ABIOTIC DISTURBANCES AND THEIR INFLUENCE ON FOREST HEALTH

2011

FOREST HEALTH & BIOSECURITY WORKING PAPER FBS/35E

Disclaimer

This paper is one of a series of FAO documents on forest-related health and biosecurity issues. The purpose of these papers is to provide early information about on-going activities and programmes, and to stimulate discussion.

Comments and feedback are welcome.

For further information, please contact:

Gillian Allard
Forestry Officer (Forest Protection and Health)
Forest Assessment, Management and Conservation Division
Forestry Department
FAO
Viale delle Terme di Caracalla
00153 Rome, Italy
Tel: + 39 06 570 53373
E-mail: gillian.allard@fao.org

Acknowledgements

The authors would like to thank FAO Forestry Department personnel, Nora Berrahmouni, Jim Carle, Thomas Hofer, Doug McGuire and Pieter van Lierop, for reviewing this document and providing valuable comments, and Roberto Cenciarelli and Tullia Baldassarri Höger von Högersthal for the design and layout.

Cover photos:
Lightning strikes, Canberra, Australia (flickr/PRESCOTT)
Dead vegetation in drought-stricken area, Senegal (FAO/CH. ERRATH/12787)
Chile’s Lonquimay Volcano erupting (FAO/R. GRISOLIA/21843)
Ice covers trees and power lines after a major storm, Canada (B. MOORE)
Flooded forest, Hungary (FAO/M. KERESZTES/FO-6082)

Forest Health and Biosecurity Working Papers

Abiotic disturbances and their influence on forest health

A review

Beverly A. Moore and Gillian Allard

2011

Forest Assessment, Management and Conservation Division
Forestry Department

Working Paper FBS/35E FAO, Rome, Italy

Contents

Foreword

The United Nations declared 2011 to be the International Year of Forests which aims to increase public awareness of forests' important ecological, economical and social functions. Forests provide shelter for people and habitat to biodiversity. They are a source of food, medicine and clean water and play a vital role in maintaining a stable global climate and environment. With such immeasurable values, protecting the world's forests from devastating disturbances is crucial.

Disturbances are a natural and integral part of forest ecosystems. When they exceed their normal range of variation, however, the impacts on forests can be extreme affecting entire landscapes, causing large-scale tree mortality and complete destruction of undergrowth and soils. Global climate change is exacerbating many of these impacts by making forests more prone to damage by altering the frequency, intensity and timing of some events such as cyclones, landslides, insect and disease outbreaks, and heat waves and droughts which increase the risk of large-scale fires.

Much more information is available on the impacts of biotic disturbances, such as pest outbreaks, on forests than on the impacts of abiotic disturbances, those caused by non-living factors such as storms, drought and tsunamis. FAO's Global Forest Resources Assessment (FRA), carried out at five-year intervals, provides the data and information needed to support policies, decisions and negotiations in all matters where forests and forestry play a part. For the first time ever, countries were asked to report on the area of forest damaged by abiotic disturbances for FRA 2010. Information provided was sparse, mostly qualitative and did not allow for any trend analysis. To supplement the information in FRA 2010, and in acknowledgement of the increasing importance of abiotic influences on forest health, FAO prepared this more detailed study.

Abiotic disturbances are expected to increase in intensity, quantity and frequency. Adaptive forest management is therefore essential to protect the world's forests resources. Effective management practices and policies are built upon relevant and timely information and accurate data on disturbances and their impacts on forests. This paper is a first step in synthesizing such information to assist with the management and protection of forest health. Taking care of the world's forests and effectively managing them not only ensures that they meet their objectives but also reduces the risk of damage from future abiotic disturbances and addresses global climate change concerns.

Jose Antonio Prado
Director, Forest Assessment, Management
and Conservation Division
FAO Forestry Department

EXECUTIVE SUMMARY

Abiotic disturbances, disturbances caused by non-living factors, are a natural and integral part of forest ecosystems that have major impacts, positive and negative. They influence forest structure, composition and functioning and can be important for maintaining biological diversity and facilitating regeneration. When disturbances exceed their normal range of variation, however, the impacts on forests can be extreme affecting entire landscapes, causing large-scale tree mortality and complete destruction of undergrowth and soils. Global climate change is exacerbating many of these impacts by making forests more prone to damage by altering the frequency, intensity and timing of some events such as cyclones, storms, landslides, insect and disease outbreaks, and heat waves and droughts which increase the risk of large-scale fires.

This paper reviews the current knowledge on the impacts of abiotic disturbances. Events are discussed within five categories:

- Meteorological – cyclones, storms (wind, snow, ice and hail, dust and sand), tornadoes, and thunderstorms and lightning;
- Climatological – drought;
- Hydrological – floods and flash floods, avalanches, landslides and mudslides;
- Geophysical – tsunamis, earthquakes and volcanic eruptions;
- Anthropogenic[1] – fire, oil spills, air pollution and radioactive contamination.

Almost 4 000 abiotic disturbance events occurred from 2000 to 2009, killing over one million people, impacting over 2.5 billion people and costing almost a trillion US dollars (over US$971 billion) (IFRC and RCS, 2010). While considerable information may exist on individual events, often little information is readily available on the specific impacts of an event on forests. Global reporting on such impacts, particularly quantitative information on areas affected, is low and sporadic. The data that is available however, indicates the significance, magnitude and severity of abiotic disturbances.

- For example, abiotic factors damaged 1.2 million hectares of forest in Sweden in 2005. The majority of the damage occurred as a result of a major storm that caused severe windthrow in the south of the country.
- Tropical Cyclone Sidr hit Bangladesh in 2007 affecting approximately 8.7 million people (FAO, 2008) and damaged nearly 1.5 million houses and 4.1 million trees. Approximately 20 000–25 000 hectares of the Sundarban mangrove forests, a UNESCO World Heritage Site, incurred severe damages and a further 60 000 hectares were partially damaged by the cyclone (FAO, 2008).
- The 2004 Indian Ocean Tsunami killed approximately 230 000 people, displaced more than one million people, and caused billions of dollars of property damage. In Indonesia, the hardest hit country, it was estimated that almost 49 000 hectares of coastal forests (not including mangroves) were impacted by the tsunami representing an economic loss of US$21.9 million and 300-750 hectares of mangrove forests suffered approximately 90 percent damage representing a loss of US$2.5 million (UNEP, 2005).
- The 2010 earthquake, and subsequent tsunami, in central Chile killed more than 700 people and caused widespread damage in many parts of the country. Temporary shutdowns at many of the country's pulp and paper producers occurred raising global pulp prices. Losses to Chile's economy were estimated at US$15-30 billion (UNEP, 2011).
- In 2010, over 32 000 fires in the Russian Federation burned approximately 2.3 million hectares of conifer and mixed forests, with some areas of peat bogs, killing 62 people and destroying hundreds of homes (Williams *et al.*, 2011).

---

[1] These anthropogenic, or human-caused, disturbances are included in this review since the agent itself, i.e. fire or pollutants, is abiotic or non-living.

- The 2010 floods in Pakistan affected over 18 million people and killed approximately 2 000 people, ruined crops, and damaged or destroyed 1.7 million homes as well as livestock, forests and wildlife (UNEP, 2011). The flood severely damaged the natural forests, plantations, community forests, trees grown for fuelwood, wildlife habitat and conservation areas (Khan *et al*., 2010).

The condition of forests themselves can have an influence on disturbances. For example, deforestation or poor management practices can increase flooding and landslides during cyclones and degradation of mangrove forests may increase the damage caused by storm surges or tsunamis. In some areas, climate change is increasing the incidence of drought and heat waves resulting in an increased risk and incidence of wildfires which in turn contributes to global warming through carbon emissions.

Abiotic disturbances will continue to increase in intensity, quantity and frequency. Adaptive forest management is therefore essential to protect the world's forest resources. Activities such as diversifying species, using windbreaks and mixed cropping patterns for resilience and not planting susceptible species in areas prone to abiotic disturbances can all help to reduce or divert potential impacts. Reducing the effects of disturbances on forests will contribute to countries' efforts to reduce carbon emissions from deforestation and forest degradation through forest conservation, sustainable forest management and enhancement of forest carbon stocks (REDD+)[2]. Taking care of the world's forests and effectively managing them not only ensures that they meet their objectives but also reduces the risk of damage from future abiotic disturbances and addresses global climate change concerns.

---

[2] Reducing Emissions from Deforestation and Forest Degradation (REDD) is an effort to create a financial value for the carbon stored in forests, offering incentives for developing countries to reduce emissions from forested lands and invest in low-carbon paths to sustainable development. "REDD+" goes beyond deforestation and forest degradation, and includes the role of conservation, sustainable management of forests and enhancement of forest carbon stocks (UNFCC, DECISION 1/CP.16).

INTRODUCTION

Disturbances are a natural and integral part of forest ecosystems. They influence forest structure, composition and functioning and can be important for maintaining biological diversity and facilitating regeneration. However, global climate change, primarily the result of human activities, is reportedly making forests more prone to damage by altering the frequency, intensity and timing of some events such as fires, cyclones, storms, landslides, and insect and disease outbreaks. When disturbances exceed their normal range of variation, the impacts on forests can be extreme. Poor management practices and climate-related shifts in the range of forest pest species can further exacerbate abiotic impacts on forest health.

Abiotic disturbances, disturbances caused by non-living factors, differ in duration, ranging from hours to days for cyclones or windstorms, weeks to months for fires, and days or weeks for volcanic eruptions (Turner, 2010). The timing of many disturbances is largely controlled by climate. Tropical cyclones, for example, typically occur from April to December in the Northern Hemisphere and from November to April in the Southern Hemisphere, tornadoes in spring and autumn, floods during seasons of precipitation or snowmelt, and fires during periods of low fuel moisture and high temperatures (Foster, Knight and Franklin, 1998).

Socio-economic impacts

Information on the number of abiotic disturbances, some estimates of their associated damage, and the number of people affected are available from several sources. The International Federation of Red Cross (IFRC) and Red Crescent Societies (RCS), for example, reported in their 2010 World Disasters Report that almost 4 000 such events occurred from 2000 to 2009 (Table 1; IFRC and RCS, 2010). Asia experienced the most natural disturbances during this period – 1 536 events representing over 38 percent of all those reported. The Americas experienced 943 natural disturbances, Africa – 716, Europe – 661 and Oceania – 158. Windstorms and floods together accounted for approximately 70 percent of the total abiotic natural disturbances reported and 72 percent of the total economic loss. Estimated damage from windstorms alone represented over 50 percent of the total costs for the decade. Earthquakes and tsunamis were the third costliest disturbance at over 18 percent of the total. It should be noted that the economic figures correspond to the damage value at the moment of the event and usually only represent direct damage. The numbers are the total for all reported damage (i.e. damage to infrastructure, crops, housing, etc.); specific costs for impacts on forests and the forest sector are not available. Estimates also vary depending on a country's economy and the financial values placed on items damaged such as infrastructure; values are much higher in developed countries. Also data on economic damages are missing for 67 percent of disturbances therefore these figures should be regarded as indicative (IFRC and RCS, 2010). Even with large gaps in reporting of economic impacts, it is quite clear that natural disturbances have substantial impacts.

Table 1. Total number of reported natural abiotic disturbances and the associated impacts, 2000-2009

Disturbance type	Number of events reported	Number of deaths reported	Number of people reported affected (thousands)	Estimated damage (US$ millions)
Droughts	273	230 181	1 025 446	26 811
Earthquakes/tsunamis	290	453 553	82 612	183 425
Extreme temperatures	237	90 743	85 651	39 798
Floods, waves, surges	1 739	53 795	949 112	186 584
Forest/scrub fires	142	636	2 140	24 651
Mass movement: dry and wet (landslides, avalanches)	201	7 905	1 574	1 212
Volcanic eruptions	61	230	1 556	193
Windstorms	1 054	172 334	400 144	508 717
Total abiotic disturbance	**3 997**	**1 009 377**	**2 548 234**	**971 391**

(*Source*: adapted from IFRC and RCS, 2010)

The most devastating impacts of abiotic disturbances are the loss of human lives, and the impacts on the survivors related to the loss of family members, homes, livelihoods and the basic necessities of life. People may die as a direct result of a disturbance or may succumb in the aftermath. Over one million people died as a result of the reported events from 2000 to 2009 (Table 1; IFRC and RCS, 2010). Earthquakes and tsunamis were the deadliest events, responsible for approximately 45 percent of all reported deaths; the majority of these attributable to the 2004 Indian Ocean disaster. Droughts resulted in the deaths of 23 percent of all extreme weather events reported and windstorms took the lives of approximately 17 percent. The total number of people affected by abiotic disturbances during the last decade is immense – over 2.5 billion – and illustrates the widespread impacts of these events. Drought impacted the greatest number of people, followed by floods and windstorms.

Impacts on forests

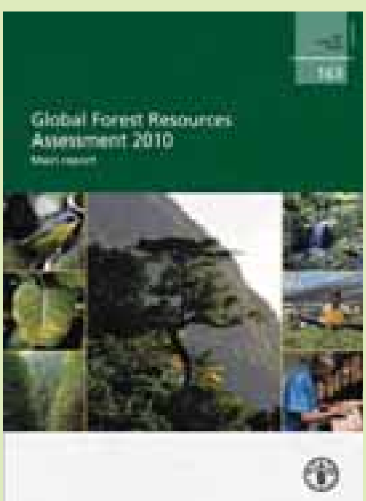
Seasonal timing of extreme events controls the potential range of impact in forest ecosystems. Trees with leaves are much more susceptible to blowdown by cyclones and tornadoes whereas late-season storms, occurring after leaf fall, create different impacts (Foster, Knight and Franklin, 1998).

