be tested and deployed to enhance carbon sequestration.

   Proposed Actions: High-quality site-matched planting material of priority species, with a broad genetic base to ensure adaptive potential; Assessment of existing trials, and testing through new trials.

2. Phenotype- site matching through silvicultural interventions for enhanced productivity.

   Proposed Actions: Develop a portfolio of clones / species that have phenotypic plasticity and that perform well across a range of environments (national/regional/ local level)

3. Develop an understanding on inter-relationship of climate change, forest fire and alien invasive species.

Proposed Actions: Forest fire hazards, soil characteristics, water resource systems/ hydrological functions and growth of AIS to be assessed in forest ecosystems for adaptation and mitigation measures of climate change

4. Development of a value chain for species in production forestry.

   Proposed Actions: Demand and supply status of forest produce to be evaluated on a bi-annual basis; Rationalise legal barriers on felling and transport of produce; introduce market reforms to foster farmer-industry linkages.

5. Undertake fundamental research to enhance understanding of forest and urban ecosystem so that they can be managed to sustain the ecosystem services in the changing environment.

   Proposed action: MoEF&CC may initiate funding ICFRE for fundamental research to enhance understanding of forest and urban ecosystem so that they can be managed to sustain the ecosystem services in the changing environment.

Management

1. Identification of appropriate species and technologies for effective eco-restoration of degraded forest ecosystems.

   Proposed Actions: SFDs to prioritise species and their seed / plant sources for plantations, gap planting etc. Redesign ANR techniques and accelerate REDD+ schemes for eco-restoration of degraded forests.

2. Improving hydrological functions in forest ecosystems through appropriate forestry interventions.

   Proposed Actions: Watershed management, catchment area treatment and improving vegetation at the landscape level giving priority to species with proven hydrological functions.

3. Critical and vulnerable ecosystems need utmost attention.

   Proposed Actions: SFDs to treat Western Himalayas, North Western Ghats, parts of Eastern Ghats, mangroves, riparian forests and swamp forests on priority.

4. Local communities to be involved in forest management.

   Proposed Actions: Active involvement of communities in management interventions like GIM, REDD-Plus, NFFP management etc. Involvement of women and marginalised sections of the communities to empower through self-help groups.

5. Forest dwellers and forest dependent communities should be made resilient to climate change.

   Proposed actions: MoEF&CC may initiate programs for capacity building of forest dwellers and forest dependent communities to be climate smart and to adapt their livelihood and lifestyle to changing climate.

Policy

1. Incorporate all climate change concerns in the New Forest Policy being finalised..

   Proposed Actions: MoEF&CC may constitute a special committee to recommend inclusion of climate change concerns for the new Forest policy.

2. REDD+ to be operationalised in all States, with appropriate Monitoring Reporting & Verification (MRV) protocols and benefit-sharing mechanisms.

   Proposed Actions: REDD+ readiness requirements for the country need to be fulfilled so that the country may get funding from different sources including GCF.

3. Green Skill development to be encouraged among entrepreneurs and forest dependent communities.

   Proposed Actions: Presently only three courses have been recognised for the forestry sector – bamboo growing, bamboo craft and raising quality planting material. More courses including agroforestry, NTFP management, Timber market information, innovative wood products making etc. may be included by the MoEF&CC.

4. Monitor and evaluate the implementation of various climate smart initiatives.

   Proposed action: MoEF&CC may develop performance indicators and scorecard to evaluate various climate smart initiates of the Central and State government at landscape level.

5. Promote wood as green building material.

   Proposed action: MoEF&CC may initiate policy decision favouring promoting timber outside forest. The state governments may initiate decision to harvest timber in forest areas and regrow carbon sinks.

6. Develop a platform for agencies working on climate smart forestry initiatives and network them to develop responsive and adaptive strategies.

   Proposed action: MoEF&CC may initiate steps to create a centre in ICFRE that will act as a platform for agencies working on climate smart forestry initiatives and network them to develop responsive and adaptive strategies.

