Forest Science and Technology

ISSN: 2158-0103 (Print) 2158-0715 (Online) Journal homepage: https://www.tandfonline.com/loi/tfst20

An overview of interrelationship between climate change and forests

Inkyin Khaine & Su Young Woo

To cite this article: Inkyin Khaine & Su Young Woo (2015) An overview of interrelationship between climate change and forests, Forest Science and Technology, 11:1, 11-18, DOI: 10.1080/21580103.2014.932718

To link to this article: https://doi.org/10.1080/21580103.2014.932718

Published online: 05 Aug 2014.

Forest Science and Technology
Vol. 11, No. 1, March 2015, 11–18

Taylor & Francis
Taylor & Francis Group

An overview of interrelationship between climate change and forests

Inkyin Khaine[a,b] and Su Young Woo[a*]

[a]*Department of Environmental Horticulture, University of Seoul, Seoul 130–743, Republic of Korea;* [b]*Forest Department, Ministry of Environmental Conservation and Forestry, Naypyitaw, Myanmar*

(*Received 27 March 2014; Accepted 4 June 2014*)

Global warming is a well-known natural phenomenon that needs to be controlled for environmental conservation. Based on the ecological interrelationship between forest and climate, the concept of our review was formulated with the aim of providing current information about deforestation and its effects on climate change, the impacts of climate change on forests and the role of forests in climate change. Based on recent research findings, the annual rate of deforestation is 0.14% per year with 2.3 million square kilometers lost between 2000 and 2012. The net carbon emission from deforestation and forest degradation, which can cause climate change, was high and it has not changed significantly over the last two decades. On the other hand, temperature, drought, precipitation and fire can affect forest health (especially for young trees). But if we define these factors in detail, solar radiation alone may not affect tree growth, although together with temperature it can affect growth. Moreover, the frequency of fire affected the regeneration of tropical moist deciduous and Amazonian forest types more significantly than temperate and tropical dry deciduous forest types. Non-equilibrium species distribution has been occurring and frequency of species has been changed throughout the world. However, the amount of carbon storage by world forests is significant (650 billion tons) although carbon sequestration potential varies with forest types and water deficiency.

Keywords: global warming; deforestation; forests types; water deficiency; carbon storage

Introduction

Living and non-living organisms, their ecosystems, the environment and climatic conditions can be considered as dependent components of the world on each other and their balance is essential for the sustainability and stability of the world. According to the Intergovernmental Panel on Climate Change (IPCC) report, global average temperature of the period 1880–2012 has increased by 0.85 °C and the temperature increase between the 1850–1900 period and the 2003–2012 period was 0.78 °C (IPCC 2013). Consequently, the rate of sea level rise was also high (annual rate of 3.2 mm/yr). Furthermore, carbon dioxide (CO_2) concentration has increased by more than 25% during the last century (Smith and Smith 2009), and according to the IPCC fifth assessment report of climate change, CO_2 concentration has increased by 40% primarily due to two anthropogenic processes: fossil fuel emission and deforestation (land use change) (IPCC 2013).

There is no doubt that these recent climate changes can intrinsically affect forest ecosystems. Severe climate change is one of the causes of deforestation, which can lead to desertification, while at the same time this deforestation is a major driver of climate change. The increasing temperature and drought have negative impacts on species diversity as well as ecosystem goods and services to humanity (Gnacadja and Lesch 2009). This review focuses on climate change and forests based on the ecological concept of the interdependent natures of climate and ecosystems (Figure 1). So, we review, firstly, the deforestation and its effects on climate change; secondly, the impacts of that climate change on forests; and then the role of forests on carbon sequestration and its relation to climate change.

Deforestation and its effects on climate change

The major drivers of climate change can be divided into two types: anthropogenic causes such as land use changes, deforestation and forest degradation, fossil fuel burning and industrial processes and natural causes such as solar radiation changes and volcanic activity. So, deforestation and forest degradation play a role in global climate change, and reciprocally, deforestation is indirectly affected by climate change.

About 10,000 years ago, the world's forests covered around 6 billion hectares which is about 45% of total land area. However, the forest covers has been decreasing from that period and only about 31% of the world's area is covered by forests in 2010 (FAO 2010). Agricultural expansion including shifting cultivation is one of the major anthropogenic divers for deforestation in the tropical region (Houghton 2012). According to the reports of the Forest and Agrculture Organization (FAO), annual rate of deforestation is 0.14% per year (5.2 million hectares per year of net annual deforestation) (FAO 2010; FAO 2012) and, during the twenty-first century, deforestation was slow in temperate forests whereas deforestation was still high in tropical forests (FAO 2012).