Some disturbances may occur as individual discrete events or may occur concurrently or in quick succession with other events. For example, flooding and tornadoes often accompany tropical cyclones, earthquakes can trigger tsunamis, avalanches or landslides, and winter storms can trigger avalanches and also lead to flooding later in the season. Such combinations of disturbances will have an impact on the severity and pattern of the impacts observed in forests.

Each disturbance event affects forests differently; some cause extensive tree mortality, whereas others affect community structure and organization with little mortality. They can reduce leaf function, deform tree structure, cause tree death, alter regeneration patterns, disrupt the physical environment through soil erosion or nutrient loss, and increase landscape heterogeneity of forest communities (Dale *et al.*, 2000). The potential impacts of a disturbance depend on its severity or intensity, frequency of occurrence, duration, spatial scale, and point(s) of interaction with the ecosystem (Lugo, 2008). The impacts of disturbances are seen over a broad spatial scale, from a leaf through to the entire forest ecosystem.

Considerable information may exist on individual events but often little information is readily available on the specific impacts of an event on forests. Global reporting on such impacts, particularly quantitative information on areas affected, is low and sporadic (Box 1; FAO, 2010).

Box 1. Global information on impacts of abiotic disturbances



To attempt to quantify the impacts of the many factors that affect the health and vitality of a forest, FAO, through the Global Forest Resources Assessment (FRA) 2010, asked countries to report on the impact of insect pests and diseases, fire, other biotic factors (such as wildlife browsing, grazing and physical damage by animals), and abiotic factors (such as air pollution, wind, snow, ice, floods, landslides, tropical storms, drought and tsunami) on their forests. Countries were asked to provide data (area affected) averaged over five years, so that large fluctuations in a single year did not significantly skew the figures. Data were thus presented for 1990 (an average of the period 1988–1992), 2000 (average of 1998–2002) and 2005 (average of 2003–2007).

Most countries were not able to provide reliable quantitative information because they do not systematically monitor these variables for many reasons. Very little quantitative data exist for many regions, and existing data are often not available in an easily accessible format. In addition it is often difficult to determine the cause of forest damage or decline. Data are often collected only after significant damage has been caused. Consistent data on the impacts of disturbances over time are not available for most regions.

For abiotic disturbances, reporting was more detailed in FRA 2010 than in FRA 2005 however, in general, information was highly sporadic. There may only be occasional reporting after a major storm or other event and most often the volume of wood that is damaged is reported (e.g. through salvage felling reports) but not the area affected.

Data were provided by 45 countries on the area of forest affected by abiotic factors other than fire for all three reporting periods, together accounting for 24 percent of the total forest area. A further 15 countries provided data for the 2005 reporting period only.

Sweden, for example, recorded 1.2 million hectares affected by abiotic factors including a major storm in January 2005 which caused severe windthrow in the south of the country, especially affecting middle-aged and old spruce stands. The Russian Federation reported that abiotic factors affected 1.3 million hectares of forests and Italy reported snow, storm and drought affecting 0.5 million hectares of forest. Storms and blizzards in January 2008 caused great damage to 18.6 million hectares of forest in eight provinces in China including Hunan; 1 781 state-owned farms and 1 200 nurseries were severely damaged, while 760 tonnes of tree seed and 10 billion seedlings were frozen (State Forestry Administration, 2008).

Most information on forest health is descriptive (i.e. qualitative) in nature and many countries described a variety of abiotic disturbances affecting their forests. Storms (snow, wind, ice) were the most reported abiotic event especially from European countries including Belgium, Czech Republic, Denmark, Estonia, France, Iceland, Ireland, the Netherlands, Slovakia, Slovenia, Sweden, Switzerland, Ukraine and the United Kingdom. Damage from storms was also reported from countries in Africa (Sudan, Togo), Asia and the Pacific (New Zealand, Republic of Korea) and the Near East (Lebanon).

Hurricanes were reported from countries in Africa (Madagascar, Mauritius, Mayotte, Réunion), Asia and the Pacific (Cook Islands) and Latin America and the Caribbean (Belize, Cuba, Jamaica, Martinique). Drought was reported from countries in Africa (the Gambia, Togo), Asia and the Pacific (Australia, Sri Lanka), Europe (Hungary, Slovakia) and the Near East (Yemen). Floods were reported from countries in Asia and the Pacific (Republic of Korea), Europe (Estonia) and Latin America and the Caribbean (Panama).

In the Philippines, an oil spill of 2.1 million litres of bunker oil damaged mangrove forests in the provinces of Guimaras and Iloilo in August 2006. Eruption of the volcano, Piton de la Fournaise, in Réunion destroyed sections of old natural forest by lava flows; lava flows were subsequently colonized by introduced plant species. The Maldives reported considerable destruction of trees and forest vegetation as a result of the Indian Ocean Tsunami in 2004. Avalanches were reported from Slovenia, earthquakes in Panama and air pollution in Slovakia and Slovenia.

About this review

This paper reviews the current knowledge on the impacts of abiotic disturbances, such as storms, drought, tsunamis and oil spills, on forests. Examples provided are not an exhaustive list of events but a selection of those occurring most recently or those having known impacts on forests and the forest sector. Anthropogenic, or human-caused, disturbances are included in this review since the agent itself, i.e. fire or pollutants, is abiotic or non-living.

METEOROLOGICAL EVENTS

Cyclones (synonyms hurricanes and typhoons)

Cyclones (a system of winds rotating inwards to an area of low barometric pressure) can and do occur at any latitude and in any climate. Those occurring within 30 degrees north or south of the equator are called tropical cyclones; those found above 60 degrees north or south of the equator are arctic or polar cyclones; and those between 30 and 60 degrees are called extratropical cyclones.

While extratropical cyclones are not as strong as tropical cyclones, they can produce very intense thunderstorms, powerful winds, hail and tornadoes. Such cyclones are impacting forests around the world. For example, the Great Storm of 15–16 October 1987 hit northern France and southern United Kingdom resulting in the loss of 19 lives, the death of 25 million trees as well as widespread damage to homes, transport and infrastructure and an estimated economic cost of US$2.3 billion in the UK alone (RMS, 2007). The storm was felt from Spain to Norway though damage was most severe in the UK and France. Trees of great scientific and aesthetic value were windblown or damaged in the UK including trees in collections in Kew, Wakehurst, Ventnor and Bedgebury.

Tropical cyclones are areas of very low atmospheric pressure over tropical and subtropical waters which build up into a huge, circulating mass of wind and thunderstorms up to hundreds of kilometres across (IHRC, 2011; WMO, 2011). Surface winds can reach speeds of 200 km/h or more. Cyclones have a very different wind profile and distribution and significantly higher precipitation levels than storms.

The terms 'hurricane' and 'typhoon' are regionally specific names for a strong tropical cyclone: in the western North Pacific Ocean and South China Sea the term typhoon is used; in the Atlantic Ocean, Caribbean Sea, and in the eastern North and central Pacific Ocean – hurricane; and in the Indian Ocean and South Pacific region – tropical cyclone (NOAA, 2011; WMO, 2011).

As a tropical cyclone makes landfall its energy is transferred directly to coastal regions over a large area by high velocity winds, with effects extending inland for hundreds of kilometres during severe events (Stanturf, Goodrick and Outcalt, 2007). Three primary features of cyclones that cause damage are rainfall, storm surges and winds.

BUGWOOD.ORG/R.L. ANDERSON/3036081

Hurricane Hugo damage, South Carolina, USA

Torrential rains accompanying tropical cyclones frequently cause extensive flooding, leading to tree mortality from anoxia (absence of oxygen). Flooding and rainfall saturates soil, which may increase susceptibility to windthrow in shallow soils. Even at some distance from the cyclone centre and with lower wind velocities, heavy rains with moderate winds may cause windthrow (Stanturf, Goodrick and Outcalt, 2007).

A **storm surge** is a large dome of water, sometimes greater than five metres, that floods the coast at high speed and with immense force as the storm makes landfall (IHRC, 2011). Storm surges can cause extensive damage to coastal vegetation by bending, breaking or uprooting trees. Scouring and erosion may expose root systems leading to desiccation, and deposition may lead to root suffocation. Salinity and inundation increased by the storm surge can cause plant and tree mortality (Stanturf, Goodrick and Outcalt, 2007).

Wind is the feature that is linked to a vast majority of a cyclone's damage, both directly and indirectly, through waves and storm surge. The strongest winds occur in a semicircle to the right of the storm's path a short distance from the centre. As the storm moves inland and its oceanic energy source is removed, it rapidly loses energy and weakens. Tornadoes (see following section on Tornadoes) frequently occur embedded within the rain bands that spiral out from the eye of the cyclone though they are typically short-lived and less intense than ordinary tornadoes (Stanturf, Goodrick and Outcalt, 2007).

The most common impacts of wind include defoliation, loosening and shredding of bark, and abrasion of stem surfaces (Stanturf, Goodrick and Outcalt, 2007). Trees can sway, twist and rock, and large branches may break off and cause damage to understory trees. Individual stems may bend, break or suffer some level of uprooting from leaning to complete blowdown of the tree (Boose, Serrano and Foster, 2004; Lugo, 2008; Stanturf, Goodrick and Outcalt, 2007).

Tree mortality can follow as a result of almost any of the impacts noted above. Estimates of plant and tree mortality following a cyclone vary from two percent (Hurricane David, 1979 in Dominica) to 95 percent (Hurricane Betsy, 1956 in Puerto Rico) (Stanturf, Goodrick and Outcalt, 2007). Injuries to the trees and loss of vigour can also increase their susceptibility to other disturbances such as insect pests and pathogens (Lugo, 2008). See Box 2 for some examples of tropical cyclones and their impacts on forests.

Predicting the damage caused by tropical cyclones is difficult with a variety of factors influencing forests at all levels. At the individual plant level, rooting conditions (soil depth and moisture) and growth form influence a tree's resistance to windthrow (Boose, Serrano and Foster, 2004). At the stand level, the amount and type of damage is related to the cyclone's intensity as well as to site-specific conditions such as: tree height, age, health and other factors affecting susceptibility to high winds; species composition; stand structure, condition and disturbance history; and soil conditions, geology and other factors affecting rooting strength (Kupfer *et al.*, 2008). At the regional scale, patterns of forest damage are controlled by cyclone size, intensity, and storm track; large topographic features that weaken storms such as coastlines and mountain ranges; and regional variation in vegetation (Foster, Knight and Franklin, 1998).

Cyclone impacts could be considered beneficial ecologically, at least in naturally regenerated forests. Lugo (2008) suggested the main ecological roles of cyclones include: altering the ecological space available to organisms; increasing the heterogeneity of the landscape and the variability in ecosystem processes; rejuvenating the landscape and its ecosystems and redirecting succession; shaping forest structure, influencing species composition and diversity and regulating their function; and inducing evolutionary change.

Box 2. Examples of major tropical cyclones and their impacts on forests

Tropical Cyclone Nargis

Cyclone Nargis made landfall in Myanmar on 2 May 2008 with wind speeds of up to 200 km/h and heavy rain. The damage was most severe in the Delta region where the effects of the extreme winds were compounded by a 3.6 metre storm surge. The cyclone killed 84 537 people plus 53 836 people missing and 19 359 injured (TCG, 2008). More than 2.4 million people were estimated to be significantly affected by the storm. The total amount of damage and losses in the affected areas of Myanmar was estimated at about US$4 057 million (TCG, 2008). To date, it is considered the worst natural disaster in the recorded history of Myanmar.

Some 17 000 hectares of natural forest and 21 000 hectares of forest plantations were damaged (TCG, 2008). The loss of mangrove forests and associated ecosystem goods and services will have a significant impact on local communities that are heavily or partially dependent on forests for their livelihood. Besides cash employment from the forest sector, villagers obtain construction material and food (i.e. fish) from the mangrove forests.

Tropical Cyclone Sidr

On 15 November 2007 Tropical Cyclone Sidr hit Bangladesh with wind speeds of up to 240 km/h causing significant damage to life, livelihoods and productive infrastructure. Approximately 8.7 million people or nearly 2 million households were affected (FAO, 2008). Nearly 1.5 million houses and some 4.1 million trees were damaged. The Sundarban mangrove forests, the largest such forest in the world (140 000 hectares) and a UNESCO World Heritage Site, incurred severe damages. They form a natural buffer protecting millions of people in Bangladesh from the Bay of Bengal. In addition to significant environmental and ecological functions, the Sundarbans also play major social and economic functions and many communities depend on them for their livelihoods. The area is also known for its wide range of fauna, including 260 bird species, the Bengal tiger and other threatened species such as the estuarine crocodile and the Indian python (UNESCO, 2011).


flickr/JOISEYSHOWAA

Damage to the Sundarban mangove forests in Bangladesh after Tropical Cyclone Sidr

In the Sundarbans some 4-5 percent (20 000–25 000 hectares) of forest area were severely damaged and nearly 15 percent (60 000 hectares) partially damaged by the cyclone (FAO, 2008). Some introduced species, which were planted in various parts of the Sundarbans, were uprooted while in the severely affected areas a large number of trees had stem break or were uprooted. In the partially damaged areas many branches were broken but the main trunks remained intact.

Hurricane Katrina

Hurricane Katrina made landfall in Louisiana, United States of America on 29 August 2005 damaging coastal and inland forests of Mississippi, Louisiana, and Alabama. In addition to strong winds, Katrina brought massive amounts of rain over a very short time; a storm surge of up to 8.5 metres across southern Louisiana and Mississippi; extensive wind, rain and tornado damage throughout Mississippi, western Tennessee and western Kentucky; and hurricane-associated precipitation as far north as New York State (Oswalt and Oswalt, 2008).

