ISSN (Online): 2349-1183; ISSN (Print): 2349-9265
TROPICAL PLANT RESEARCH
The Journal of the Society for Tropical Plant Research

7(1): 196–204, 2020
DOI: 10.22271/tpr.2020.v7.i1.025

Review article

Climate change impacts on the distribution and phenology of plants: A review

Mesfin Woldearegay

Department of Biology, Debre Birhan University, P. O. Box 445, Debre Birhan, Ethiopia

Corresponding Author: mesfinwa@gmail.com

[Accepted: 12 April 2020]

Abstract: This paper reviews about the impacts of climate change on plant distribution and phenology. The existence of climate change is confirmed by various evidences from different sources that can be used to reconstruct past climates. Some of these facts are obtained from temperature measurements, glaciers retreat, arctic sea ice decline, sea level rise and variability of precipitation in different parts of the world. Empirical evidences have also indicated that climate change affects life on earth in many ways. On plants, some of the most important climate change impacts include, the change in phenological characteristics like flowering time, species distributions and richness as well as the composition of assemblages. Plant species have responded to climate change by range shifting and increasing species richness on alpine summits, as well as by altering the time of leafing, flowering and fruiting. Evolutionary adaptation could be an important way for natural populations to counterbalance rapid climate change. Adaptive changes are likely to influence the ability of species to take advantage of potentially favorable conditions arising from climate change. Plant species can also adjust to new conditions through phenotypic plasticity.

Keywords: Climate change - Evolutionary adaptation - Phenology - Plant distribution.

[Cite as: Woldearegay M (2020) Climate change impacts on the distribution and phenology of plants: A review. *Tropical Plant Research* 7(1): 196–204]

INTRODUCTION

Climate change can be defined as any change in climate over time, which is caused by natural variability or due to human activity (IPCC 2007). Climate is largely regulated by processes like the flows of heat entering and leaving the planet and the storage of heat in the various compartments of the Earth System - ocean, land, atmosphere and snow/ice. This heat ultimately comes from the sun. Only a very small amount of the heat is stored in the atmosphere; by far the largest amount of heat stored at the Earth's surface is found in the ocean. The heat flux into the atmosphere proceeds very fast than into the ocean. However, since the ocean stores so much heat, a change in ocean temperature is a better indicator of change in the climate than changes in air temperature.

There are various evidences for the existence of climate change from different sources that can be used to reconstruct past climates. For instance, temperature measurements have shown that the global temperature is warming by approximately 0.6ºC during the last three decades (Hansen *et al.* 2006). Glaciers are believed to be among the most sensitive indicators of climate change (Seiz & Foppa 2007). The mass balance between snow inputs and melt outputs helps to determine the size of glaciers. When the temperature warms, the glaciers retreat unless snow precipitation increases to balance what has been melt. According to the World Glacier Monitoring Service, glaciers throughout the world have been found to be shrinking significantly, with strong glacier retreats in the 1940s, although it showed stable or growing conditions during the 1920s and 1970s, it again starts retreating from the mid-1980s to present.

Another evidence for rapid climate change is the decline in Arctic sea ice over the last several decades both in extent and thickness. Satellite observations show that Arctic sea ice is now declining at a rate of 11.5 percent per decade, relative to the 1979 to 2000 average (NSIDC 2013). The sea level rise and variability of precipitation in different parts of the world can also be taken as an evidence of climate change. Sea level rises

Received: 26 October 2019

https://doi.org/10.22271/tpr.2020.v7.i1.025

are consistent with warming and the global average sea level rose at an average rate of 1.8 mm per year over the last four decades. Trends over the past 100 years have shown that precipitation increased significantly in eastern parts of North and South America, northern Europe and northern and central Asia whereas it decreased in the Sahel, the Mediterranean, southern Africa and parts of southern Asia (IPCC 2007).

Empirical evidences have also indicated that climate change affects life on earth in many ways. Some of the most important examples are phenological characteristics like flowering time of plants (Walther *et al.* 2002, Parmesan 2006), breeding and arrival of migratory species (Both & Visser 2001). Species distributions and richness, as well as the composition of assemblages are also influenced by climate change (Root *et al.* 2003). With changing environmental conditions, species may either keep their current range or respond to the change with range expansions, contractions or shifts. Therefore, this review paper tries to show the impacts of climate change on plant life cycles and distributions, as well as adaptation of plants to resist the impacts of climate change.