Globally, greenhouse gas (GHG) emissions from deforestation and forest degradation have been found to

*Corresponding author. Email: woosuyoung19@naver.com

ISSN 2158-0103 print/ISSN 2158-0715 online

http://dx.doi.org/10.1080/21580103.2014.932718
http://www.tandfonline.com

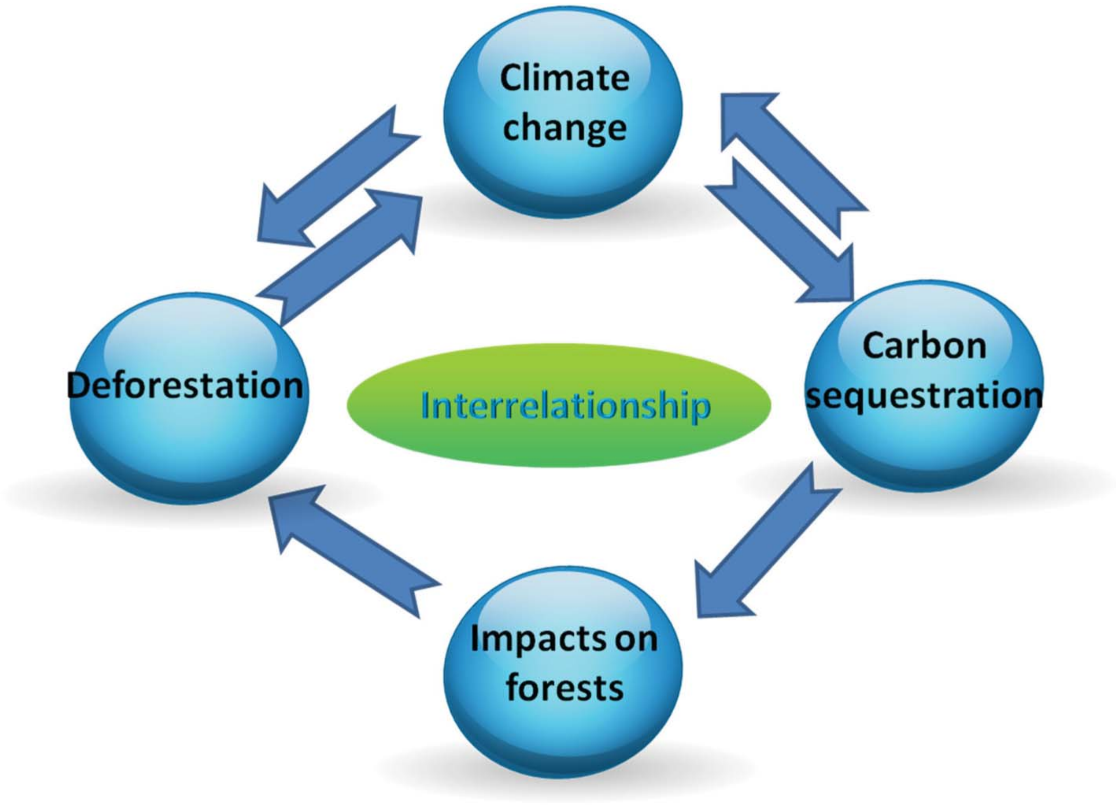

Figure 1. Relationship between climate change and forest ecosystem according to recent studies.

account for about one-fifth of the total GHG emissions. Among the GHGs, annual CO_2 emission by anthropogenic land use change in the world was 0.9 Gt C/yr (IPCC 2013). Houghton (2012) revealed that, in the tropics, 1.4 ± 0.5 Pg C/yr came from emission of carbon from deforestation and forest degradation over the period of 1990 to 2010. Evidence of vast impacts on climate change by CO_2 emission from deforestation was found in Indonesia and Brazil, which are the third and fourth largest CO_2 emitters of the world.

The net annual carbon emission from deforestation and forest degradation has seen no significant change over the last two decades (Houghton 2012). Hansen et al. (2013) revealed that 2.3 million square kilometers of world forest area have been lost between 2000 and 2012 and only 0.8 million square kilometers of forest have been created. Based on the above considerations, deforestation and forest degradation are vital considerations for sound environmental management because they significantly affect on climate change, and the rate of deforestation has not been reduced until now.