Hurricane Katrina was the costliest natural disaster, as well as one of the five deadliest hurricanes, in the history of the United States. At least 1 836 people died in the actual hurricane and in the subsequent floods. Total property damage was estimated at US$81 billion.

It was predicted that Hurricane Katrina killed or severely damaged 320 million large trees in Gulf Coast forests and the resulting loss of carbon represented 50 to 140 percent of the net annual carbon sink of all forests in the USA (Chambers *et al*., 2007). Initial estimates in Mississippi indicated potential timber losses of up to 84.9 million cubic metres across 1.4 million hectares of damaged forest land which corresponded to approximately 90 percent of standing timber in severe damage zones, and an average of 37 percent of standing timber across all damage zones (Oswalt and Oswalt, 2008). Hardwoods experienced severe bole damage and windthrow. In Louisiana's Pearl River basin, hurricane-related tree mortality was more than four times greater than annual pre-Katrina mortality rates (Chapman *et al.*, 2008). The estimated economic loss of timber from wind damage was between US$1.4-2.4 billion (Stanturf, Goodrick and Outcalt, 2007).

flickr NASA GODDARD SPACE FLIGHT CENTER

Satellite images of the New Orleans area, USA, before and after Hurricane Katrina. Healthy vegetation appears bright green before the storm, indicating growing trees (left); bright red depicts plant mortality just weeks after the storm (right).

Forests damaged from Hurricane Katrina are currently being invaded by exotic species such as Chinese tallow (*Triadica sebifera*) (Chapman *et al.*, 2008). This species, which was present before the hurricane but with a restricted distribution, now thrives in some areas in the large canopy gaps created by the hurricane winds.

Typhoon Sudal

In April 2004, Typhoon Sudal passed over the state of Yap in the Federated States of Micronesia with impacts on mangrove forests. Practically all trees suffered canopy damage, and significant proportions of trees were snapped or uprooted but this varied by species. Mortality of mangrove species ranged from six to 32 percent among stands (Kauffman and Cole, 2010).

Tropical Cyclone Gafilo

Cyclone Gafilo struck Madagascar in March 2004 causing devastating damage, killing approximately 250 people, injuring many more and leaving 300 000 people homeless. Just over one hundred people died when the ferry 'Le Samson' sank in heavy seas off the Comoros; only two survived. Heavy rain after the

(continues)

cyclone resulted in widespread flooding in the north, northwest and southwest of the country. Soon after the cyclone struck, the Ministry for the Environment, Water and Forests (MINENVEF) issued temporary permits for the collection of wood that had been windthrown or damaged by the cyclone outside of protected areas only. With little enforcement and the post-disaster economic stress, this cleared the way for illegal logging of large amounts of precious woods such as rosewood, palisandre, and ebonies and subsequent export as 'salvage'; the amounts of logged wood being much greater than the actual amount damaged by the cyclone (Patel, 2007). Hundreds of tonnes of rosewood and ebony were confiscated, most of which were logged within the two largest protected areas in the region. Such selective logging threatens the valuable protected forests and can result in increased incidence of fire and species invasions, altered habitats, and loss in genetic diversity.

Tropical Cyclone Waka

On 31 December 2001, Tropical Cyclone Waka passed directly over the Vava'u island group, Kingdom of Tonga, with sustained and maximum wind speeds of 185 km/h and 230 km/h respectively. Cyclone-related tree mortality averaged six percent and varied depending on species type: 0–7 percent for lowland late-successional species and 4–19 percent for early successional species (Franklin *et al.*, 2004). Severe damage (i.e. uprooting, snapped stems) affected 25 percent of stems measured; the highest frequency of snapped stems occurred in the small-medium diameter trees (10–15 cm dbh) while uprooting was more prevalent among larger trees (>20 cm dbh) (Franklin *et al.*, 2004).

Hurricane Mitch

Hurricane Mitch is considered the worst disaster of the 20th century in Central America. The hurricane hit Honduras and then from 29 October to 3 November 1998, the slow-moving hurricane and then tropical storm dropped huge amounts of rain in Honduras, Guatemala, Nicaragua and Belize, resulting in massive flooding and mudslides. An estimated 11 000 people died, with thousands more unaccounted for and approximately 2.7 million left homeless. The flooding and mudslides damaged or destroyed tens of thousands of homes, with total damage amounting to over US$5 billion, most of which was in Honduras and Nicaragua.

The hurricane caused damage, deforestation and disruption of the forest sector in general. Mangrove forests in the coastal zones of the Atlantic and Pacific coasts were severely impacted both directly and indirectly by the storm (Doyle *et al*., 2002; Hensel and Proffitt, 2002). Winds caused near complete defoliation of the vegetation on the Bay Island of Guanaja, Honduras, including mangrove forests, and taller trees were either broken or uprooted (Hensel and Proffitt, 2002). Damage to mangroves was also caused by waves and sediment burial (Hensel and Proffitt, 2002).

In the five years following Hurricane Mitch, over 100 000 hectares of pine forest in Central America were infested with the southern pine beetle, *Dendroctonus frontalis*, in association with other species of *Dendroctonus* and *Ips* spp. The resulting extensive tree mortality severely increased the risk of wildfires and negatively affected wildlife and recreation causing widespread and significant economic impacts.

Hurricane Hugo

In September 1989, Hurricane Hugo struck Guadeloupe, Montserrat, St. Croix, Puerto Rico, Antigua and South Carolina, USA. In Guadeloupe, tall mixed mangroves experienced a 78 percent decrease in average tree density and 71 percent reduction in average basal area after the storm's passage (Lugo, 2008). The hurricane passed over the northeast corner of Puerto Rico with sustained winds of over 166 km/h resulting in defoliation, windthrow and landslides (Turner, Dale and Everham, 1997). The storm also resulted in population outbreaks of 15 species of Lepidoptera (moths and butterflies) in the same country, including larvae of *Spodoptera eridania* (Noctuidae) which were feeding on early successional plant species (Lugo, 2008). The outbreak of these insects ended with the decline of the host plants. This storm also impacted forests in South Carolina, United States where it caused extensive damage for 325 kilometres inland (Stanturf, Goodrick and Outcalt, 2007).

Storms (wind, snow, ice, hail, dust and sand)

Storms bringing wind, snow, ice or hail or a combination of these factors have always impacted the health of forests and thus are a regular consideration in forest management plans. They can occur as catastrophic events affecting entire landscapes, the quality of wildlife habitats, and forest stand structure, which can lead to major disruptions in management goals. Alternatively they may occur as small scale disturbances that affect individual trees or groups of trees within a stand increasing the amount of dead wood and diversifying stand structure, which can have positive benefits for biological diversity.

Damaging winds vary from short-lived gusts, to strong prevailing winds, to powerful hurricanes, to brief but intense downdrafts from thunderstorms (Laurance and Curran, 2008). The impact of wind on forests is determined by a complex of many biotic and abiotic factors and is similar to those experienced during cyclones (See previous section). Storm damage can include initial mechanical damage from the storm, subsequent damage from other biotic or abiotic factors (i.e. insects, fire, sun, snow, ice, etc.), and loss of production. The severity and extent of windstorm damage in forests are a function of: the damage potential (i.e. the amount of growing stock exposed to strong winds); the susceptibility to wind, which is determined by tree and stand characteristics (i.e. tree species, tree/stand height, slenderness of trees, crown and rooting characteristics, stand density) and site characteristics (i.e. soil type, soil moisture content, topography); and the extent and severity of the event itself (i.e. storm extent, wind speed and gusts) (Martin and Ogden, 2006; Seidl *et al.*, 2011; Usbeck *et al*., 2010). Whether trees are uprooted or broken is determined primarily by its position within the canopy and by its rooting depth (Martin and Ogden, 2006).

In some areas, storms have been causing increased damage to forests in recent decades (Schelhaas, Nabuurs and Schuck, 2003). In Europe, for example, storms cause more than 50 percent of all damage to forests and thus they have become such a major concern to the forest sector that the Directorate-General for the Environment of the European Commission commissioned a study into the problem.

FAO/V. CABOUN/FO-6095

Storm damage, Slovakia

This study identified 130 separate windstorms that caused considerable damage to forests within the last 60 years (Gardiner *et al*., 2010). By analysing information on these storms, the authors noted that gust peak wind speed is strongly correlated to the maximum potential levels of damage, tree height has an important impact on its vulnerability, and recent thinning, particularly in older stands, is often associated with increased damage.

Spruce and poplar appear to be among the most vulnerable species and silver fir and oak among the least vulnerable of the conifers and broadleaves respectively although such findings, and the generally higher susceptibility of conifers to damage, are possibly related more to variations in management and site. Soil condition had a large influence on the extent of damage. Root anchorage strength is increased by soil freezing and reduced by waterlogging, heavy rain and by poor drainage that allows soil saturation during storms. With climate change, increased temperatures will decrease the period of time in which soils are frozen, particularly in northern countries, potentially increasing the damage from wind. Storms will also be accompanied by heavier precipitation resulting in more saturated soils and increased risk of damage.

Snow most commonly impacts trees by breaking stems but trees can also be bent or uprooted (Nykänen *et al*., 1997). The severity of snow damage is related to tree characteristics; factors controlling the stability of trees such as stem taper and crown characteristics are the most important (Nykänen *et al*., 1997). Conifers are particularly damaged by heavy snowfall, while broadleaved trees are generally more resistant to storms and snow in the late autumn and winter due to better root systems and lack of foliage (FAO/ECE/ILO, 1995).

Ice storms result when liquid precipitation falls through a layer of cold air. If this layer of cold air is thick enough and the air temperature is below freezing, the precipitation freezes on contact with ground-level objects, forming a coat of ice. The level of ice accumulation varies with topography, elevation, aspect, and the amount of area in the region in which conditions favour ice accumulation (Irland, 2000).

In a matter of minutes an ice storm can deposit a layer of ice heavy enough to bring down power and telephone lines and snap branches from trees (WMO, 2011). Impacts of individual storms are highly patchy and variable, and depend on the nature of the storm, its severity, frequency, timing and extent. Ice storm damage to forest canopies is related to canopy architecture, tree size, age, health and the mechanical properties of the wood itself (Irland, 1998).

Ice accumulation on trees can cause minor branch breakage; major branch loss, up to total crown loss; temporarily or permanently bending over of crowns; root damage (when soil is not frozen); breakage of trunks within or below the crown; and for some hardwoods, split trunks (Irland, 2000). Freezing rain immediately following heavy snowfalls can be very damaging to vegetation because of the increased loading on branches (Irland, 2000). Softwoods seem to suffer less damage than hardwoods. Recently-thinned stands can be highly vulnerable, as crowns have spread into newly-opened space but branch strength may not be fully developed. Trees damaged by ice storms or windthrow can be more susceptible to other disturbances such as insect pests or fire.

Ice storms, like other disturbances, can influence stand composition, structure and condition over wide areas (Irland, 2000). As a recurring event they play a role in determining forest succession and are important factors influencing the dynamics of the forests in affected regions (Hooper, Arii and Lechowicz, 2001). Ice storms redistribute living and dead biomass in forests, reduce canopy height and stratification, increase organic inputs to the soil and expose mineral soil (Hooper, Arii and Lechowicz, 2001).

In January 1998, a major ice storm occurred affecting large portions of New England in the USA and the Canadian provinces of New Brunswick, Ontario and Quebec. Millions of trees fell, and more continued to break and fall throughout the rest of the winter season. Non-native species and trees


B. MOORE

Ice covers trees and power lines after a major storm, Canada

planted outside their natural ranges, such as *Robinia* and *Salix* spp., suffered severely, while nearby native species suffered far less damage (Irland, 1998). In an old-growth hardwood forest at Mont St. Hilaire, Quebec the storm brought down 19.9 metric tonnes or 33.6 cubic metres of woody debris per hectare which represented about 7–10 percent of the total aboveground biomass in this forest before the storm (Hooper, Arii and Lechowicz, 2001).

A February 1994 ice storm in northern Mississippi had major impacts, including damage to 1 500 000 hectares of forests and heavy losses to urban trees and pecan orchards (Irland, 1998). A storm in November 1996 in eastern Washington and Idaho, USA caused widespread tree damage and heavy losses to garden and street trees (Irland, 1998).

Large **hailstones** that can reach diameters of over 10 centimetres and can fall at speeds of over 150 km/h (WMO, 2011) can also cause considerable damage to forests.

A topic related to the impacts of ice and snow on trees is the impact of de-icing salts, such as sodium chloride, used liberally on roads to maintain safe winter driving conditions in many cold regions of the world. Sodium chloride can damage roadside vegetation and affect surface water and groundwater quality (Munck *et al*., 2010). Conifers are more susceptible to damage from salt spray compared to hardwoods because they retain their foliage through the winter months when salt is applied to roads. Tip dieback and leaf scorch are the typical symptoms associated with salt damage on conifers. Salt ions cause osmotic and ionic stress in plants and soil salinity interferes with both water and nutrient uptake by roots (Munck *et al*., 2010).

Dust storms and sandstorms are natural events that occur throughout the world, especially in dryland areas which cover approximately 41 percent of the earth's land surface (more than 6 billion hectares) (MEA, 2005). Drylands occur in the Mediterranean region, Sahara and sub-Saharan Africa, Central and South Asia, Australian Outback, South American Patagonia and the North American Great Plains.