Major causes of climate change

Factors that can affect the condition or state of the climate are known as climate forcings or "forcing mechanisms" (IPCC 2007). Processes such as variations in solar radiation, deviations in the Earth's orbit, mountain-building and continental drift and changes in greenhouse gas concentrations are some examples of climate forcing. The initial forcing can be either intensified or diminished by a variety of climate change feedbacks. Some parts of the climate system do not respond equally in reaction to climate forcings, for instance, the oceans and ice caps respond slowly while others respond more quickly.

Forcing mechanisms can be classified as “internal” or “external”. Within the climate system itself, internal forcing mechanisms (*e.g.*, the thermohaline circulation) are natural processes while external forcing mechanisms (*e.g.*, changes in solar output) can be either natural or anthropogenic (*e.g.*, increased emissions of greenhouse gases).

Internal forcings

Ocean variability

Internal climate variability is caused by natural changes in the components of the earth's climate system and their interactions. For example, El Nino-southern oscillation, the Pacific decadal oscillation, the North Atlantic oscillation, and the Arctic oscillation, which are short-term fluctuations (years to a few decades) that represent climate variability rather than climate change. On the other hand, alterations to ocean processes such as thermohaline circulation which occurs on longer time scales play a key role in redistributing heat by carrying out a very slow and extremely deep movement of water, and the long-term redistribution of heat in the world's oceans.

External forcings

Solar radiation and volcanism

Both long-term and short-term variations in solar intensity affect global climate. The change in the amount of radiation emitted by the sun and in its spectral distribution over years to millennia is known as Solar variation. Although these variations have periodic components, the major solar variation being the approximately 11-year solar cycle (or sunspot cycle). Total solar output is now measured to vary (over the last three 11-year sunspot cycles) by approximately 0.1%, (IPCC 2007) or about 1.3 Watts per square meter (W/m^2). It is hypothesized that solar variations together with volcanic activity have contributed to climate change. Climate is affected by eruption several times per century and this phenomenon cause cooling by partially blocking the transmission of solar radiation to the Earth's surface for a period of a few years. The first largest eruption of the 20th century occurred in 1912 at Novarupta on the Alaska Peninsula; while the second largest terrestrial eruption of the 20th century, the eruption of Mount Pinatubo, which occurred in 1991, affected the climate substantially. This decreased the global temperature by about 0.5°C (0.9°F). The 1815s eruption of the Mount Tambora caused the next year 1816 without a summer in the region (Oppenheimer 2003).

Tectonic plate

Both global and local patterns of climate and atmosphere-ocean circulation can be affected by the motion of tectonic plates that reconfigures and generates topography over the course of millions of years (Forest 1999).

The position of the continents determines the shape of the oceans which in turn influences the patterns of ocean circulation. The formation of the Isthmus of Panama about 5 million years ago, which shut off direct mixing between the Atlantic and Pacific Oceans, is an example of tectonic control on ocean circulation. This phenomenon strongly affected the ocean dynamics of what is now the Gulf Stream and may have led to Northern Hemisphere ice cover. Plate tectonics may have triggered large-scale storage of carbon and increased glaciation about 300 to 360 million years ago (Bruckschen *et al.* 1999).

Human influence

The general agreement of scientists on climate change is that "climate is changing and that these changes are in large part (>90%) caused by human activities", and it "is largely irreversible". The most important of these human activities are the emission of green-house gases and the clearing of natural vegetation (IPCC 2007). The most important greenhouse gases in Earth's atmosphere include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), water vapor (H_2O), and halocarbons (a group of gases containing fluorine, chlorine or bromine) (NAS 2001). These green-house gases are commonly characterized by their ability to absorb terrestrial infrared radiation. However, based on their different radiative properties and lifetimes in the atmosphere the green-house gases differ in their warming influence (radiative forcing) on the global climate system (IPCC 2007).

Global CO_2 concentration increases primarily due to the burning of fossil fuels and land-use change such as the conversion of forests into agricultural land. It is very likely that the observed increase in CH_4 concentration is predominantly due to agriculture and fossil fuel use while N_2O concentration increases primarily due to agriculture (IPCC 2007). The major source of gaseous water is evaporation from the oceans and the CFCs are synthetic compounds produced and released into the atmosphere by human beings (NAS 2001).