Impacts of climate change on forests

Forest growth

Tree and forest growth rate is significantly correlated with climate. The growth rate is strongly influenced by water availability (Toledo et al. 2011). If there is sufficient water availability, a short and not very intense dry period, and high temperature, a high growth rate will be found (Toledo et al. 2011). In lowland Bolivia where the temperature ranges from 24.2 to 26.4 °C with a 4−7 month dry season, the diameter and basal area tree growth rate increased with increased temperature and annual precipitation, but the growth rate decreased with increased dry period (Table 1). Vayreda et al. (2012) undertook research work in peninsular forest where mean temperature ranged from 4 to 18 °C and found that water availability had a

Table 1. Correlation between climate factor and growth rate.

Variables	Diameter growth rate	Basal area (stand) growth rate
Temperature (°C)	0.44 (Pearson correlation coefficient) $p \leq 0.01$	0.39 (Pearson correlation coefficient) $p \leq 0.01$
Precipitation (mm)	0.41 (Pearson correlation coefficient) $p \leq 0.01$; t value = 15.19, $p < 0.0001$	0.37 (Pearson correlation coefficient) $p \leq 0.01$
Dry period (< 100 mm)	−0.48 (Pearson correlation coefficient) $p \leq 0.01$	-0.33 (Pearson correlation coefficient) $p \leq 0.01$
Soil water content	t value = 10.04, $p < 0.0001$	
Solar radiation	t value = 13.48, $p < 0.0001$; R^2 = 0.88, $p < 0.001$	

positive relation with growth rate but mean temperature showed a negative relation ($R^2 = 0.622$, $p < 0.001$). In pan-tropical forests, also, the precipitation and soil water content had positive correlations with tree growth rate (Wagner et al. 2014).

Solar radiation is another factor that affects tree growth rate. However, the effect on tree growth rate is more significant if solar radiation effect is combined with temperature effect. Variation in solar radiation and temperature together affected tree growth rate at stand level although each factor separately did not affect tree growth rate (Dong and Moorcroft 2011). In tropical forests of the Neotropics, South and Southeast Asia, and Africa, the correlation between variation in tree growth rate at stand level and variation in incoming solar radiation was positive whereas correlation between the growth rate and nighttime temperature was negative at $R^2 = 0.88$, $p < 0.001$ level (Dong and Moorcroft 2011). Wagner et al. (2014) showed that precipitation and solar radiation had a positive association with tree growth at $p < 0.0001$. Precipitation caused 19.82% of tree growth variation while solar radiation caused 16.3% of growth variation. Moreover, the combined impacts of precipitation, solar radiation, temperature increase and soil water content caused 29.79% of tree growth variation in pan-tropical forests ($p < 0.001$). In polar regions, solar weighted UV-B radiation caused 10% reduction in plant height at $p < 0.05$ (Newsham and Robinson 2009).

Forest regeneration

Climate changes such as high range of temperature shift and high variation in water availability can limit the regeneration capacity of tree species because tree seedlings are very susceptible to climate change. In Eucalyptus forest of Australia, it was shown that tree species regeneration will be affected at both the landscape level and site level in future decades by increasing temperature in the range of 1.0−4.5 °C and decreasing precipitation by 3 to 25%. But decreasing or increasing rate of regeneration varied between species and between ecosystem (Mok et al. 2012). Moreover, a threshold of a shift in species regeneration niches has been found because of these climatic variations. In the Central Highlands region of Victoria of Australia, *Eucalyptus delegatensis* and *Eucalyptus pauciflora* species are sensitive to climate change. These species niches retreated from lower elevation and concentrated at higher elevation because of temperature increase and precipitation decrease (Mok et al. 2012). In temperate forests, seedling mortality rate of *Aextoxicon punctatum* was significantly affected by reduced precipitation and increased temperature (Parada and Lusk 2011).

Drought can be considered as one of the limitations for seedling establishment. Drought-induced canopy losses of *Pinus sylvestris* can reduce understory *Quercus* spp. germination although they can favor the growth of light-demanding species which have already established before drought (Galiano et al. 2013). Furthermore, one of the consequences of climate change, fire, can affects seedling density. In tropical moist deciduous forest, the seedling density of burned forest was 63% lower than unburned forest (Kodanadapani et al. 2008). Additionally, frequency of fire can change seedling density. In tropical dry thorn forest, the seedling density of forest which had been affected by moderate and high fire frequency was greater than that of the forest which had been affected by lower fire frequency. The seedling density of forest with moderate fire frequency was 82% greater than that of the forest with lower fire frequency while the seedling density of forest with high fire frequency was 47% greater than that of the forest with lower fire frequency (Table 2). However, in tropical dry deciduous forest, seedling density was 30% lower in forest which had high frequency of fire than forest with low frequency of fire. There was no significant difference between medium (two to five fires) and high (over five fires) frequency of fire (Kodanadapani et al. 2008). In Amazonian forests, the seedling density showed 63% and 85% reduction in forest burned twice and forest burned five times, respectively (Balch et al. 2013). In transitional dry forest types, number of seedlings appeared to be more than five times higher in unburned plots than in burned plots (Massad et al. 2013). The research findings relating to seedling survival are shown in Table 2.