Dust storms and sandstorms are a result of wind erosion and are driven by poor land management and degradation of the dryland vegetation cover. Strong winds and favourable surface atmospheric conditions (i.e. turbulence level, stability, soil moisture) can allow for large amounts of sand and dust to be lifted from bare, dry soils into the atmosphere. Every year one and a half tonnes of sand and

Dust storm in New South Wales, Australia, 2009

dust are emitted from drylands into the atmosphere where it can be transported downwind affecting regions hundreds to thousands of kilometres away depending on meteorological conditions (WMO, 2011). Dust from the Gobi Desert, for example, is carried to the Pacific coasts of North America and dust from the Sahara Desert is carried to the Caribbean islands and the Amazon basin (MEA, 2005).

Dust can have numerous impacts on human and veterinary health, the environment, agriculture, marine ecosystems, fisheries, transport, visibility, aviation, and weather and climate at larger scales (WMO, 2011). A major sand-dust storm in northwest China on 5 May 1993 illustrates the devastation and serious economic loss that such storms can produce. A total of 85 people died, 31 people were lost and 264 people were injured. Approximately 373 000 hectares of crops were destroyed, 120 000 animals died or were lost, 16 300 hectares of fruit trees were damaged, 90 000 individual trees were blown down and thousands of greenhouses and plastic mulching sheds were broken (UNCCD, 2002).

In some cases, however, the deposition of dust can produce positive results. For example, mineral-rich Saharan dust transported across the Atlantic Ocean to the Amazon rain forest in South America provides iron and phosphorus to the nutrient-poor rainforest soils acting as fertilizer (WMO, 2011).

Measures to combat the occurrence and impacts of sand and dust storms include the use of windbreaks or shelterbelts to reduce the impact of wind speeds and decrease soil erosion (Sivakumar, Motha and Das, 2005).

Tornadoes

Tornadoes are short-lived, relatively small, complex, violent and unpredictable storms that can cause severe damage though usually in limited areas (Foster, Knight and Franklin, 1998; Fujita, 1971). They are most common in spring in late afternoon and are concentrated in interior continental regions, particularly in Tornado Alley of the Great Plains of North America, but they can and do occur anywhere, especially in temperate latitudes (WMO, 2011). Tornado winds greatly surpass tropical cyclone winds in intensity, reaching an estimated maximum exceeding 400 km/h (Foster, Knight and Franklin, 1998).

Tornado damage, Hoosier National Forest, Indiana, USA

They develop under three meteorological conditions: long-lived supercell[3] thunderstorms, which generate the largest and most damaging tornadoes; ordinary thunderstorms; and in cyclones after they make landfall (Foster, Knight and Franklin, 1998). Those associated with cyclones tend to be more short-lived and less intense than other tornadoes (Stanturf, Goodrick and Outcalt, 2007).

Tornadoes can create complex damage patterns owing to their extreme variability in intensity, path length, width, and continuity; the potential for multiple touchdowns; and the high frequency of multiple storms in clusters (Foster, Knight and Franklin, 1998). Damage to trees and forests can range from branch break and single tree gaps to extensive areas of complete blowdown. Peterson (2007) noted an increase in the probability of wind-related damage with increasing tree diameter in a study of tornado damage across eastern North America. Some of the damage caused by tornadoes may be positive. The loss of canopy can allow for other species to flourish thereby increasing biodiversity and the consequent increases in soil temperature may increase microbial activity and thereby enhance nutrient cycling in the soil (Peterson, 2000).

Tornadoes cause more human mortality in the United States than any other weather event except lightning (Peterson, 2000) and despite their small size, they have massive economic costs. A single North Carolina tornado caused an estimated US$100 million in damage in November 1988, as did the Catoosa, Oklahoma tornado of April 1993 (Peterson, 2000). Other examples include a November 1992 tornado outbreak that caused approximately US$291 million in damage, a system of tornadoes in Mississippi, Alabama, Georgia and Tennessee on 8 April 1998 (US$300 million), the Oklahoma-Kansas tornadoes of May 1999 (US$1 billion), the Arkansas-Tennessee tornadoes of January 1999 (US$1.3 billion), and the combined flooding and tornadoes of March 1997 in the Mississippi and Ohio valleys (US$1 billion) (Peterson, 2000).

The 2011 tornado season in the United States is currently on record pace and proving likely to be the most damaging yet. As of 04 July 2011, 1 583 tornadoes were reported (some of these are yet to be confirmed) (NOAA/NWS, 2011). Since the beginning of the year, 537 people have died, approximately 346 from the outbreaks of tornadoes in April alone.

---

[3] A supercell is a thunderstorm with a deep rotating updraft or mesocyclone.

Thunderstorms and lightning

Severe thunderstorms give rise to sudden electrical discharges in the form of lightning and thunder. They often bring heavy rain or hail, strong winds and occasionally snow and in some parts of the world they trigger tornadoes (WMO, 2011). In areas where lightning is not accompanied by rain, so-called dry lightning, it may also be a source of ignition for forest fires (Päätalo, 1998) as noted in some remote areas of Canada and the Russian Federation (FAO, 2007). However it is generally recognized that the majority of forest fires are caused by humans and not by lightning (See section on Fire under Anthropogenic events).

Tall trees tend to be the most vulnerable to lightning strikes, especially those growing singly in open areas such as on hills, in fields, near water or in urban environments. The likelihood of a strike is greatest on exposed ridges, summits, slopes and other convex surfaces (Päätalo, 1998). Lightning can impact a tree's biological functions and structural integrity. Along the path of the strike, sap boils, steam is generated and cells explode in the wood, resulting in strips of wood and bark peeling or being blown off the tree (Clatterbuck, Vandergriff and Coder, 2011). Trees may survive if only one side of the tree shows evidence of a lightning strike; however when the strike completely passes through the trunk, trees are usually killed. Many trees can suffer severe internal or below-ground injury despite the absence of visible, external symptoms when the lightning passes through the tree and dissipates in the ground (Clatterbuck, Vandergriff and Coder, 2011). Major root damage may cause the tree to decline and die. Lightning-induced mortality can create gaps in forest canopies (Magnusson, Lima and de Lima, 1996).

Flickr/PRESCOTT

Lightning strikes, Canberra, Australia

CLIMATOLOGICAL EVENTS

Drought

Droughts are caused by a deficiency of precipitation over time and as such can develop slowly, sometimes over years. Often associated with the arid regions of Africa, particularly the Sahel, in recent years, droughts have also struck India and parts of China, the Near East, the Mediterranean, Australia, parts of North America, South America and Europe (WMO, 2011). 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. Of particular concern are increases in tree mortality associated with climate-induced physiological stress and interactions with other disturbances such as pest outbreaks and fire (Allen *et al.*, 2010).

Allen *et al.* (2010) identified 88 well-documented episodes of increased mortality due to drought and heat throughout a variety of forest types, from monsoonal savannas with mean precipitation <400 mm/year, to subalpine conifer forests with a Mediterranean climate, to tropical rainforests with mean precipitation >3000 mm/year, illustrating that drought-induced mortality is not restricted to forests normally considered water-limited. They noted a complex set of mortality patterns ranging from small, short-lived local increases in background mortality rates to episodes of acute, regional-scale forest die-off, which may involve biotic disturbances such as disease or insect outbreaks. Regional-scale mortality of overstory trees is of particular concern as it rapidly alters ecosystem type, associated ecosystem properties, and land surface conditions for decades (Breshears *et al.*, 2005).

Quaking aspen (*Populus tremuloides*) in Western Canada exhibited steep productivity declines and dieback after a particularly severe drought in 2001-2003, with effects continuing for years (Hogg, Brandt and Michaelian, 2008). Impacts were exacerbated by attacks of defoliating and wood-boring insects and pathogens (Hogg and Bernier, 2005; Hogg, Brandt and Michaelian, 2008). Steep growth declines and stand replacement of European beech (*Fagus sylvatica*) at the lower edge of its range has been observed in Spain and other southern European countries in response to drought (Jump, Hunt and Peñuelas, 2006). In Italy, Spain and Portugal native oaks are declining due to warming,

FAO/CH. ERRATH/12787

Dead vegetation in drought-stricken area, Senegal drought or *Phytophthora* species and in Spain, *Pinus uncinata*, *P. pinaster*, and *P. pinea* have been exhibiting decline and dieback (Resco de Dios, Fischer and Colinas, 2007). Carnicer *et al.* (2011) reported a generalized increase in crown defoliation in southern European forests from 1987 to 2007 in response to drought conditions.

Park Williams *et al.* (2010) concluded that projected rises in temperature and aridity in the southwestern United States will substantially reduce tree growth and likely increase mortality rates. Breshears *et al.* (2005) reported a regional-scale vegetation die-off across woodlands in the same region in 2002–2003 in response to drought and associated bark beetle infestations. Other examples of recent die-offs caused by elevated temperatures and/or water stress have been well documented for southern parts of Europe (Bigler *et al.*, 2006; Breda *et al.*, 2006; Peñuelas, Lloret and Montoya, 2001) and for temperate and boreal forests of western North America, where background mortality rates have increased rapidly in recent decades (van Mantgem *et al.*, 2009) and widespread death of many tree species in a variety of forest types has affected well over 10 million hectares since 1997 (Raffa *et al.*, 2008). In semiarid and Mediterranean systems, several studies have recently reported increased plant mortality rates and die-off events, reduced seedling recruitment, long-term shifts in vegetation composition, reduced radial growth, and increased crown defoliation responses (Carnicer *et al.,* 2011).

A primary response of forests to future drought will be a reduction in net primary production (NPP) and stand water use (Hanson and Weltzin, 2000). Droughts have been reported to reduce NPP in: North America and China (2000); North America and Australia (2002); Europe (2003); Amazon region, Africa and Australia (2005); and large parts of Australia (2007-2009) (Zhao and Running, 2010).

Forest drought usually results in reduced shoot growth, reduced nitrogen and water foliar concentrations, and increased allocation to secondary defensive compounds, such as tannins (Carnicer *et al.,* 2011). Drought-induced reductions in decomposition rates may cause a buildup of organic material on the forest floor which could influence nutrient cycling and increase susceptibility to fire (Hanson and Weltzin, 2000).

Susceptibility of forest ecosystems to drought is mainly determined by site (i.e. soil texture, soil depth, water holding capacity) and stand (i.e. leaf area, species composition, and rooting depth) characteristics (Seidl *et al.*, 2011), stand management as well as human pressure. Young plants such as seedlings and saplings are particularly susceptible to drought whereas large trees with a more developed rooting system and greater stores of nutrients and carbohydrates tend to be less sensitive, though they are affected by more severe conditions (Hanson and Weltzin, 2000). Shallow-rooted trees and plants as well as species growing in shallow soils are more susceptible to water deficits. Deep-rooted trees can absorb water from greater depths and therefore are not as prone to water stress.

Strategies for forest managers to adapt to future drought events might include thinning stands to reduce competition or selecting appropriate genotypes, such as those with improved drought resistance.

A severe drought has been affecting the countries of Djibouti, Ethiopia, Kenya and Somalia since early 2011, the worst one to hit the region for six decades. The region has experienced two consecutive seasons of significantly below-average rainfall, resulting in failed crop production, depletion of grazing resources and significant livestock mortality. As of June 2011, high levels of acute malnutrition were widespread and more than 8 million people were in need of emergency assistance. Impacts have been worsened by high food prices and in some areas, conflict. At time of print, the impacts on forests were not known.

HYDROLOGICAL EVENTS

Floods and flash floods

Floods occur when the rate of water supply exceeds the capacity of stream-channel drainage such as during periods of heavy rains and rapidly melting snow and ice. They can be triggered by cyclones, severe thunderstorms, tornadoes and monsoons or can result from the building of dams (i.e. by beavers) or by dam breaks caused by general failure, ice jams, landslides, or by tectonic and other geological processes (Foster, Knight and Franklin, 1998). Excessive rainfall on saturated soils in flat areas can also create floods. In coastal areas, storm surges caused by tropical cyclones and tsunamis, or by a combination of high river flows and back-water effects as a result of high tides, can also cause flooding.

The ecological damage of regular flooding may be minor as floodplain plants and animals are well adapted to such conditions (Foster, Knight and Franklin, 1998). In addition, the mechanical force of floodwater is not typically adequate to increase plant mortality rates, especially when flooding occurs in spring before bud break of deciduous trees. Oxbow formation, ice scouring, and bank erosion may cause the death of some trees and changes in the landscape mosaic, but impacts are generally affected only over limited areas (Foster, Knight and Franklin, 1998). Floods caused by waterlogging of large, flat areas, however, can persist for several days and cause damage to trees and forests. Some examples of recent flood events can be found in Box 3.

Flash floods can occur after heavy storms or after a period of drought when heavy rain falls onto very dry, hard ground that the water cannot penetrate (WMO, 2011). Such events may have much more impact on forests, especially in areas not accustomed to high waters.


FAO/M. KERESZTES/FO-6082

Flooded forest, Hungary

Box 3. Some recent flood events

Beginning in July 2010, a heavier than normal monsoon season resulted in devastating floods in Pakistan that killed approximately 2 000 people, ruined crops, and damaged or destroyed 1.7 million homes as well as livestock, forests and wildlife (UNEP, 2011). Over 18 million people have been affected. The flood severely damaged natural forests, plantations, community forests, trees grown for fuelwood, wildlife habitat and conservation areas (Khan *et al*., 2010). The remaining intact forests are at risk of further degradation as local communities extract timber to rebuild homes and for fuelwood and fodder, and sell forest products and wildlife to earn cash (Khan *et al*., 2010).

Significant flooding occurred in many areas of Queensland, Australia during late December 2010 and early January 2011. Three quarters of the state was declared a disaster zone and cleanup efforts are expected to cost billions of dollars. Thousands of people were evacuated from their homes and more than 200 000 people have been affected. The impacts on forests remain to be seen.