The impacts of climate change on plants

Life processes of plants such as establishment, growth, reproduction etc., are directly related to the environmental conditions sensed by the plant. Therefore, changes in temperature and precipitation, especially when occur rapidly or goes up to extreme level, directly affect species, and therefore, can also influence the course of competition among species (Sykes 2009). Globally, the degree of climate change is unlikely to be uniform and the outcome at the level of individual species, and the plant populations are likely to vary. For example, predictions from general circulation models (GCMs) suggest warmer winter (and to a lesser extent summer) temperatures, especially in northern latitudes (*e.g.* northern Europe), while decline in precipitation and increased droughts in some areas, such as, southern Europe (IPCC 2007).

Generally plants respond to climate change impacts in three different ways: firstly, by increasing growth and population size (positive), secondly, by decreasing growth with likely local extinctions (negative) and thirdly, by dispersal to new and more favorable sites. The two most commonly measured plant processes in response to climate change impacts are range shifting (geographical distribution) and phenology (Sykes 2009).

A. *Global distribution of plants*

In general, climate is a major factor that controls the broad-scale distributions of plant species and vegetation. Other factors such as local environmental conditions including soil nutrient status, pH, water-holding capacity of the soil and the physical elements of aspect or slope influence the potential presence or absence of a species (Chaturvedi *et al.* 2011, Chaturvedi & Raghubanshi 2014, Bajpai *et al.* 2020). However, intra-and inter-specific interactions, such as competition for resources (light, water, nutrients), ultimately determine whether an individual plant is actually found at any particular location (Sykes 2009).

Increasing green-house gas emission which results in a rapid climate change (IPCC 2007) influences the current and future vegetation patterns. The two most important human-induced factors that are expected to affect global biodiversity distribution over the next 100 years are climate change and land use change (Sala *et al.* 2000).

A number of reviews (Lenoir *et al.* 2008, Chen *et al.* 2011, Pucko *et al.* 2011, Fei *et al.* 2017) have summarized the existence of some evidences that species have responded to climate change by range shifting. Although, latitudinal movements have been recorded in various studies, the range changes in plant species are less easy to observe. For example, Holly (*Ilex aquifolium* L.), a species well known to have a close link to winter temperatures, has a northern limit closely associated with the location of the 0ºC isotherm. In the past 50 years this isotherm has moved north with a corresponding movement in the distribution of Holly, which now occupies new climate space along the more southerly coasts of Sweden. Altitudinal range changes have also been observed, for instance, in tree-lines moving upslope in the Scandinavian mountains (Kullman 2001), whereas in Vermont the upper limits of the northern hardwood-boreal forest ecotone moved 91–115 m upslope between 1962 and 2005 (Beckage *et al.* 2008). The average elevation of the dominant plant species rose by 65 m between 1977 and 2006–2007 surveys along an elevation gradient in southern California that was attributed to regional climate change involving both warming and changing precipitation variability (Kelly & Goulden, 2008).

Walther *et al.* (2005) reported an increasing trend of species richness on alpine summits, which suggests an upward shift in species ranges due to the favorable climate in the European Alps. This is likely to lead to more specialized alpine species facing local extinction as they are outcompeted by migrating species moving upwards in response to changing climate. Biome shifts have also been observed in Mediterranean mountain. According to Penuelas & Boada (2003), there is an upward migration of beech forest (*Fagus sylvatica* L.) by 70 m since 1945 and the replacement of beech and heath-lands at lower levels by holm oak (*Quercus ilex* L.).

The situation with regard to the tropics seems to be more complicated. However, Colwell *et al.* (2008) explored possible effects of climate change over a tropical elevation gradient using plant datasets in Costa Rica. They conclude that upslope movements of biota on mountain-sides may be compensated as in higher latitudes by species from further down the mountain or the lowlands.

In recent decades, a northward extension of various plant species has been observed in Europe which is likely to be attributable to increases in temperatures. In Western Europe, thermophilic plant species have become more abundant, as compared to their status 30 years ago, while a remarkably small decline in the presence of traditionally cold-tolerating species has also been observed.

In the mountain regions of Europe, endemic species have been replaced by other species due to Alien species invasion (Dainese *et al.* 2014), Moisture availability (Fei *et al.* 2017), including climate change. Factors associated with climate change such as higher temperatures and longer growing seasons appear to have created suitable conditions for certain plant species that have migrated upward, and which now compete with the endemic species. Evidence exists in the Alps, for instance, that climate warming over the past 60 years may have encouraged spruce and pine species in the sub-alpine region and sub-alpine shrubs to move upward on summits (Theurillat & Guisan 2001).