Species composition and diversity

Drought and heat impacts of climate change can cause tree mortality that alters species composition and diversity (Allen et al. 2010). Likewise, species distribution and migration are directly affected by fire responses to climate change. In tropical lowland and moist forests, water deficiency increased the rate of tree mortality and this effect was severe by increasing frequency and rate of water deficiency (Nishimua et al. 2007). However, tropical moist forests have a greater tendency to resist water shortage compared with tropical dry forests. Therefore species mortality through water deficiency was found to occur more in the tropical dry forests, and it severely affected trees of small diameter (Suresh et al. 2010).

Another factor that can change the species composition and stand structure is fire. In both tropical moist and dry deciduous forests, seedling and sapling densities decreased and species diversities decreased by 50% and 60% by moderate and intense fire frequency, respectively when compared with low fire frequency (Kodanadapani et al. 2008; Massad et al. 2013). In coniferous and evergreen forest, the number of species was lower in both severely and moderately burned forest than unburned coniferous forest. The same condition was found in mixed coniferous and evergreen broad-leaved forest (Tang et al. 2013). Natural fire also affects the survival percentage of species. In lowland tropical rainforest which had been affected by natural fire 2 years before the experiment, the survival percentage of the burned area (32%) was significantly lower than that of the unburned area (91%) (Cerda et al. 2012). Table 3 shows the climate change effects on species composition and density.

Table 2. Seedling survival among different forest types.

Forest type	Parameters	Variables and descriptions		Citation
		Variables	Numerical value	
Temperate forest (*Aextoxicon punctatum*)	Decreased rainfall and increased temperature (2-year study)	Seedling mortality	47 trees (38% of origin)	Parada and Lusk 2011
Transitional dry forests	Fire (comparison of three types: control, burn every 3 years and burn every year)	1. Number of seedlings in unburned plots 2. Number of seedlings in burned plots	3 to 97 0 to 15	Massad et al. 2013
Tropical dry deciduous forests	Fire (research on long- term 16-year period) (burned 1 time (low frequency), 2 to 5 times (medium frequency) and over 5 times (high frequency)	1. Seedling density per hectare in low frequency fire (L) 2. Seedling density per hectare in medium frequency fire 3. Seedling density per hectare in high frequency fire	1596 1101 (30% lower than L) 1120 (30% lower than L)	Kodanadapani et al. 2008
Tropical moist deciduous forests	Fire (research on long-term 16-year period) (burned 1 time (low frequency), 2 to 5 times (medium frequency) and over 5 times (high frequency)	1. Seedling density per hectare in unburned forest 2. Seedling density per hectare in burned forest	6270 2484 (63% lower)	Kodanadapani et al. 2008
Tropical dry thorn forests	Fire (research on long-term 16-year period) (burned 1 time (low frequency), 2 to 5 times (medium frequency) and over 5 times (high frequency)	1. Seedling density per hectare in low frequency fire (L) 2. Seedling density per hectare in medium frequency fire 3. Seedling density per hectare in high frequency fire	262 478 (82% higher than L) 355 (47% higher than L)	Kodanadapani et al. 2008
Amazonian forest	Fire (control, burn twice: triennially, burn five times: annually) (6-year period)	1. Regeneration density in the year before fire 2. Regeneration density in the year after fire	13.2(±3.1), 13.1 (±3.3), 12.4 (±2.4) (control, burn twice, burn five times) 7.3(±1.1), 4 (±0.6), 1.2 (±0.3) (control, burn twice, burn five times)	Balch et al. 2013

Table 3. Changes in species composition and density in response to climate change