Unusually heavy rainfall since January 2011 has caused widespread flooding in southern Africa, particularly in Angola, Botswana, Lesotho, Madagascar, Malawi, Mozambique, Namibia, South Africa, Zambia and Zimbabwe. The affected countries report deaths, displacements, evacuations as well as damage to crops, houses and infrastructure (OCHA, 2011). In Namibia, the hardest hit country, flood waters are subsiding, however the number of people affected by the floods continues to rise as new information is received; it is estimated that the total number of people affected is 500 000 with 65 related deaths and approximately 60 000 displaced and 19 000 in relocation camps (as of 02 July 2011). In Malawi, 14 people have died, over 61 000 people are affected and over 3 800 hectares of crops damaged (as of 29 April 2011). At least 234 people died in Angola with approximately 254 000 people directly affected (as of 02 June 2011). Impacts on forests are not yet known.

The Mississippi River floods of 2011 are among the largest and most damaging along the flood-prone US river in the past century. Comparisons are being drawn to the major Mississippi River floods in 1927 and 1993, the latter in which more than 10 million acres of land were flooded. In April 2011, two major storm systems, also responsible for large tornado outbreaks, produced large amounts of rainfall across much of the vast Mississippi River watershed. Combined with springtime snowmelt, the river began to rise to record levels by early May. States experiencing flooding include Illinois, Missouri, Kentucky, Tennessee, Arkansas, Mississippi and Louisiana. The impacts on forests remain to be seen.

Avalanches

Avalanches are rapid, gravity driven mass flows of snow, air and debris (Bebi, Kulakowski and Rixen, 2009). They can generally be classified into loose snow avalanches (starting at a single area or point) and slab avalanches (release of a cohesive snow layer initiated by a failure at depth in the snow cover). They can be highly destructive, moving at speeds in excess of 150 km/h (WMO, 2011). Avalanches claim approximately 150 lives per year and that number continues to rise as more people participate in winter sports thereby spending more time in vulnerable areas. On 17 February 2010, for example, an avalanche fuelled by heavy snowfalls struck several towns in North West Frontier Province of Pakistan killing over 100 people.

Avalanche disturbance regimes are two-way interactions in which forest structure and composition affect avalanches, and avalanches, in turn, affect forest structure and composition (Bebi, Kulakowski and Rixen, 2009). Avalanches primarily affect subalpine forests (those forests closest to upper tree line). They can damage or kill individual trees over tens to hundreds of hectares in forests that are located in vulnerable areas. At a stand scale, avalanches typically result in forest communities that are characterized by smaller and shorter trees, shade intolerant species, lower stem densities, and

Damage caused by a large avalanche, Switzerland

greater structural diversity. Such communities provide valued habitat for various animal and plant species and can contribute to overall higher biodiversity. At a broader scale, avalanche tracks provide increased landscape heterogeneity and edge density and can serve as firebreaks.

The impacts of avalanches on trees are closely related to the size and flexibility of the tree and where the avalanche occurs in relation to the tree. In trees with larger diameters, the stresses exerted by avalanches can exceed the breaking strength of the tree, resulting in bole breakage or uprooting of the tree if the pressure is high enough. If a tree is flexible enough, it may be deflected and be largely undamaged. Small trees (height <5 metres) can tolerate snow pressure by bending and leaning in the snowpack (Kajimoto *et al.*, 2004). Critical tree diameters for breakage range for common subalpine tree species from 6 to 14 centimetres, and are higher for broadleaved, relatively short-lived trees with flexible stems such as *Betula*, *Alnus*, *Acer* or *Salix* species (Bebi, Kulakowski and Rixen, 2009).

When avalanche severity and/or frequency are high, they can be the dominant factor that controls survival, growth rates and growth forms of trees. With decreased severity and increasing intervals between avalanche events, the growth of tree species shifts from shrubs to erect trees (Bebi, Kulakowski and Rixen, 2009). Stands that are frequently disturbed by avalanches are typically dominated by trees with smaller diameters, shorter stature, and slow annual growth rates in comparison to undisturbed stands (Bebi, Kulakowski and Rixen, 2009). Disturbed stands also tend to be characterized by a dominance of shade intolerant species and lower tree densities (Butler, 1979; Johnson, 1987; Bebi, Kienast and Schönenberger, 2001). Forest recovery after avalanches is normally by way of surviving vegetation as opposed to new species establishment.

One of the most important ecological effects of avalanches is increased structural and compositional diversity (Bebi, Kulakowski and Rixen, 2009). In montane and subalpine areas, coniferous forests composed of relatively large trees usually dominate; avalanche disturbance allows for smaller individuals to dominate plant communities. Avalanches create open habitat in otherwise closed forests which contributes to the complexity and diversity of the ecosystem. Bebi, Kulakowski and Rixen (2009) noted that the number of vascular plant species was greatest in areas of highest disturbance intensity and frequency as opposed to areas that experienced avalanches less frequently.

Landslides and mudslides
Landslides and mudslides occur when heavy rain, rapid snow or ice melt or an overflowing crater lake sends large amounts of earth, rock, sand or mud flowing swiftly down hill and mountain slopes (WMO, 2011). Earthquakes, volcanic eruptions, heavy rain storms, and cyclones can trigger landslides. Land-use intensification and climate change are increasing landsliding in mountainous regions (Restrepo *et al.* 2009). In fact, more information is available on the impacts of forest activities on landslides than on the impacts of landslides on forests. Forest harvesting, particularly clearcutting, and road building can result in increased surface erosion, changes in hydrology, and increases in landslides and debris flows (Guthrie, 2005; Imaizumi, Sidle and Kamei, 2008; Sidle, 2005).

Shallow landslides typically have little impact on trees. Deep landslides, triggered by major earthquakes or volcanic activity, however can denude hundreds or even thousands of square kilometres of land (Schuster and Highland, 2004). In such major landslides, all of the soil down to bedrock is carried downslope, taking all of the trees and other vegetation with it. Because no soil is left for new plants to grow on, the bare tracks of landslides can remain visible for hundreds of years. Shallow landslides can be prevented by tree cover whereas deep landslides can not be prevented, even with high forest cover.

Widespread stripping of forests by mass movements has been noted in many parts of the world, particularly in earthquake-prone tropical areas (Schuster and Highland, 2001; 2004).

- In September 1935, two shallow earthquakes in the Torricelli Range, Papua New Guinea, caused hillsides to slide away, carrying with them millions of tonnes of earth and timber and revealing bare rock. Approximately 130 square kilometres (eight percent of the region affected) was denuded by the landslides.
- In November 1970, an earthquake triggered landslides along the north coast of Papua New Guinea. They removed shallow soils and stripped tropical forest vegetation from about 25 percent of the 240 square kilometres area affected.
- In 1976 two shallow earthquakes occurred in Panama, causing huge areas of landsliding and removing an estimated 54 square kilometres of forest cover or 12 percent of the affected region.
- Similar subtropical forest devastation due to earthquake-induced landslides occurred in the 1987 Reventador and 1994 Paez events in Ecuador and Colombia, respectively. In both cases, the earthquakes occurred after long periods of rainfall, and the saturated soils rapidly gave way. The Reventador landslides removed the subtropical forests from more than 75 percent of the southwestern slopes of the volcano. It was estimated that 230 square kilometres of natural forest were lost in the region. The Paez landslides stripped soil and vegetation from 250 square kilometres of steep valley walls.
- In the Luquillo Mountains of Puerto Rico, which are especially hard-hit by landslides, it was reported that landslides denude between 0.08 and 1.1 percent of the forest area per century.

The destruction of temperate forests by landslides has also been observed (Schuster and Highland, 2001; 2004).

- Many forest areas in New Zealand have been damaged by landslides. Studies of forest losses in the upper drainage basin of the Pohangina River on the North Island noted that in 1946 the erosion surface exposed by mass movements in a red beech forest was 1.7 percent of the drainage area. By 1963, the denuded area was 2.7 percent, an increase of 60 percent in 17 years.
- During the 1960 Chilean earthquake, more than 250 square kilometres of temperate forest slopes were denuded.
- Numerous studies have investigated landslide damage in southwestern Canada and the northwestern United States. Especially noteworthy have been studies of landslide-caused forest damage on the Queen Charlotte Islands off the coast of British Columbia, which include vast expanses of valuable commercial timber.


FAO/M. KASHIO/FO-6749

Deposition of sand and debris after a landslide and flash flood, Thailand

More recently, a number of events have caused considerable damage though the impacts on forests remain to be seen. In January 2011, heavy rains resulted in flooding and massive mudslides in three towns of Brazil - Nova Friburgo, Petrópolis and Teresópolis. Hundreds of people have died and some 14 000 people were left homeless. This event was the deadliest single natural disaster to occur in the country.

In Haiti in 2004, mudslides triggered by the heavy rains brought by Hurricane Jeanne resulted in more than 3 000 deaths and another 2 600 injured. The coastal city of Gonaïves was especially hard hit; 80 000 of the city's 100 000 residents were affected.

On 13 November 1985, the long dormant volcano Nevado del Ruiz in Colombia came alive and within hours it left approximately 23 000 people buried in a mile-wide avalanche of mud and ash and destroyed more than US$339 million in property (Pierson *et al*., 1990; Schuster and Highland, 2001). The hardest hit town was Armero where more than 20 000 people died and 5 000 more were injured (Schuster and Highland, 2001). No lava was produced; rather the magma within the cone melted the overlying snow and ice which created catastrophic lahars (volcanic flows composed of hot or cold water and rock fragments) that eventually came tumbling down. Specific impacts on forests are not known.

Geophysical events

Tsunamis

A tsunami is a series of enormous traveling ocean waves of extremely long length generated primarily by earthquakes occurring below or near the ocean floor. They may also be generated by underwater landslides and volcanic eruptions, or meteorites. Tsunami waves are distinguished from ordinary ocean waves by their great length between wave crests, often exceeding 100 kilometres or more in the deep ocean, and by the time between these crests, ranging from 10 minutes to an hour (ITIC, 2011). In the deep ocean, the tsunami waves travel at over 800 kilometres per hour, with a short wave height of only a few tens of centimetres or less. As they reach shallow coastal waters, the waves slow down and the water can pile up into a wall of destruction dozens of metres or more in height. Large tsunamis have been known to rise over 30 metres and even a tsunami 3-6 metres high can be very destructive and cause many deaths and injuries (ITIC, 2011). Although 60 percent of all tsunamis occur in the Pacific Ocean, they can also threaten coastlines of countries in other regions, including the Indian Ocean, Mediterranean and Caribbean Seas, and the Atlantic Ocean (ITIC, 2011).

The most devastating event occurred in December 2004, when an earthquake off northwestern Sumatra, Indonesia produced a destructive tsunami that struck coasts throughout the Indian Ocean, killing approximately 230 000 people, displacing more than one million people, and causing billions of dollars of property damage. Mangroves, coastal forests, home gardens, agroforestry systems and trees in coastal landscapes were damaged by the tsunami (FAO, 2011). Trees were snapped and uprooted by waves and strong currents. Observed changes in topography, soil salinity and freshwater input may also adversely affect the mangroves, coastal forests and other trees in the longer term.

In Indonesia, the hardest hit country, the degradation and conversion of mangroves into shrimp farms exacerbated the damage caused by the tsunami (Adger *et al.*, 2005; Srinivasa and Nakagawa, 2008; UNEP, 2005). It was estimated that almost 49 000 hectares of coastal forests (not including mangroves) were impacted by the tsunami representing an economic loss of US$21.9 million (UNEP, 2005). Approximately 90 percent damage to 300-750 hectares of mangrove forests was also noted representing a loss of US$2.5 million (UNEP, 2005). Only about 306 hectares of mangrove forests were impacted by the tsunami in Thailand representing less than 0.2 percent of their total area (Srinivasa and Nakagawa, 2008; UNEP, 2005). In some areas in Sri Lanka, large mangrove trees were uprooted and found far from the beach (UNEP, 2005). The tsunami also caused widespread impacts to mangroves and coastal vegetation in the Seychelles and the Maldives. Direct impacts to the mangroves were caused by inputs of sand and silt that covered the pneumatophores (breathing roots).

FAO/H. HIRAOKE/FO-6354

Soil erosion and debris resulting from the 2004 Indian Ocean Tsunami, Indonesia

Areas with healthy, mature and extensive mangroves were generally protected from the force of the tsunami and suffered less damage (Srinivasa and Nakagawa, 2008). Observations from the Maldives showed that coastal forests were most resilient to the tsunami impacts when left as an undisturbed, mixed-species community (UNEP, 2005). Although mature mangroves are quite resistant to water surges, there are limits to this resilience. Sand dunes, mangrove forests and coral reefs all help to reduce the energy of tsunami waves. Considerable international interest in the role of coastal forests in the mitigation of tsunami impacts arose after the Indian Ocean Tsunami in 2004.

More recently, on 11 March 2011, a massive earthquake off the northeastern coast of Japan, the strongest ever recorded in the country, triggered a devastating tsunami of up to 30 metres in height that pushed up to five kilometres inland, resulting in massive loss of life, environmental devastation and infrastructural damage. Aftershocks persisted for some time after. The tsunami also damaged the Fukushima nuclear power plant, leading to serious concerns over radiation contamination (see Radiation contamination section).

While events are still unfolding, the scale of the disaster is all too apparent: as of 01 May 2011, 14 704 people were confirmed dead, 5 278 injured and 10 969 were missing. With a preliminary estimated cost of US$309 billion, it is also believed to be the most costly disaster to date worldwide. The estimate covers destruction to infrastructure in seven prefectures affected by the disaster, including damages to nuclear power facilities north of Tokyo. Wider implications on the economy, including how radiation will affect food and water supply, are not included in the estimate.