Similar changes have been observed in the mountainous areas of other continents. For example, (i) In the Olympic Mountains of Washington State, higher-elevation alpine meadows have been invaded by sub-alpine forest, partly in response to warmer temperatures. This increased species richness is caused by increasing air temperatures, on average 1ºC per decade over the last three decades. (ii) The populations of two native Antarctic flowering plants increased rapidly between 1964 and 1990 in the Argentine Islands corresponding to strong regional warming over the Antarctic Peninsula. The unusually rapid increases in the populations of these species are attributed to warmer summer temperatures and/or a longer growing season, which enhance the plant's ability to reproduce (Fowbert & Smith 1994).

B. *Phenology of plants*

Phenology of plants refers to the timing of events, such as leaf emergence, leaf fall, flowering, and fruiting over the annual cycle (Chaturvedi & Raghubanshi 2016). Since climate strongly influences seasonal plant and animal events, changes in phonological patterns are useful bio-indicators of climate change. Some easily observed plant phenological events include flowering, leaf emergence, fruit ripening and leaf falling (Sykes 2009, Bajpai *et al.* 2012a). The oldest known records of such events are, however, from Japan and they record the flowering of cherry trees connected with the timing of the annual blossom festival which date back to 801 AD (Anon & Kazui 2007).

The flowering time is one of the most important events for plants. It affects their chances of pollination, especially when the pollinator (for example, an insect) is itself seasonal, and determines the timing of seed ripening and dispersal. Flowering time also influences animals for which pollen, nectar, and seeds are important resources for survival. An earlier flowering time also entails an earlier activity in other processes such as leaf expansion, root growth, nutrient uptake etc., that are important for niche differentiation among coexisting species and hence it can alter competitive interactions between species. Therefore, large changes in flowering date may disrupt ecosystem structure.

A number of reviews and analyses have been conducted about the influence of climate change on phenology (Menzel *et al.* 2006, Bajpai *et al.* 2017). In the period between 1971–2000, earlier leafing, flowering and fruiting had increased to 2.5 days per decade with a delay in leaf fall by 0.2 days per decade (Menzel *et al.* 2006). An examination of changes in spring timing during the period 1900–1997 was carried out with regard to lilac across North America. Although, there exists regional variations, an average advance of spring by 5–6 days between 1959 and 1993, driven by warmer spring temperatures was also recorded (Schwartz & Reiter 2000).

A lot of research has been conducted regarding climate change interaction with phenology at the country level. Fitter & Fitter (2002) reported that the first flowering date of 385 species advanced 4.5 days on average per decade in the 1990s in the United Kingdom. Four tree species including *Ginkgo biloba* L. were examined in

Japan in four different areas exhibiting the greatest warming for 50 years, and found out that budburst had advanced by up to 5.6 days per decade (Doi & Katano 2007). These changes were assumed to be caused by the increase in temperature during March.

Changes in the timing of leaf emergence and flowering of perennials such as lilac, apple, and grapes have also been studied in the 20th century (Wolfe *et al.* 2005). According to the study, spring phenology had advanced for these species for 2 to 8 days over 35 years in the Northeastern United States. Most of these studies have indicated that changes in temperature are the main driver; however, this may not always be true.

The phenological observations of flowering in four *Eucalyptus* species from the 1920s to the 1980s in Australia, exhibited significant relationships of temperature and rainfall with the beginning of flowering for all species (Keatley *et al.* 2002). However, the responses for temperature and rainfall were not similar for the four species. The two species registered flowering later, while the other two species earlier under predicted increases in temperature and summer rainfall. Generally, the timing of phenological events of many species of plants, but not all species, has responded to climate change.

Expansion of invasive plant species

Native ecosystems, natural resources, and managed lands are highly threatened by Invasive plant species worldwide. Climate change has been expected to further expand the harmful impact of invasive plant species, as favorable climatic conditions allow invaders to expand into new ranges. Higher concentrations of CO_2 in the surrounding environment have been shown to increase the competitiveness of invasive plants relative to native species (Ziska *et al.* 2007) and many invasive plants are capable of spreading rapidly into disturbed areas, such as recently burned sites, which may become more common with climate change (Dukes & Mooney 1999, Yadav *et al.* 2016, Lone *et al.* 2019). As a result, native ecosystems are being threatened by invasive plant species since they outcompetes the native ones (Zavaleta 2000, Kumari & Choudhary 2016).

The distribution of land area at risk of invasion is likely to alter due to changes in precipitation and temperature conditions. Higher precipitation has been reported to cause non-native grasses to spread in the western United States (Martin *et al.* 1995), and the range of invasive species has been observed to expand northward in the southeastern United States due to higher temperature (Rogers & McCarty 2000).