Forest type	Parameters	Variables and descriptions: Variables	Variables and descriptions: Numerical value	Citation
Tropical dry deciduous forests	Fire (research on long-term 16-year period) (burned 1 time (low frequency), 2 to 5 times (medium frequency) and over 5 times (high frequency)	1. Number of tree species (low frequency) 2. Number of tree species (medium frequency) 3. Number of tree species (high frequency)	33 16 13	Kodanadapani et al. 2008
Tropical moist deciduous forests	Fire (research on long-term 16-year period) (burned 1 time (low frequency), 2 to 5 times (medium frequency) and over 5 times (high frequency)	1. Number of tree species (unburned) 2. Number of tree species (burned)	26 24 (8% lower)	Kodanadapani et al. 2008
Pine forest, mixed coniferous and evergreen broad-leaved forest	Intensity of fire (5 years after mega-fire)	1. Number of species in mixed coniferous and evergreen broad-leaved forest 2. Number of species in unburned pine forest 3. Number of species in moderately burned forest 4. Number of species in moderately burned forest	38 35 26 13	Tang et al. 2013
Tropical dry deciduous forests	Fire (research on long-term 16-year period) (burned 1 time (low frequency), 2 to 5 times (medium frequency) and over 5 times (high frequency)	1. Tree density (low frequency) 2. Tree density (medium frequency) 3. Tree density (high frequency)	441 320 324	Kodanadapani et al. 2008)
Tropical moist deciduous forests	Fire (research on long-term 16-year period) (burned 1 time (low frequency), 2 to 5 times (medium frequency) and over 5 times (high frequency)	1. Tree density (unburned) 2. Tree density (burned)	496 300	Kodandapani et al. 2008
Tropical rain forest	Time after fire (original (A1), 1 year after fire (A2), two years after fire (A3))	1. Tree density (unburned) 2. Tree density (burned)	762 (A1) 710 (A2) 693 (A3) 1101 (A1) 563 (A2) 355 (A3)	Cerda et al. 2012

Forest habitat and forest ecosystems

A habitat can be defined as a natural environment or natural region that is inhabited by particular species or living organisms, and an ecosystem consists of abiotic and biotic components that depend on each other and exist together in balance with the corresponding surrounding environment. Forest habitats and forest ecosystems respond to climate change. According to Garcia-Valdes et al. (2013), who used an inventory and model, montane conifer (*Pinus sylvestris*), sub-Mediterranean conifer (*Pinus nigra*) and sub-Mediterranean deciduous (*Quercus pyrenaica*) oak are facing high vulnerability to climate change, whereas low vulnerabilities to climate change was found in *Quercus robur*, *Quercus petraea*, *Pinus pinaster*, *Quercus faginea and Quercus ilex* species. But some species, *Pinus pinea* and *Pinus halepensis*, have been found the increase in their frequency of occurrence with climate change. By simulation analysis, the number of trees of *Pinus halepensis* species will increase 50% with climate change in comparison with a stable climate by 2100. Nevertheless, most of the species in Iberian Peninsula region have a non-equilibrium species distribution, which means distributional shift (increased regional frequency) could be found even in a stable climate (Garcia-Valdes et al. 2013). On the other hand, a long history of anthropogenic activities and a good forest management system should also be considered as one of the factors for increasing species occurrence. All the above findings relate to common species only. However, the habitat losses of endemic species in the Australian alpine region were found to be a consequence of shifting of species from other regions in response to a warming climate. Habitat losses had positive correlation with endemic species richness (Dirnbock et al. 2011). In the Eastern United States, most of the tree species have reduced their habitats even though a few species expanded their habitats because of the warming climate (Zhu et al. 2012). But the changes in precipitation alone were not shown to be related to species distribution pattern (Zhu et al. 2012). Tree species make natural adjustments to respond to global warming by shifting to higher latitudes for their survival (Chen et al. 2011).