Earthquakes

In tectonically active regions of the world, large earthquakes disturb forests over extensive areas and as such are important determinants of forest structure and function (Allen, Bellingham and Wiser, 1999; Vittoz, Stewart and Duncan, 2001). The intensity of damage to forests varies strongly with distance from the earthquake's epicentre.

Earthquakes can trigger landslides while those occurring underwater can produce tsunamis. It is generally considered that the primary cause of tree mortality during earthquakes is as a result of the landslides they create (Allen, Bellingham and Wiser, 1999); forests are often completely removed or submerged by such landslides. However much of the immediate impact of an earthquake is widespread, low-intensity tree mortality and injury (Allen, Bellingham and Wiser, 1999).

Damage is caused by the shaking or shearing of tree roots, the uplift of the ground surface, or changes in the water table (Allen, Bellingham and Wiser, 1999; Vittoz, Stewart and Duncan, 2001). The movement of soil or boulders downslope can also damage trees. Damaged trees may survive but they will exhibit signs of the disturbance such as fractures in the wood, growth suppression or the production of reaction wood (Vittoz, Stewart and Duncan, 2001). The diversity of earthquake impacts is a major source of heterogeneity in forest structure and regeneration. Some examples of recent earthquakes and their impacts on forests can be found in Box 4.

flickr/F. GRAHAM

Damage caused by the 2011 earthquake in Christchurch, New Zealand

Box 4. Recent earthquakes and their impacts on forests

A 6.3 magnitude earthquake struck Christchurch, New Zealand on 22 February 2011 killing at least 160 people and causing billions of dollars in damage. Many trees in urban areas and parks were damaged and needed to be removed to ensure public safety.

The devastating 7.0 magnitude earthquake of 12 January 2010 in Haiti resulted in more than 230 000 deaths, left 1.5 million homeless in the region around Haiti's capital, Port-au-Prince and delivered a severe blow to the country's already shaky economy and infrastructure (UNEP, 2011). Forest damage as a result of the earthquake was unknown at time of print.

An earthquake of 8.8 magnitude hit central Chile on 27 February 2010 killing more than 700 people and causing widespread damage in many parts of the country, particularly near Concepción, the second largest metropolitan area. Following the earthquake a tsunami hit the coastline severely impacting coastal communities. Approximately half a million homes were seriously damaged. The impacted region is home to important industries including fishing, shipping, power generation, petroleum refining, and forest products. Losses to Chile's economy were estimated at US$15-30 billion (UNEP, 2011). The country's pulp and paper producers, such as Arauco, Empresas CMPC, Papelera Concepcion and Norske Skog, were among the hardest hit with severely damaged production facilities forcing a temporary shutdown of all plants. Global prices for pulp rose significantly as a result.

In addition to a catastrophic loss of human life and destruction of towns and villages, the earthquake in Wenchaun, Sichuan Province, China in 2008 caused forest fragmentation and severely damaged ecosystems that support some of the last remaining giant panda (*Ailuropoda melanoleuca*) populations in the wild (Xu *et al*., 2009).

On 08 October 2005 a magnitude 7.6 quake struck Kashmir in northern Pakistan killing approximately 30 000 people in just hours. By the onset of winter, more than 87 000 people were dead and some three million were homeless. The earthquake magnified the impact of environmental degradation, causing significant land destabilization and damage. Several major landslides and thousands of minor landslips occurred, affecting about ten percent of hillside arable land, forests and rangelands (FAO, 2009). Many trees were also damaged by rock falls and in some areas the earthquake truncated trees about two metres above the ground (IUCN, 2006). The inner core of many trees were likely damaged which was predicted to affect their future use and value (IUCN, 2006). Flash floods and mudslides destroyed agricultural land and fruit tree plantations, and altered runoff routes on hillsides and in valley lowlands. The total cost of damage and losses in the agricultural and livestock sectors was estimated at US$409 million (FAO, 2009).

Volcanic eruptions

There are approximately 1 500 potentially active volcanoes worldwide, plus hundreds more on the ocean floor. About 500 of these have erupted in historical time. Many of these are located along the Pacific Rim in what is known as the "Ring of Fire".

Of the various disturbances discussed here, volcanic eruptions have the least potential of leaving residual materials behind. The intense force of the blast, and the large amount of earth that is either moved or covered with various kinds of debris, makes it a disturbance that is more severe than the hottest fire or the most intense windstorm (Foster, Knight and Franklin, 1998). Impacts diminish as distance from the volcano increases.

Volcano hazards that may impact forests include:

- gases, such as sulphur dioxide, carbon dioxide and hydrogen fluoride;
- lahars – volcanic flows composed of hot or cold water and rock fragments;
- landslides;

- lava flows;
- pyroclastic flows – fast-moving currents of hot rock and gas that travel downhill along slope depressions (Grishin, 2009);
- tephra – fragments of volcanic rock and lava that become airborne through explosions or the rise of hot gases (USGS, 2011). The smallest fragments are volcanic ash.

Young forests are most at risk from ashfall; stands of trees less than two years old are likely to be destroyed by ash deposits thicker than 100 millimetres (USGS, 2011). Mature trees are unlikely to succumb from ashfall deposition alone, but the accumulated weight of ash can break large branches in cases of heavy ashfall (>500 mm). Defoliation of trees may also occur.

One of the most documented volcanic eruptions and its subsequent impacts on forests and natural environments is Mount St. Helens in Washington, USA. On 18 May 1980 the volcano erupted killing some 57 people, impacting more than 700 square kilometres of land and creating several distinct disturbances including: a 0.25 square kilometre pyroclastic flow; a 550 square kilometre area of blown down trees bordered by 96 square kilometres of scorched trees; a 60 square kilometre debris avalanche or landslide; and massive mudflows (Turner, Dale and Everham, 1997).

No plants survived on the pyroclastic flows at Mount St. Helens, and the recovery of these areas has been slow, being colonized by herbaceous and forb species with wind-dispersed seeds (Turner, Dale and Everham, 1997). The force of the eruption in the blowdown zone was strong enough to knock over trees, although herbs and understory vegetation survived (Halpern *et al.*, 1990). In the scorch perimeter around the blowdown zone, temperatures were hot enough to burn leaves, but the winds were not strong enough to fell the trees. Coniferous trees in this area died, but some deciduous trees survived (Turner, Dale and Everham, 1997).

No viable seeds survived the debris avalanche or landslides and the very few surviving plants developed from rootstocks or stems that were moved by the landslide and came to rest near the surface (Turner, Dale and Everham, 1997). By 1994, vegetation cover on the debris avalanche had gradually increased from zero to 35 percent and was composed of early successional species with wind-dispersed seeds, a few conifers and red alder (Alnus rubra) (Turner, Dale and Everham, 1997). Mudflows washed away most of the understory vegetation and small trees; large trees, those taller

FAO/R. GRISOLIA/21843

Chile's Lonquimay Volcano erupting

GEOPHYSICAL

than the surface of the flow, survived. The proximity of surviving vegetation and seeding by humans resulted in almost 100 percent cover on the mudflows within a few years (Halpern and Harmon, 1983). Further examples of volcanic eruptions can be found in Box 5.

Box 5. Examples of volcanic eruptions and their impacts on forests[4]

One of the oldest well-known events is that of Mount Vesuvius in Italy which erupted in A.D. 79 and completely buried the cities of Pompeii and Herculaneum, preserving the ancient life there. More recent eruptions occurred in 1906, which killed over 100 people, and in 1944, which destroyed the villages of San Sebastiano al Vesuvio, Massa di Somma, Ottaviano and part of San Giorgio a Cremano. The volcano remains one of the most threatening active volcanoes with the greatest deadly potential as it is located near large populations; over 11 million people live close by in Naples and other towns.

The most powerful modern eruption is that of the Krakatau volcano in the Krakatau Islands, Indonesia in 1883 which killed 40 000 people. It created catastrophic tsunamis in the region and emitted so much ash into the stratosphere that global temperatures were lowered for about a year after. Each of the three islands (Krakatau, Panjang, Sertung) were entirely stripped of all vegetation by a thick layer of ash, lava and pumice (Whittaker, Bush and Richards, 1989; Zabka and Nentwig, 2002).

The eruption of Mount Pinatubo in the Philippines in 1991 killed approximately 300 people, injured hundreds more and displaced millions. The eruption produced high-speed avalanches of hot ash and gas, giant mudflows, and a cloud of volcanic ash hundreds of miles across (UGSG, 2005). The toxic ash cloud reduced global temperatures 0.5 °C below normal for two years after the eruption (Hansen *et al*., 1996)

The Soufrière Hills volcano in Montserrat began erupting in 1995 and continues at the time of writing. By late 1997, pyroclastic flows had almost completely destroyed the tropical forest in the southern hill ranges of the island (Dalsgaard *et al*., 2007). The remaining forested hill range, the Centre Hills, have been impacted by frequent and heavy periods of ashfall and acid rain, interspersed with periods of recovery. Field studies in the area have noted that populations of canopy insects and bird species were often reduced after major ashfalls, but the impact was short-lived and recovery followed in subsequent years (Dalsgaard *et al*., 2007; Marske, Ivie and Hilton, 2007).

Piton de la Fournaise in Réunion is one of the world's most active volcanoes; it has erupted more than 150 times since 1640. Recent eruptions include 2002 and twice in 2010. The 2002 eruption resulted in the colonization of lava by exotic plant species and the destruction of natural forests by lava flows (FAO, 2010).

The eruption of Iceland's volcano, Eyjafjallajökull, in April 2010 created a massive cloud of ash that shut down air travel in Europe for more than a week, inconveniencing millions. Costs to the global air travel sector were estimated at US$200 million per day. The grounding of European flights avoided an estimated 344 109 tonnes of carbon dioxide (CO_2) emissions per day while the volcano emitted about 150 000 tonnes of CO_2 per day (UNEP, 2011).

The eruption of Chile's Puyehue volcano in June 2011 wreaked similar havoc. The ash cloud circled the world disrupting flights in Argentina, Brazil, Chile, Uruguay, Australia and New Zealand.

[4] Little information is available on the direct impacts of volcanoes on forests; many of these examples have been included to illustrate the impacts of ash and carbon emissions.

ANTHROPOGENIC EVENTS

Fire

The impact of fire on forests is mentioned only briefly here. Considerably more information on this topic can be found at FAO's Forests and fire Web site at: www.fao.org/forestry/firemanagement/

Fire has a major influence on the development and management of many of the world's forests. Some forest ecosystems have evolved in response to frequent fires from natural (See section on Thunderstorms and lightning under Meteorological events) as well as human causes, but most others are negatively affected by wildfire. Every year millions of hectares of the world's forests are consumed by fire, which results in significant loss of life and livelihoods and enormous economic losses from destroyed timber and infrastructure, the high costs of fire suppression, and loss of environmental, recreational and amenity values. FAO's Global Forest Resources Assessment 2010 noted that, on average, one percent of all forests, or 19.8 million hectares, were reported to be significantly affected each year by forest fires (FAO, 2010). However, the area of forest affected by fires was severely underreported and thus the numbers are considered an underestimate of the true area affected. In addition to direct losses, the associated soil erosion, site deterioration and subsequent difficulties in re-establishing the forest due to the dry climate and poor soil conditions have major impacts on the forest sector (FAO, ECE and ILO, 1995).

Forest structure may be abruptly changed by intense canopy fires, which burn leaves and small branches and which are accompanied by surface fires that consume forest floor and understory vegetation (Foster, Knight and Franklin, 1998). Notably, most of the larger tree boles are not burned, even if killed, and they often remain standing for 10–50 years after a fire. Such residual living and dead organic matter are important for wildlife habitat, nutrient dynamics, ecosystem function and forest recovery (Harmon *et al*., 1986), though it may provide a breeding substrate for insect pests thus possibly leading to devastating outbreaks.

FAO/M. KASHIO/FO-6479

Bush fire during the dry season, Thailand

ANTHROPOGENIC

Fires can be triggered during and after periods of drought, by heat waves, dry lightning, human action or a combination of these factors in almost all parts of the world. People are the overwhelming cause of fires however, through such activities as land clearing and other agricultural activities, maintenance of grasslands for livestock management, extraction of non-wood forest products, industrial development, resettlement, hunting, negligence and arson (FAO, 2007).

Susceptibility to fire depends on the properties of living and dead vegetation as fuel, i.e. its amount and spatial distribution, which are related to forest composition and structure (Seidl *et al.*, 2011). Dry conditions are a prerequisite for significant fire events. However, generally dry climate conditions also reduce productivity and thus fuel availability, exerting a negative feedback on fires (Seidl *et al.*, 2011).

Fire risk and incidence can also increase as a result of other disasters, such as pest and disease outbreaks and storms, which increase the amount of dry dead biomass, or by a lack of silvicultural treatments for economical reasons or out of fear (presence of landmines).

In many forests, low- to medium-intensity surface fires burning in regular intervals help to reduce fuel loads without damaging the timber. In several countries like the USA, decades of fire suppression has drastically altered the composition and structure of vegetation and has resulted in forests with high tree densities and unnaturally high fuel loads that increase the risk of more frequent and higher intensity fires (Allen *et al.*, 2010). These fires have quite different impacts from low-intensity fires and result in significant economic and ecological losses such as stand destruction, habitat loss and susceptibility to secondary disturbances. There are many examples from around the world, such as Australia, North America and the Mediterranean area, of such problems associated with removing fire from fire-adapted ecosystems.