NATIONAL CONFERENCE
ON
TOWARDS RESILIENT ECOSYSTEMS: THE ROLE OF FORESTRY RESEARCH

8th -9th May, 2018

Institute of Forest Genetics and Tree Breeding, Coimbatore

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75.	Dr. C. Kunhikannan	Scientist, IFGTB, Coimbatore
76.	Dr. A. Nicodemus	Scientist, IFGTB, Coimbatore
77.	Dr. Modhumita Dasgupta	Scientist, IFGTB, Coimbatore
78.	Dr. K.R. Sasidharan	Scientist, IFGTB, Coimbatore
79.	Dr. N.V. Mathish	Scientist, IFGTB, Coimbatore
80.	Dr. C. Buvaneswaran	Scientist, IFGTB, Coimbatore
81.	Dr. Kannan Warrier	Scientist, IFGTB, Coimbatore
82.	Dr. A. Karthikeyan	Scientist, IFGTB, Coimbatore
83.	Sh. M.M. Dominic Savio	Scientist, IFGTB, Coimbatore
84.	Dr. S. Saravanan	Scientist, IFGTB, Coimbatore
85.	Dr. R. Anandalakshmi	Scientist, IFGTB, Coimbatore
86.	Dr. Maheswar Hegde	Scientist, IFGTB, Coimbatore
87.	Dr. Rekha Warrier	Scientist, IFGTB, Coimbatore
88.	Dr. D.Raja Suguna Sekar	Scientist, IFGTB, Coimbatore
89.	Dr .N. Senthil kumar	Scientist, IFGTB, Coimbatore
90.	Dr.A. Vijayaraghavan	Scientist, IFGTB, Coimbatore
91.	Dr. K. Paneerselvam	Scientist, IFGTB, Coimbatore
92.	Dr. V.K.W. Bachpai	Scientist, IFGTB, Coimbatore
93.	Dr. A. Shanthi	Scientist, IFGTB, Coimbatore
94.	Sh. A .Mayavel	Scientist, IFGTB, Coimbatore
95.	Dr. A. Rajasekaran	Scientist, IFGTB, Coimbatore
96.	Dr. D. Thangamani	Scientist, IFGTB, Coimbatore
97.	Sh. K.S.Venkataramanan	Scientist, IFGTB, Coimbatore
98.	Sh. Anil V. John	Scientist, IFGTB, Coimbatore

S.No	Name and designation	Address
99.	Smt. K. Shanthi	ACTO, IFGTB, Coimbatore
100.	Sh. K. Gireesan	ACTO, IFGTB, Coimbatore
101.	Sh. L. Manimuthu	ACTO, IFGTB, Coimbatore
102.	Smt. R. Sumathi	ACTO, IFGTB, Coimbatore
103.	Smt. S. Lalitha	ACTO, IFGTB, Coimbatore
104.	Dr. S. P. Subramanian	ACTO, IFGTB, Coimbatore
105.	P. Manivachakam	STO, IFGTB, Coimbatore
106.	Shri. P. Chandrasekaran,	STO, IFGTB, Coimbatore
107.	Smt. S. Geetha	STO, IFGTB, Coimbatore
108.	A. M. Kumar	TO, IFGTB, Coimbatore
109.	Shri. K. Soundararajan	TO, IFGTB, Coimbatore
110.	Shri. C. K. Jagannath	TO, IFGTB, Coimbatore
111.	Smt. N. Sudha	TO, IFGTB, Coimbatore
112.	Smt. C. V. Vijayam	TO, IFGTB, Coimbatore
113.	Smt. K.S. Rathinam	TO, IFGTB, Coimbatore
114.	Smt. P. Malliga	TO, IFGTB, Coimbatore
115.	Smt. S. Padmini	TO, IFGTB, Coimbatore
116.	Shri. N. Sivadasan	TO, IFGTB, Coimbatore
117.	R. Velumani	ST, IFGTB, Coimbatore
118.	K. Suresh Kumar	ST, IFGTB, Coimbatore
119.	Smt. R. G. Anithaa	ST, IFGTB, Coimbatore

Glimpses of the National Conference

Receiving of the dignitaries

Inauguration of the Exhibition on ICFRE Technologies

Shri Siddhanta Das, IFS, DGF & Spl Secy, MoEF&CC reviewing the ICFRE Technologies

Welcome address by Dr. Mohit Gera, IFS, Director ,IFGTB

Address by Sh. S.D. Sharma, IFS, DDG (Research), ICFRE

Keynote Address by Dr. S.C. Gairola, IFS, DG, ICFRE

Release of Compendium by Shri Siddhanta Das, IFS, DGF & Spl Secy, MoEF&CC

Inaugural Address by Shri Siddhanta Das, IFS, DGF & Spl Secy, MoEF&CC

Delegates during Inaugural session

Session on vulnerability Assessment chaired by Shri Siddhanta Das, IFS, DGF & Spl Secy, MoEF&CC

Session of Tree Improvement for Climate resilience chaired by Dr. C.T.S. Nair, Former, Chief Economist, FAO

Session on Forest Genetic Resources for Climate resilience chaired by Dr. Neelu Gera, DDG (Education), ICFRE

Session on Adaptive Forest Management chaired by Dr. Savita, IFS, Director, FRI

Session on Climate-Smart Forestry chaired by Dr. Subhash Ashutosh, IFS, PCCF, Meghalaya and Sh. Surendra Kumar, IFS, Director, IWST

Presentation on Adaptive Forest Management by Sh. T. Rabikumar, IFS, Secretary, NBA

वन आनुवंशिकी एवं वृक्ष प्रजनन संस्थान

INSTITUTE OF FOREST GENETICS & TREE BREEDING

(INDIAN COUNCIL OF FORESTRY RESEARCH & EDUCATION)

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