Role of forest in climate change

The role of forests in environmental stability can be seen as a wide range in the ecosystem. Forest carbon storage capacity is significantly affected by environmental conservation. The forests of the world store over 650 billion tons of carbon in various components: 44% in the biomass, 45% in the soil and 11% in dead wood and litter (FAO 2010). In the Asia and Oceania region, the carbon storage of tropical forests ranged from 89 Mg C/ha to 180 Mg C/ha whereas the carbon storage of tropical forests in Latin America and Sub-Saharan Africa ranged from 84 Mg C/ha to 160 Mg C/ha and from 44 Mg C/ha to 165 Mg C/ha, respectively (Saatchi et al. 2011). The aboveground carbon stock accumulated in vegetation of tropical teak dominant forest in India was found to be 112.19 Mg C/ha (Juwarkar et al. 2011). However, aboveground carbon storage of tropical teak-dominant forest in Myanmar is higher than that of India. Aboveground carbon storage of tropical teak dominant forest in Myanmar ranged from 185.2 Mg C/ha to 227.7 Mg C/ha and the total carbon storage ranged from 413.7 Mg C/ha to 480.5 Mg C/ha (Oo et al. 2009). In the temperate forest of Central Mexico, carbon storage ranged from 42.63 Mg C/ha to 181.88 Mg C/ha whereas carbon storage in temperate grassland ranged from 3.74 Mg C/ha to 9.83 Mg C/ha (Mendoza-Ponce and Galicia 2010). Mangrove forests are the most carbon rich forests among various forest types. In the Indo-Pacific region, mangrove forests store an average of 1023 Mg C/ha, and if these mangrove forests are differentiated in detail into two groups, estuarine and oceanic, estuarine mangroves store 1074 Mg C/ha whereas oceanic mangroves store 990 Mg C/ha (Donato et al. 2011). Global forests show substantial carbon sequestrations potential, which will vary depending on the canopy coverage of forests.

Climate change effects on forest's carbon sequestration potential

According to IPCC analysis, global carbon cycle has been affected and will be affected in future by climate change. Reduced precipitation affects the carbon storage and aboveground biomass of forests. In tropical lowland forest of Madagascar where the annual rainfall is about 3000 mm and mean temperature is approximately 27 °C, 2% of carbon storage (aboveground living biomass, deadwood pool and soil pool) is lost from the forest when the annual rainfall is reduced by 20%. But the impact is stronger when the annual rainfall is reduced by 60%: carbon storage was reduced by 22% in aboveground living biomass and by 25% in both soil pool and deadwood pool (Fischer et al. 2014). Increased water deficiency due to increased mean annual temperature and decreased annual precipitation is a dominant factor for reduction of biomass carbon sink. In Canada's boreal forests, the rate of biomass change showed a significant decrease over years in the region where increased water deficiency occurred (Ma et al. 2012). But in temperate and evergreen needle-leaf and deciduous broadleaf forests of the Southern United States, there was a net increase of carbon storage (0.8 $\pm$ 0.38 Pg) by the combined effects of temperature and precipitation, atmospheric CO_2, tropospheric O_3 concentration, nitrogen deposition and land use and land cover change. And, inter-annual carbon flux variation is significantly correlated with climate change ($R^2 = 0.85$, $p < 0.001$) (Tian et al. 2012). Climate change can increase the potential for forest fires, and forest fires can also reduce forest carbon storage. For example, in boreal forest of Finland, an increase of 1% in mean annual temperature and 2 to 5% in annual precipitation induced a 5% increase in forest fire potential in a 30-year period (Kilpenlainen et al. 2010), and carbon emission from combustion of surface and ground fuels ranged from 4.48 t C/ha to 15.89 t C/ha in southern Taiga Pine and mixed larch stands of the lower Angara region in Siberia, Russia (Ivanova et al. 2011). Moreover, solar UV-B radiation had a negative regression with aboveground biomass at $p < 0.01$. In polar regions, weighted solar UV-B radiation caused 14.7% reduction of aboveground biomass at $p < 0.05$ (Newsham and Robinson 2009). According to the meta-analysis of Ballaré et al. (2011), a 3% increase in weighted solar UV-B irradiance can cause a 1% reduction in biomass growth.

Discussion

Forests on a worldwide scale have already affected and responded to climate change. Tropical forests have been found to be vulnerable to the impacts of climate change although temperate broad-leaved and Mediterranean species are less affected. Global forests have been changing over past decades and tropical forests have been significantly reduced by annual loss of 2101 km^2/yr (Hansen et al. 2013). Deforestation is the one of the major causes of climate change, and climate change may have impacts on forest health that lead to deforestation and degradation, reciprocally. In the United States, the major disturbances that greatly affect forests are fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, and landslides (Dale et al. 2001). Seedlings are more susceptible to impacts of climate change. Furthermore, mortality rate of seedlings in forest burned by annual fire appeared to be higher than triennially burned forest. However, natural disturbances always interact with anthropogenic activities in general. There have been many research studies relating to the causes and impacts of deforestation and degradation; nonetheless investigation of the extent of management effects on mitigation of deforestation is still needed. This review aimed to summarize the current impacts of climate change on forest health among different forest types to support fundamental information for sound environmental management.

Funding

The authors wish to thank Korea Ministry of Environment (MOE) for the support under the "Environmental Health Action Program."