In recent decades a notable increase of large wildfires or mega-fires has been noted in all regions of the world. Mega-fires are the most costly, most destructive and most damaging of all wildfires. Not always a single wildfire, they are sometimes a group of multiple fires across a large geographic area. The risk of their occurrence likely increases as droughts deepen, fuels accumulate, and landscapes become more homogeneous. Mega-fires are often extraordinary for their size, but they are more accurately defined by their complex, deep and long-lasting social, economic and environmental impacts (Williams *et al*., 2011). They severely impact local communities and also have serious regional or global consequences. Environmental impacts include interrupting or adversely altering energy, water, nutrient and carbon cycles, declines in biodiversity, increased carbon emissions, and weed invasion (Williams *et al*., 2011). Examples of some notable mega-fires can be found in Box 6.

Box 6. Recent examples of mega-fires from around the world

Perhaps the first known mega-fire was China's 1987 Great Black Dragon Fire which claimed the lives of over 200 people and burned approximately 1.2 million hectares (Salisbury, 1989).

In Indonesia, a succession of extraordinary wildfires in 1982/83, 1994, and 1997/98 resulted in significant ecological damage. Biodiversity losses and greenhouse gas emissions were nearly incalculable on a global scale.

Similar effects in Brazil's Amazon region were witnessed over a period of years, ending with the Roraima fires in 1998 which burned for over 30 days and covered approximately 11 000 hectares.

Since 1998, at least nine states in the United States, have suffered their worst wildfires on record. In California, for example, multiple large fires claimed dozens of lives and destroyed thousands of homes in 2003.

In Australia, a series of disastrous bushfires in early 2003, January 2005, and 2006-2007 were exceeded by the February 2009 Black Saturday Fires, which followed a 13-year period of drought. The 2009 event is considered the deadliest civil disaster in that country's history, killing 173 people and incinerating entire towns (Teague, McClead and Pascoe, 2009).

In Botswana, a severe wildfire in 2008 spread onto the second largest game reserve in the world, disrupting a fragile local economy tied to indigenous grazing and the region's important ecotourism sector.

In 2007, severe wildfires hit Greece, killing 84 people and burning 270 000 hectares of land. The fires occurred after a deep drought and at least two heat waves.

More recently, record-setting wildfires occurred in the Russian Federation and Israel in 2010. Across all of the Russian Federation, approximately 2.3 million hectares burned as a result of over 32 000 fires. Sixty-two people died and hundreds of homes were lost. The fires created a toxic cloud of smog that hovered over Moscow and other cities for weeks particularly affecting people with respiratory diseases, the very young and the elderly. In Israel, on the outskirts of Haifa, 42 people were killed by fire and much of a treasured forest was lost.

Over the past several years, similar catastrophic wildfires have occurred in Canada, South Africa, Portugal, Spain and Turkey among others.

(*Source:* Williams *et al*., 2011, unless otherwise noted)

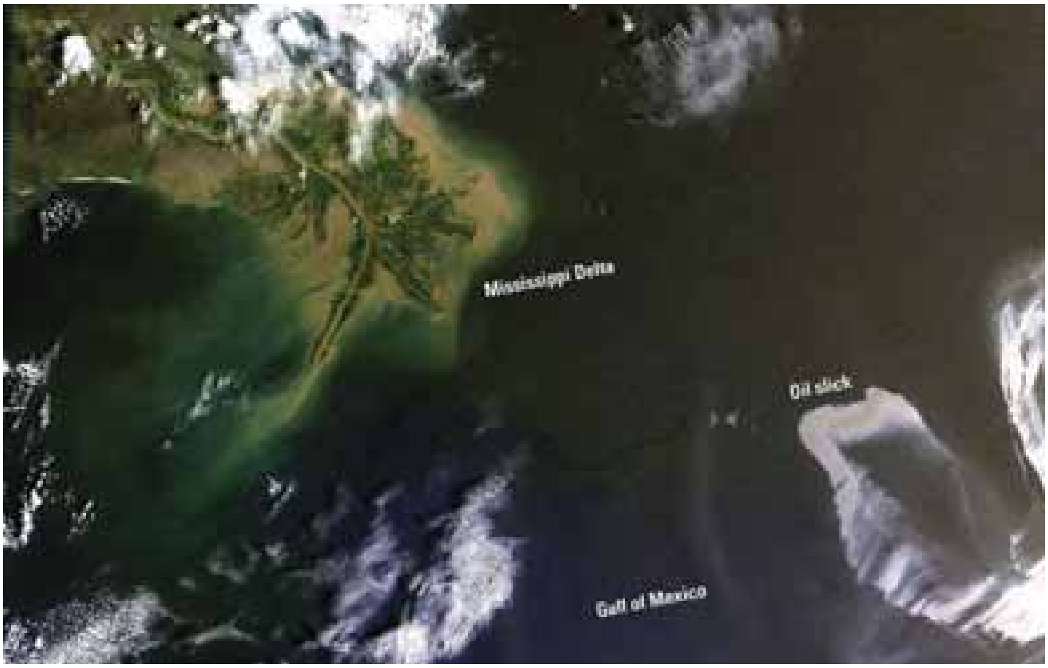
Oil spills

Oil spills can have devastating impacts on coastal forests and mangroves. Mangroves are highly susceptible to oil exposure and can be affected in two main ways: from the physical effects of oiling and from the toxicological effects of the oil (NOAA, 2010). The physical effects of oiling (e.g. covering or blocking specialized tissues needed for respiration or salt management) may include either disruption or complete prevention normal biological processes of exchange with the environment. When oil physically covers plants, animals and birds, they may die from suffocation, starvation, or other physical interference with normal physiological function.

Acute effects of oil (mortality) occur within six months of exposure and usually within a much shorter time frame (a few weeks). Visible signs of mangrove stress, including chlorosis, defoliation and death, often show within the first two weeks of a spill event. The tree may survive for a time only to succumb weeks or months later, or, depending on the severity of the damage, it may recover to produce new leaf growth. Seedlings and saplings, in particular, are susceptible to oil exposure (NOAA, 2010). More subtle responses include branching of pneumatophores (breathing roots), germination failure, decreased canopy cover, increased rate of mutation, and increased sensitivity to other stressors (NOAA, 2010).

Chronic oil impacts on mangroves include altered growth rates and reproductive timing or strategy and can be measured over long time periods, potentially a decade or decades. They may also exhibit morphological adaptations in order to survive the oiling as illustrated by the development of branched secondary pneumatophores in mangroves as a response to impairment of normal respiration after the 1991 Gulf War spill (Böer, 1993).

Root survival, canopy condition and growth rates of mangrove seedlings in oil-deforested gaps are adversely affected by oil remaining in mangrove sediments. Six years after the 1986 Bahía las Minas (Galeta) oil spill in Panama, surviving forests surrounding deforested areas exhibited canopy deterioration (Burns, Garrity and Levings, 1993). A lack of recovery in affected mangrove areas was also noted four years after the 1992 Era spill in Australia (NOAA, 2010). Such long-term impacts have also been reported from an experimental study, the TROPICS spill in Panama in 1984, whereby nearly half of the affected trees were dead ten years after the oiling compared with 17 percent mortality at seven months post-oiling (NOAA, 2010).



flickr/NASA GODDARD SPACE FLIGHT CENTER

Oil spill in the Gulf of Mexico after the explosion of the Deepwater Horizon oil rig, 2010

The severity of the impacts of oil spills on mangroves are dependant on the amount of oil spilled, the type of oil spilled (including additives), the amount of time the oil remains near the mangroves, and the weathering time of the oil itself (NOAA, 2010). Lighter oils are more acutely toxic to mangroves than heavier oils and increased weathering generally lowers oil toxicity.

An initial damage assessment survey conducted in the first month after the 1999 Roosevelt Roads Naval Air Station (Puerto Rico) spill of jet fuel, determined that 46 percent of mangrove trees, saplings, and seedlings along a transect in the most impacted basin area were exhibiting obvious signs of stress (NOAA, 2010). Within three months of the 1992 Australian Era spill, extensive defoliation of mangrove trees had begun and many appeared to be dead (NOAA, 2010). Five months after the 1986 Bahía las Minas spill, a band of dead and dying trees was noted and a year and a half after the spill, dead mangroves were found along 27 kilometres of the coast (NOAA, 2010).

One of the most publicized and studied environmental disaster in history is the 1989 Exxon Valdez oil spill in Prince William Sound, Alaska, USA. Approximately 11 million gallons or 257 000 barrels of oil spilled from the grounded tanker impacting over 2 000 kilometres of coastline (Exxon Valdez Oil Spill Trustee Council, 2011). It is widely considered the most damaging oil spill ever primarily because of the magnitude of the spill, extent of shoreline contamination, and high mortality of wildlife including algae, benthic macroinvertebrates, sea birds, bald eagles, sea otters, seals and whales. The timing of the spill, the remote location, the thousands of kilometres of wild shoreline, and the abundance of wildlife in the region combined to make it so notable.

On 20 April 2010, the oil rig Deepwater Horizon exploded in the Gulf of Mexico, resulting in the largest accidental marine oil spill in the petroleum industry's history and causing damage to wildlife and marine habitats, and to the fishing and tourism industries (UNEP, 2011). Almost five million barrels flowed into the Gulf before the well was permanently sealed on 19 September 2010. Hundreds of kilometres of coastal vegetation were impacted and recovery may take many years.

Air pollution

Air pollution has long been recognized as a detriment to the world's flora. Pollutants such as nitrogen, sulphur dioxide, heavy metals and ozone can be conveyed in the atmosphere over great distances as

gases or microscopic particles (MCPFE, 2007). Tree canopies are very efficient at capturing deposition of, or filtering, atmospheric pollutants of all kinds resulting in high inputs to forests. Deposition of pollutants can impact ecosystems directly or through soil acidification and eutrophication.
The environmental impacts of air pollutants have been of great concern, particularly in Europe, resulting in the adoption of the United Nations Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution (CLRTAP) in 1979. The Convention addresses some of the major environmental problems of the UNECE region through scientific collaboration and policy negotiation and has been extended by eight protocols that identify specific measures to be taken by Parties to cut their emissions of air pollutants such as persistent organic pollutants (POPs), sulphur and nitrogen oxides.

The International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) was launched in 1985 under the Convention due to the growing public awareness of possible adverse effects of air pollution on forests. The Programme monitors forest condition in Europe to provide an overview of the status of forest ecosystems with respect to air pollution and contribute to the understanding of the relationship between pollution and forest health. Crown condition parameters, such as defoliation and discolouration, are used as the principal indicators of forest condition.

Ground-level ozone (O_3), the most important air pollutant affecting forests worldwide, is known to reduce photosynthesis, growth, and other plant functions (Bytnerowicz *et al.*, 2008; Felzer *et al.*, 2007; Karnosky *et al.*, 2005). It also enhances susceptibility to pathogens (Karnosky *et al.*, 2002) and results in leaf chlorosis or senescence and forest decline (Emberson, 2003).

The deposition of atmospheric nitrogenous pollutants emitted from industrial, urban and agricultural sources is also of great importance in that they affect growth, biodiversity and biogeochemical cycles in forest ecosystems in many areas (Bytnerowicz *et al.*, 2008). Nitrogen oxides (NO_x) result in altered plant growth, enhanced sensitivity to secondary stresses, and eutrophication (Emberson, 2003). At low levels and in nitrogen-limited ecosystems, such as boreal forests, nitrogen may enhance growth. NO_x, ammonia (NH_3) and nitric acid (HNO_3) vapour may have direct phytotoxic effects but only at high concentrations (Bytnerowicz, Omasa and Paoletti, 2007).

BUGWOOD.ORG/P. KAPITOLA/3040065

*Air pollution damage to European larch (*Larix decidua*), Czech Republic*

ANTHROPOGENIC

The importance of some industrial air pollutants, such as sulphur dioxide (SO_2) and heavy metals, has risen in recent years as a result of the rapid industrialization of some countries which often lack adequate environmental considerations and controls (Bytnerowicz *et al.*, 2008). The major source of SO_2 is from the combustion of fossil fuels containing sulphur. Impacts on vegetation include leaf chlorosis, reduced plant growth and vitality, and forest decline (Emberson, 2003; MCPFE, 2007).

Radioactive contamination

Accidents at nuclear power plants create obvious concerns about exposure of the human population to contamination in the immediate vicinity, and there are potentially longer term problems due to the ecological impact from contamination with radionuclides. Radionuclides are radioactive atoms that are either man-made or naturally occuring but only a few are considered to present serious risks to human, wildlife and ecosystem health (FAO/IAEA, 2011).

Although many different kinds of radionuclides can be discharged following a major nuclear accident, some are very short-lived and others do not readily transfer into food and ecosystems. Those that could be significant for the food chain include radioactive hydrogen (^{3}H), carbon (^{14}C), technetium (^{99}Tc), sulphur (^{35}S), cobalt (^{60}Co), strontium (^{89}Sr and ^{90}Sr), ruthenium (^{103}Ru and ^{106}Ru), iodine (^{131}I and ^{129}I), uranium (^{235}U), plutonium (^{238}Pu, ^{239}Pu and ^{240}Pu), caesium (^{134}Cs and ^{137}Cs), cerium (^{103}Ce), iridium (^{192}Ir), and americium (^{241}Am) (INFOSAN, 2011).

Caesium-137 is the primary radionuclide of concern regarding the long-term contamination of forests and forest products, owing to its 30 year half-life (IAEA, 2006; Riesen, 2002). The transfer of radionuclides in the environment depends on the particular ecosystem. Forests with soils rich in organic matter and generally low in clay content leads to a higher transfer of radiocaesium to most forest products, such as berries or mushrooms (Riesen, 2002; FAO/IAEA, 2011).

Over time, radioactivity can build up within food, as radionuclides are transferred through soil into crops or animals, or into rivers, lakes and the sea where fish and other seafood could take up the radionuclides. Food collected from the wild, such as mushrooms, berries and game meat, may continue to be a radiological problem for a long time (INFOSAN, 2011).