In some regions, climate change could lead to expanded invasion risk for some species. For instance, invasive plants such as Yellow starthistle (*Centaurea solstitialis* L.) and tamarisk (*Tamarix* spp.) are likely to expand with climate change, whereas Cheatgrass (*Bromus tectorum* (L.) Nevski) and spotted knapweed (*Centaurea biebersteinii* (Jaub. et Spach) Walp.) are likely to shift in range, leading to both expansion and contraction (Bradley *et al.* 2009).

Human-managed systems such as agricultural lands, rangelands, forests, etc., are also threatened by invasive plants and the impact of these invasive plants on managed lands cause huge economic loss, for example, United State spends a huge amount of money, which is estimated in billions of dollars per year (Pimentel *et al.* 2000). Many areas at risk already contain small but not yet dominant populations of these invaders, creating the potential for rapid expansion in the face of climate change.

Adaptive features in plants for resisting climate change

The responses of natural populations to climate change are by shifting their geographical distribution and timing of growth and reproduction, which in turn alters the composition of communities and the nature of species interaction. Nevertheless, insufficient responses of many natural populations did not counterbalance the speed and magnitude of climate change, leaving some groups vulnerable to decline and extinction. Extinction can be avoided by shifting of populations to favorable habitats, or by means of plastic changes in species attributes, or by evolutionary adaptation of organisms to successfully overcome stressful conditions (Williams *et al.* 2008).

Recent studies (Whitney & Gabler 2008, Stotz *et al.* 2016, Colautti *et al.* 2017) have highlighted that species that have invaded new areas and in native species responding to biotic invasions undergo rapid evolutionary change, which indicates that evolutionary adaptation in natural populations could be an important way to counterbalance rapid climate change.

One way by which threatened species can persist might be through evolutionary adaptation if they are unable to disperse naturally, or through human-mediated translocation to climatically suitable habitats (Hoffmann & Sgro 2011). Adaptive changes are likely to influence the ability of species to take advantage of potentially favorable conditions arising from climate change, including the effects of CO_2 enrichment on growth rate and the extension of favorable seasonal conditions.

Climate change is taking place at a time when natural environments are becoming increasingly fragmented through habitat destruction, and when species are being moved unintentionally or intentionally around the globe at ever faster rates. That is, climate change occurs at a time when many populations are already under pressure from invading species and disturbances (Bajpai *et al.* 2012b, Chaturvedi *et al.* 2012, Bajpai *et al.* 2015, Chaturvedi *et al.* 2017, Bajpai *et al.* 2018). Evolutionary processes can be affected by changing the flow of genes around landscapes and by introducing new genotypes into populations through hybridization due to fragmentation and invasions (Hoffmann & Sgro, 2011).

When populations and species spread under favorable climatic conditions, new contact zones arise between related lineages, leading to interspecific competition but also an increased probability of hybridization between taxa. Hybridization is often regarded as a negative out-come for conservation, both because diversity is lost when a species' genome is replaced, and because fitness declines following combination. However, hybridization can also facilitate evolutionary adaptation. Molecular evidences have shown that past hybridization can be responsible for the expansion of species' climatic ranges. In addition, hybridization introduces genetic variation which can increase the evolutionary potential of populations like in Darwin's finches where interspecies hybridization has provided most of the genetic variance in morphology for adapting to the changing condition. Hybridization may also facilitate adaptation to new environments when hybridizing species are initially adapted to different conditions (Donovan *et al.* 2010).

Plant species can also adjust to new conditions through phenotypic plasticity. It is the range of phenotypes a single genotype can express as a function of its environment. Some responses are examples of adaptive plasticity, a type of phenotypic plasticity that increases the global fitness of a genotype, whereas others are inevitable responses to physical processes or resource limitations. Both adaptive and non-adaptive plasticity will play a role in the context of plant responses to climate change.

High levels of genetic variation help to improve the potential to withstand and adapt to new biotic and abiotic environmental changes, including the tolerance of climatic change within natural populations. Some of this genetic variation determines the ability of plants to sense changes in the environment and produce a plastic response. For example, plant populations adapt to changes in temperature due to genetic variation in genes encoding temperature sensors and transcription factors regulating vernalization. Plasticity, therefore, can both provide a buffer against rapid climate changes and assist rapid adaption (Lande 2009).