References

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, Kitzberger T, Rigling A, Breshears DD, Hogg EH, Gonzalez P, Fensham R, Zhang Z, Castro J, Demidova N, Lim JH, Allard G, Running SW, Semerci A, Cobb N. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For Ecol Manag. 259:660−684.

Balch JK, Massas TJ, Brando PM, Nepstas DC, Curran LM. 2013. Effects of high-frequency understorey fires on woody plant regeneration in southern Amazonian forests. Phil Trans R Soc. 368:1−10.

Ballaré CL, Caldwell MM, Flint SD, Robinson SA, Bornman JF. 2011. Effects of solar ultraviolet radiation on terrestrial ecosystems. Patterns, mechanisms, and interactions with climate change. Environmental effects of ozone depletion and its interactions with climate change. United Nations Environmental Programme, Nairobi, Kenya: Photochem & Photobiol; p. 83−111.

Cerda IGI, Lloret F, Ruiz JE, Vandermeer JH. 2012. Tree mortality following ENSO-associated fires and drought in lowland rain forests of Eastern Nicaragua. For Ecol Manag. 265:248−257.

Chen IC, Hill JK, Ohlemuller R, Roy DB, Thomas CD. 2011. Rapid range shifts of species associated with high levels of climate warming. Science. 333:1024−1026.

Dale VH, Joyce LA, Mcnulty S, Neilson RP, Ayres MP, Flannigan MD, Hanson PJ, Irland LC, Lugo AE, Peterson CJ, Simberloff D, Swanson FJ, Stocks BJ, Wotton BM. 2001. Climate change and forest disturbances. Bioscience. 51:723−734.

Dirnbock T, Essl F, Rabitsch W. 2011. Disproportional risk for habitat loss of high-altitude endemic species under climate change. Global Change Biol. 17:990−996.

Donato DC, Kauffman JB, Murdiyarso D, Kurnianto S, Stidham M, Kanninen M. 2011. Mangroves among the most carbon-rich forests in the tropics. Naturegeoscience 10:1−5.

Dong SX, Moorcroft PR. 2011. The structure and dynamics of tropical forests in relation to climate variability. Cambridge (MA), United States: Harvard University.

[FAO] Food and Agriculture Organization of United Nations. 2012. State of the World's forests. Rome, Italy: Food and Agriculture Organization of United Nations.

[FAO] Food and Agriculture Organization of United Nations. 2010. Global forest resources assessment. Rome, Italy: Food and Agriculture Organization of United Nations.

Fischer R, Armstrong A, Shugart HH, Huth A. 2014. Simulating the impacts of reduced rainfall on carbon stocks and net ecosystem exchange in a tropical forest. Env Model Soft. 52:200−206.

Galiano L, Martinez-Vilalta J, Eugenio M, Cerda IG, Lloret F. 2013. Seedling emergence and growth of *Quercus* spp. following severe drought effects on a *Pinus sylvestris* canopy. J Veg Sci. 24:580−588.

Garcia-Valdes R, Zavala MA, Araujo MB, Purves DW. 2013. Chasing a moving target: projecting climate change-induced shifts in non-equilibrial tree species distributions. J Ecol. 101:441−453.

Gnacadja L, Lesch AK. 2009. Running dry? Climate change in drylands and how to cope with it. Germany: München.

Hansen MC, Potapov PV, Moore R, Hancher M, Turubanova SA, Tyukavina A, Thau D, Stehman SV, Goetz SJ, Loveland TR, Kommareddy A, Egorov A, Chini L, Justice CO, Townshend RG. 2013. High-resolution global maps of 21st-century forest cover change. Science 342:850−853.

Houghton RA. 2012. Carbon emissions and the drivers of deforestration and forest degradation in the tropics. SciVerse ScienceDirect 4:597−603.

[IPCC] Intergovermental Panel on Climate Change. 2013. Contribution to the IPCC fifth assessment report climate change WG I, 2013: The physical science basis summary for policymakers. Stockholm, Sweden: IPCC working group I.

Ivanova GA, Comard SG, Kukavskaya EA, McRae DJ. 2011. Fire impact on carbon storage in light conifer forests of the Lower Angara region, Siberia. Environ Res Lett. 6:1−6.

Juwarkar AA, Varghese AO, Singh SK, Aher VV, Thawale PR. 2011. Carbon sequestration potential in aboveground biomass of nature reserve forest of central India. Res and Rev. 2:80−86.