CONCLUSION

Climate change is one of the major global issue which affects plant life cycles and distributions significantly. The most commonly measured plant processes in response to climate change impacts are range shifting (geographical distribution) and phenology. Although there are other factors like local environmental conditions and intra-and inter-specific interactions that affect the distribution of plants in the surrounding environment, climate is a major factor that controls the broad-scale distributions of plants. As a result plant species have responded to climate change by range shifting. Phenological events such as flowering, leaf emergence, fruit ripening and leaf falling in plants are also influenced by climate change.

Climate change is also expected to increase the harmful impact of invasive plant species, since many invasive plants are capable of spreading rapidly into disturbed areas and show enhanced competitiveness relative to native species in higher concentration of CO_2 in the surrounding environment. As a result native ecosystems and human managed systems like agricultural lands, rangelands and forests are being threatened by invasive plants since they outcompete the native ones.

Hybridization facilitates evolutionary adaptation and it can increase the evolutionary potential of populations by introducing genetic variation, as in Darwin's finches where interspecies hybridization has provided most of the genetic variance in morphology for adapting to changing conditions. It may also facilitate adaptation to new environments when hybridizing species are initially adapted to different conditions. Plant species can also adjust to new conditions through phenotypic plasticity. High levels of genetic variation help to improve the potential to withstand and adapt to new biotic and abiotic environmental changes, including the tolerance of climatic change within natural populations. Some of these genetic variations determine the ability of plants to sense changes in the environment and produce a plastic response.

ACKNOWLEDGEMENTS

I thank Mr. Abreham Assefa and Talemos Seta for conceptual discussions and suggestions to improve this review. I also thank Debre Birhan University for the study leave.

REFERENCES

Anon Y & Kazui K (2007) Phenological data series of cherry tree flowering in Kyoto, Japan, and its application to reconstruction of springtime temperatures since the 9th century. *International Journal of Climatology* 28: 905–914.

Bajpai O, Dutta V, Chaudhary LB & Pandey J (2018) Key issues and management strategies for the conservation of the Himalayan Terai forests of India. *International Journal of Conservation Science* 9(4): 749–760.

Bajpai O, Dutta V, Singh R, Chaudhary LB & Pandey J (2020) Tree Community Assemblage and Abiotic Variables in Tropical Moist Deciduous Forest of Himalayan Terai Eco-Region. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences*, Online available. [DOI: 10.1007/s40011-019-01161-2]

Bajpai O, Kumar A, Mishra AK, Sahu N, Behera SK & Chaudhary LB (2012a) Phenological study of two dominant tree species in tropical moist deciduous forest from the northern India. *International Journal of Botany* 8(2): 66–72.

Bajpai O, Kumar A, Mishra AK, Sahu N, Pandey J, Behera SK & Chaudhary LB (2012b). Recongregation of tree species of Katerniaghat Wildlife Sanctuary, Uttar Pradesh, India. *Journal of Biodiversity and Environmental Sciences* 2(12): 24–40.

Bajpai O, Kushwaha AK, Srivastava AK, Pandey J & Chaudhary LB (2015). Phytosociological status of a monotypic genus Indopiptadenia: A Near Threatened Tree from the Terai-Bhabar Region of Central Himalaya. *Research Journal of Forestry* 9(2): 35–47.

Bajpai O, Pandey J & Chaudhary LB (2017). Periodicity of different phenophases in selected trees from Himalayan Terai of India. *Agroforestry Systems* 91: 363–374.

Beckage B, Osborne B & Gavin DG (2008) *A rapid upward shift of a forest ecotone during 40 years of warming in the Green Mountains of Vermont. Proceedings of the National Academy of Sciences of the USA (PNAS)* 105: 4197–4202.

Both C & Visser ME (2001) Adjustment to climate change is constrained by arrival date in a long-distance migrant bird. *Nature* 411: 296–298.

Bradley BA, Oppenheimer M & Wilcove DS (2009) Climate change and plant invasion: restoration opportunities ahead? *Glob Change Biology* 15: 1511–1521.

Bruckschen P, Oesmann S & Veizer J (1999) Isotope stratigraphy of the European Carboniferous: proxy signals for ocean chemistry, climate and tectonics. *Chemical Geology* 161(3): 127–163.

Chaturvedi RK & Raghubanshi AS (2014) Species Composition, Distribution and Diversity of Woody Species in tropical dry forest of India. *Journal of Sustainable Forestry* 33(8): 729–756.

Chaturvedi RK & Raghubanshi AS (2016) Leaf life-span dynamics of woody species in tropical dry forests of India. *Tropical Plant Research* 3(1): 199–212.