Kilpenlainen A, Kellomaki S, Strandman H, Venalainen A. 2010. Climate change impacts on forest fire potential in boreal conditions in Finland. Climate Change. 103:383−398.

Kodanadapani N, Cochrane MA, Sukumar R. 2008. A comparative analysis of spatial, temporal, and ecological characteristics of forest fires in seasonally dry tropical ecosystems in the Western Ghats, India. For Ecol Manag. 256:607−617.

Ma Z, Peng C, Zhu Q, Chen H, Yu G, Li W, Zhou X, Wang W, Zhang W. 2012. Regional drought- induced reduction in the biomass carbon sink of Canada's boreal forests. PNAS. 109:2423−2437.

Massad TJ, Balch JK, Davidson EA, Brando PM, Mews CL, Porto P, Quintino RM, Vieira SA, Junior BHM, Trumbore SE. 2013. Interactions between repeated fire, nutrients, and insect herbivores affect the recovery of diversity in the southern Amazon. Oecol. 172:219−229.

Mendoza-Ponce A, Galicia L. 2010. Aboveground and belowground biomass and carbon pools in highland temperate forest landscape in Central Mexico. Forestry. 83:497−506.

Mok HF, Arndt SK and Nitschke CR. 2012. Modelling the potential impact of climate variability and change on species regeneration potential in the temperate forests of South-Eastern Australia. Global Change Biol. 18:1053−1072.

Newsham KK, Robinson SA. 2009. Responses of plants in polar regions to UVB exposure: a meta-analysis. Global Change Biol. 15:2574−2589.

Nishimua TB, Suzuki E, Kohyama T, Tsuyuzaki S. 2007. Mortality and growth of trees in peat-swamp and heath forests in Central Kalimantan after severe drought. Plant Ecol. 188:165−177.

Oo TN, Hyun JO, Lee DK, Woo SY, Park PS, Cruz RVO. 2009. Carbon sequestration of tropical deciduous forests and forest plantations in Myanmar. Seoul, Republic of Korea: Seoul National University.

Parada T, Lusk CH. 2011. Pattern of tree seedling mortality in a temperate-mediterranean transition zone forest in Chile. Gayana Bot. 68:236−243.

Saatchi SS, Harris NL, Brown S, Lefsky M, Mitchard ETA, Salas W, Zutta BR, Buermann W, Lewis SL, Hagen S, Petrova S, White L, Silman M. 2011. Benchmark map of forest carbon stocks in tropical regions across three continents. PNAS. 108:9899−9904.

Smith TM, Smith RL. 2009. Elements of ecology. 7th ed. San Francisco: Pearson Benjamin Cummings, United State of America. Chapter 29, Global climate change; p. 622−646.

Suresh HS, Dattaraja HS, Sukumar R. 2010. Relationship between annual rainfall and tree mortality in a tropical dry forests: Results of a 19-years study at Mudumalai, southern India. For Ecol Manag. 259:762−769.

Tang CQ, He LY, Su WH, Zhang GF, Wang HC, Peng MC, Wu ZL and Wang CY. 2013. Regeneration, recovery and succession of a *Pinus yunnanensis* community five years after a mega-fire in central Yunnan, China. For Ecol Manag. 294:188−196.

Tian H, Chen G, Zhang C, Liu M, Sun G, Chappelka A, Ren W, Xu X, Lu C, Pan S, Chen H, Hui D, McNulty S, Lockaby G, Vance E. 2012. Century- scale responses of ecosystem carbon storage and flux ato multiple environmental changes in the southern United States. Ecosystems. 15:674−694.

Toledo M, Poorter L, Pena-Claros M, Alarcon A, Balcazar J, Leano C, Licona C, Lianque O, Vroomans V, Zuidema P, Bongers F. 2011. Climate is a stronger driver of tree and forest growth rates than soil and disturbance. J of Ecol. 99:254−264.

Vayreda J, Martinez-vilalta J, Gracia M and Retana J. 2012. Recent climate changes interact with stand structure and management to determine changes in tree carbon stocks in Spanish forests. Global Change Biol. 18:1028−1041.

Wagner F, Rossi V, Aubry-Kientz M, Bonal D, Dalitz, Gliniars R, Stahl C, Trabucco A, Hérault B. 2014. Pan-tropical analysis of climate effects on seasonal tree growth. PLOS ONE. 9 (2):e92337.

Zhu K, Woodall CW and Clark JS. 2012. Failure to migrate: lack of tree range expansion in response to climate change. Global Change Biol. 18:1042−1052.