Chaturvedi RK, Raghubanshi AS & Singh JS (2011) Effect of small scale variations in environmental factors on the distribution of woody species in tropical deciduous forests of Vindhyan Highlands, India. *Journal of Botany* 2011: Article ID 297097 [DOI:10.1155/2011/297097]

Chaturvedi RK, Raghubanshia AS & Singh JS (2012) Effect of grazing and harvesting on diversity, recruitment and carbon accumulation of juvenile trees in tropical dry forests. *Forest Ecology and Management* 284(2012): 152–162;

Chaturvedi RK, Raghubanshia AS, Tomlinson KW & Singh JS (2017) Impacts of human disturbance in tropical dry forestsincrease with soil moisture stress. *Journal of Vegetation Science* 28(5): 997–1007.

Chen I-C, Hill JK, Ohlemüller R, Roy DB & Thomas CD (2011) Rapid range shifts of species associated with high levels of climate warming. *Science* 333: 1024–1026.

Colautti RI, Alexander JM, Dlugosch KM, Keller SR & Sultan SE (2017) Invasions and extinctions through the looking glass of evolutionary ecology. *Philosophical Transactions of the Royal Society Biological Science* 372: 20160031. [DOI: 10.1098/rstb.2016.0031]

Colwell RK, Brehm G, Cardelu CL, Gilman. AC & Longino JT (2008) Global warming, elevational range shifts, and lowland biotic attrition in the wet tropics. *Science* 322: 258–261.

Dainese M, Kuhn I & Bragazza L (2014) Alien plant species distribution in the European Alps:influence of species' climatic requirements. *Biological Invasions* 16: 815–831.

Doi H & Katano I (2007) Phenological timings of leaf budburst with climate change in Japan. *Agricultural and Forest Meteorology* 148: 512–516.

Donovan LA, Rosenthal DM, Sanchez-velenosi M., Rieseberg LH & Ludwig F (2010) Are hybrid species more fit than ancestral parent species in the current hybrid species habitats? *Journal of Evolutionary Biology* 23: 805–816.

Dukes JS & Mooney H.A (1999) Does global change increase the success of biological invaders? *Trends in Ecology & Evolution* 14: 135–139.

Fei S, Desprez JM, Potter KM, Jo I, Knott JA & Oswalt CM (2017) Divergence of species responses to climate change. *Science Advances* 3: e1603055. [DOI: 10.1126/sciadv.1603055]

Fitter AH & Fitter RSR (2002) Rapid changes in flowering time in British plants. *Science* 296: 1689–1691.

Forest CE (1999) Paleoaltimetry incorporating atmospheric physics and botanical estimates of paleoclimate. *Geological Society of American Bulletin* 111(4): 497–511.

Fowbert JA & Smith LRI (1994) Rapid population increases in native vascular plants in the Argentine Islands, Antarctic Peninsula. *Arctic and Alpine Research* 26: 290–296.

Hansen J, Sato M, Ruedy R, Lea DW & Medina-Elizade M (2006) Global temperature change. *Proceedings of the National Academy of Sciences of the USA (PNAS)* 103: 288–293.

Hoffmann AA & Sgro CM (2011) Climate change and evolutionary adaptation: A review. *Nature* 470: 479–485.

IPCC (2007) Summary for policymakers. In: Solomon, et al. (eds) *Climate change 2007: The physical science basis.* Fourth Assessment Report, Intergovernmental Panel on Climate change. Cambridge University Press, Cambridge, UK.

Keatley MR, Fletcher TD, Hudson IL & Ades PK (2002) Phenological studies in Australia: potential application in historical and future climate analysis. *International Journal of Climatology* 22: 1769–1780.

Kelly AF & Goulden ML (2008) Rapid shifts in plant distribution with recent climate change. *Proceedings of the National Academy of Sciences of the USA (PNAS)* 105: 11823–11826.

Kullman L (2001) 20th century climate warming and tree-limit rise in the southern Scandes of Sweden. *Ambio* 30: 72–80.

Kumari P & Choudhary AK (2016) Exotic species invasion threats to forests: A case study from the Betla national park, Palamu, Jharkhand, India. *Tropical Plant Research* 3(3): 592–599.

Lande R (2009) Adaptation to an extraordinary environment by evolution of phenotypic plasticity and genetic assimilation. *Journal of Evolutionary Biology* 22: 1435–1446.

Lenoir J, Gégout JC, Pierrat JC, Bontemps JD & Dhôte JF (2009) Differences between tree species seedling and adult altitudinal distribution in mountain forests during the recent warm period (1986–2006). *Ecography* 32: 765–777.

Lone PA, Dar JA, Subashree K, Raha D, Pandey PK, Ray T, Khare PK & Khan ML (2019) Impact of plant invasion on physical, chemical and biological aspects of ecosystems: A review. *Tropical Plant Research* 6(3): 528–544.

Martin-R MH, Cox JR & Ibarraf F (1995) Climatic effects on buffelgrass productivity in the Sonoran Desert. *Journal of Range Management* 48: 60–63.

Menzel A, Sparks TH & Estrella N (2006) European phenological response to climate change matches the warming pattern. *Global Change Biology* 12: 1969–1976.

NAS (2001) *Climate change science: An analysis of some key questions.* National Academy of Sciences (NAS), National Academy Press, Washington D.C.

NSIDC (2013) *State of the Cryosphere*. National Snow and Ice Data Center (NSIDC), Nsidc.org. Available from: http://nsidc.org/sotc/sea_ice.html. (accessed: 01 Dec. 2013).

Oppenheimer C (2003) Climatic, environmental and human consequences of the largest known historic eruption: Tambora volcano (Indonesia) 1815. *Progress in Physical Geography* 27(2): 230–259.

Parmesan C (2006) Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics* 37: 637–669.

Penuelas J & Boada M (2003) A global change-induced biome shift in the Montseny mountains (NE Spain). *Global Change Biology* 9: 131–140.

Pimentel D, Lach L, Zuniga R & Morrison D (2000) Environmental and economic costs of nonindigenous species in the United States. *Bioscience* 50: 53–65.

Pucko C, Beckage B, Perkins T & Keeton WS (2011) Species shifts in response to climate change: Individual or shared responses? *The Journal of the Torrey Botanical Society* 138(2): 156–176.

Rogers CE & McCarty JP (2000) Climate change and ecosystems of the mid-Atlantic region. *Climate Research*

14: 235–244.

Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C & Pounds A (2003) Fingerprints of global warming on wild animals and plants. *Nature* 421: 57–60.

Sala OE, Stuart CF & Armesto JJ (2000) Global biodiversity scenarios for the year 2100. *Science* 287: 1770–1774.

Schwartz MD & Reiter BE (2000) Changes in North American spring. *International Journal of Climatology* 20: 929–932.

Seiz G & Foppa N (2007) The activities of the World Glacier Monitoring Service (WGMS) report.

Stotz GC, Gianoli E & Cahill JF Jr (2016) Spatial pattern of invasion and the evolutionary responses of native plant species. *Evolutionary Applications* 9(8): 939–951.

Sykes MT (2009) Climate Change Impacts: Vegetation. In: *Encyclopedia of Life Sciences (ELS)*. John Wiley & Sons, Ltd., Chichester.

Theurillat JP & Guisan A (2001) Potential impact of climate change on vegetation in the European Alps: a review. *Climatic Change* 50: 77–109.

Walther GR, Beibner S & Burga CA (2005) Trends in the upward shift of alpine plants. *Journal of Vegetation Science* 16: 541–548.

Walther GR, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin JM, Guldberg OH & Bairlein F (2002) Ecological responses to recent climate change. *Nature* 416: 389–395.

Whitney KD & Gabler CA (2008) Rapid evolution in introduced species, ‘invasive traits’ and recipient communities: challenges for predicting invasive potential. *Diversity and Distributions* 14: 569–580.

Williams SE, Shoo LP, Isaac JL, Hoffmann AA & Langham G (2008) Towards an integrated framework for assessing the vulnerability of species to climate change. *PLoS Biology* 6: 2621–2626.

Wolfe DW, Scwatrz MD & Lakso AN (2005) Climate Change and shifts in spring phenology of three horticultural woody perennials in northeastern USA. *International Journal of Bio-meteorology* 49: 303–309.

Yadav V, Singh NB, Singh H, Singh A & Hussain I (2016) Allelopathic invasion of alien plant species in India and their management strategies: A review. *Tropical Plant Research* 3(1): 87–101.

Zavaleta E (2000) The economic value of controlling an invasive shrub. *Ambio* 29: 462–467.

Ziska LH, Sicher RC, George K & Mohan JE (2007) Rising atmospheric carbon dioxide and potential impacts on the growth and toxicity of poison ivy (*Toxicodendron radicans*). *Weed Science* 55: 288–292.