After a nuclear accident, monitoring the agricultural, forestry and fisheries environment and restricting the movement and export of possibly contaminated products is an important factor. Implementation of such monitoring can be complex, expensive and technically demanding and requires advance training and quality assurance of laboratory performance.

One of the most well-known and well-studied incidents occurred at the Chernobyl nuclear power plant in the Ukraine on 26 April 1986. A sudden power surge during a systems test caused a reactor vessel to rupture, leading to a series of blasts. An intense fire burned for ten days. Substantial radioactive contamination of forests occurred in Belarus, the Russian Federation and Ukraine, but radionuclides from Chernobyl were carried in the atmosphere into other countries in Europe including Austria, Bulgaria, Croatia, Czech Republic, Finland, Germany, Greece, Hungary, Italy, Moldova, Norway, Poland, Romania, Slovenia, Sweden, Switzerland and the United Kingdom (FAO/IAEA, 2011; IAEA, 2002; IAEA, 2006). Other affected areas included Asia (including China, Armenia, Georgia, Turkey, United Arab Emirates), northern Africa, and North America (FAO/IAEA, 2011).

The Exclusion Zone is a 30 kilometre area of heavy contamination around the site of the Chernobyl nuclear reactor disaster. Wildlife in this area were exposed to high levels of radionuclides via food, water and air; levels in some individuals were many hundred times higher than in unaffected populations (FAO/IAEA, 2011). Many individuals that remained in this zone died from radiation-induced illnesses and today, mammals, birds, fish and amphibians still exhibit morphological deformities and genetic disorders (FAO/IAEA, 2011). Very high levels of contamination on the canopies of pine trees were noted within a seven kilometre radius of the reactor; these trees received lethal doses of radiation. This small area of forest became known as the Red Forest, as the trees died and became reddish-brown in colour, the most observable effect of radiation damage on organisms in the area (IAEA, 2006).

In affected forests, there was an initial filtering of contaminants by the tree canopy though canopy contamination was reduced rapidly over a period of weeks to months from rain run-off and leaf or needle fall (FAO/IAEA, 2011; IAEA, 2006). The soil of the forest floor became the main repository for radionuclides and trees and plants continued to become contaminated through root uptake. Radiocaesium can be recycled in trees through root uptake and regular leaf or needle fall, and stored long-term in the trunks of the tree (FAO/IAEA, 2011). Forest fruits and fungi became contaminated with very high levels of Caesium-137, which led to increased contamination of forest animals such as deer and moose (FAO/IAEA, 2011). Since the Chernobyl accident it has become apparent that the natural decontamination of forests is proceeding extremely slowly (IAEA, 2006). Preventing wildfires within the Exclusion Zone remains a high priority since they could release clouds of radioactive particles that still persist in the trees. Smoke from fires can spread thousands of kilometres which could substantially increase the area of impact to humans and the environment.

More recently, on 11 March 2011 in Japan, a magnitude 9.0 earthquake and associated tsunami damaged the power systems of the Fukushima Daiichi nuclear power plant causing cooling systems to fail. A series of gas explosions followed. Reports from the Government of Japan indicated that several radionuclides of consequence to human health, including Iodine-131 and Caesium-137, were found in the soil, vegetation and in animals, or their products; some of which exceeded acceptable levels (FAO/IAEA, 2011). While no data were available at time of print on the impacts of contamination on forests in the region, lessons learned and precautionary measures lead to recommendations that people refrain from hunting, gathering forest products and burning fuelwood. The situation in Japan illustrates the severity of the impacts of geophysical events on infrastructure whereby a sophisticated and well-prepared society can quickly experience situations normally associated with developing countries, such as large-scale food shortages, water and shelter crises, logistics collapse and the displacement of hundreds of thousands of people.

flickr/TIMM SUESS

Radioactive contamination of forests in the Exclusion Zone at Chernobyl, Ukraine. This forest became known as the Red Forest as the trees died and turned reddish-brown in colour.

Conclusions

Abiotic disturbances are having major impacts on trees and forests and there are many similarities in the types of impacts they have, both positive and negative. They influence forest structure, composition and functioning and can be important for maintaining biological diversity and facilitating regeneration. They may however, occur as catastrophic events affecting entire landscapes, causing large-scale tree mortality and complete destruction of undergrowth and soils. Global climate change is exacerbating many of these impacts and there is still major uncertainty about the interactions between disturbance, climate change and forests. In November 2011, the Intergovernmental Panel on Climate Change (IPCC) will release a Special Report on managing the risks of extreme events and disasters to advance climate change adaptation. The report aims to become a resource for decision-makers to prepare more effectively for managing the risks of these events.

While the damage can be devastating in the short-term, recovery of the forests is possible. Forests are quite resilient and will eventually return to a stable state, though not necessarily to the same state as pre-disturbance, over a period of time. While this is good news from an ecological point of view, the short-term damage is of considerable concern for forest managers who are maintaining forests for a specific purpose, be it protective or productive. In managed forests, damage results in economic losses. In areas where such disturbances are known or possible to occur, managers must incorporate them into their management plans. Since such disturbances do not respect borders, regional or international cooperation is often required.

Abiotic disturbances are expected to increase in intensity, quantity and frequency. Adaptive forest management using a landscape-level approach involving all sectors and stakeholders is therefore essential to protect the world's forest resources. Activities such as diversifying species, using windbreaks and mixed cropping patterns for resilience and not planting susceptible species in areas prone to such disturbances will help in this regard. More data is needed and the impacts of abiotic disturbances on forests must be recorded and reported so that appropriate actions may be taken to mitigate future damage. Reducing the impacts of disturbances on forests will contribute to countries' efforts to reduce carbon emissions from deforestation and forest degradation through forest conservation, sustainable forest management and enhancement of forest carbon stocks (REDD+[5]).

Another item of note for forest managers is the fact that the condition of forests themselves can have an influence on disturbances. For example, deforestation or poor management practices can increase flooding and landslides during cyclones and degradation of mangrove forests may increase the damage that storm surges or tsunamis cause. In some areas, climate change is increasing the incidence of drought and heat waves resulting in an increased risk and incidence of wildfires which in turn, contributes to global warming through carbon emissions. As such, taking care of the world's forests and effectively managing them not only ensures that they meet their objectives but also reduces the risk of damage from future abiotic disturbances and addresses global climate change concerns.

---

[5] Reducing Emissions from Deforestation and Forest Degradation (REDD) is an effort to create a financial value for the carbon stored in forests, offering incentives for developing countries to reduce emissions from forested lands and invest in low-carbon paths to sustainable development. "REDD+" goes beyond deforestation and forest degradation, and includes the role of conservation, sustainable management of forests and enhancement of forest carbon stocks (UNFCC, DECISION 1/CP.16).

References

Adger, W.N., Hughes, T.P., Folke, C., Carpenter, S.R. & Rockström, J. 2005. Social–ecological resilience to coastal disasters. *Science*, 309: 1036–1039.

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.H., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J-H., Allard, G., Running, S.W., Semerci, A. & Cobb, N. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, 259 (4): 660–684.

Allen, R.B., Bellingham, P.J. & Wiser, S.K. 1999. Immediate damage by an earthquake to a temperate montane forest. *Ecology,* 80(2): 708–714.

Ayres, M.P. & Lombardero, M.J. 2000. Assessing the consequences of global change for forest disturbance from herbivores and pathogens. *Science of The Total Environment*, 262(3): 263-286.

Bebi, P., Kienast, F. & Schönenberger, W. 2001. Assessing structures in mountain forests as a basis for investigating the forests' dynamics and protective function. *Forest Ecology and Management*, 145: 3–14.

Bebi, P., Kulakowski, D. & Rixen, C. 2009. Snow avalanche disturbances in forest ecosystems – State of research and implications for management. *Forest Ecology and Management*, 257: 1883–1892.

Bigler, C., Braker, O.U., Bugmann, H., Dobbertin, M. & Rigling, A. 2006. Drought as an inciting mortality factor in Scots pine stands of the Valais, Switzerland. *Ecosystems*, 9: 330–343.

Böer, B. 1993. Anomalous pneumatophores and adventitious roots of *Avicennia marina* (Forssk.) Vierh. mangroves two years after the 1991 Gulf War oil spill in Saudi Arabia. *Marine Pollution Bulletin*, 27: 207–211.

Boose, E.R., Serrano, M.I. & Foster, D.R. 2004. Landscape and regional impacts of hurricanes In Puerto Rico. *Ecological Monographs,* 74(2): 335–352.

Breda, N., Huc, R., Granier, A. & Dreyer, E. 2006. Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long-term consequences. *Annals of Forest Science*, 63: 625–644.

Breshears, D.D., Cobb, N.S., Rich, P.M., Price, K.P., Allen, C.D., Balice, R.G., Romme, W.H., Kastens, J.H., Floyd, M.L., Belnap, J., Anderson, J.J., Myers, O.B. & Meyer, C.W. 2005. Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Science USA*, 102: 15144–48.

Burns, K.A., Garrity, S.D. & Levings, S.C. 1993. How many years until mangrove ecosystems recover from catastrophic spills? *Marine Pollution Bulletin*, 26(5): 239–248.

Butler, D.R. 1979. Snow avalanche path terrain and vegetation glacier national park, Montana. *Arctic, Antarctic, and Alpine Research*, 11: 17–32.

Bytnerowicz, A., Arbaugh, M., Fenn, M., Sanchez Gimeno, B. & Paoletti, E. 2008. Introduction: Forests under anthropogenic pressure - Effects of air pollution, climate change and urban development. *Environmental Pollution*, 155: 389–390.

Bytnerowicz, A., Omasa, K. & Paoletti, E. 2007. Integrated effects of air pollution and climate change on forests: A northern hemisphere perspective. *Environmental Pollution*, 147: 438–445.

Carnicer, J., Coll, M., Ninyerola, M., Pons, X., Sánchez, G. & Peñuelas, J. 2011. Widespread crown condition decline, food web disruption, and amplified tree mortality with increased climate change-type drought. *PNAS*, 108(4): 1474–1478.

Chambers, J.Q., Fisher, J.I., Zeng, H., Chapman, E.L., Baker, D.B. & Hurtt, G.C. 2007. Hurricane Katrina's Carbon Footprint on U.S. Gulf Coast Forests. *Science*, 318(5853): 1107.

Chapman, E.L., Chambers, J.Q., Ribbeck, K.F., Baker, D.B., Tobler, M.A., Zeng, H. & White, D.A. 2008. Hurricane Katrina impacts on forest trees of Louisiana's Pearl River basin. *Forest Ecology and Management*, 256(5): 883–889.

Clatterbuck, W.K., Vandergriff, D.S. & Coder, K.D. 2011. Tree damage and hazard assessment - Understanding lightning and associated tree damage. Available at: essmextension.tamu.edu/treecarekit/index.php/after-the-storm/tree-damage-and-hazard-assessment/understanding-lightning-and-associated-tree-damage/

Dale, V.H., Joyce, L.A., McNulty S. & Neilson, R.P. 2000. The interplay between climate change, forests, and disturbances. *Science of The Total Environment*, 262(3): 201–204.

Dalsgaard, B., Hilton, G.M., Gray, G.A.L., Aymer, L., Boatswain, J., Daley, J., Fenton, C., Martin, J., Martin, L., Murrain, P., Arendt, W.J., Gibbons, D.W. & Olesen, J.M. 2007. Impacts of a volcanic eruption on the forest bird community of Montserrat, Lesser Antilles. *Ibis*, 149: 298–312.

Doyle, T.W., Michot, T.C., Roetker, F., Sullivan, J., Melder, M., Handley, B. & Balmat, J. 2002. Hurricane Mitch: Landscape Analysis of Damaged Forest Resources of the Bay Islands and Caribbean Coast of Honduras. USGS Open File Report 03-175.

Emberson, L. 2003. Chapter 1: Air Pollution Impacts on Crops and Forests: An Introduction. *In*: Emberson, L., Ashmore, M. & Murray, F. (eds), *Air Pollution Impacts on Crops And Forests. A Global Assessment*. Air Pollution Reviews, Vol. 4. Imperial College Press, London.

Exxon Valdez Oil Spill Trustee Council. 2011. Exxon Valdez Oil Spill Trustee Council Web site. Available at: www.evostc.state.ak.us

Felzer, B.S., Cronin, T., Reilly, J. M., Melillo, J.M. & Wang, X. 2007. Impacts of ozone on trees and crops, *C. R. Geoscience*., 339: 784–798.

FAO. 2007. *Fire management - Global assessment 2006. A thematic study prepared in the framework of the Global Forest Resources Assessment 2005*. Rome.

FAO. 2008. Bangladesh - Emergency livelihood protection and rehabilitation. Programme appraisal document. Cyclone SIDR, November 2007, Disaster Needs Assessment.

FAO. 2009. *Evaluation of the FAO Response to the Pakistan Earthquake, May-July 2008 - Final Report*. Prepared by Watt, J., Cossee, O., Ahmed, J., Khalid, N., Riaz, M. & Shah, P.

FAO. 2010. *Global Forest Resources Assessment 2010. Main report*. FAO Forestry Paper No. 163. Rome.

FAO. 2011. FAO Tsunami reconstruction – forestry Web site. Available at: www.fao.org/forestry/tsunami (Accessed 06/03/11)

FAO/ECE/ILO. 1995. *Acute forest damage manual: Managing the impact of sudden and severe forest damage*. Discussion Paper No. 7. Geneva, Food and Agriculture Organization (FAO)/Economic Commission for Europe (ECE) & International Labour Organization (ILO).

FAO/IAEA. 2011. Joint FAO/IAEA Programme Web site. Nuclear techniques in food and agriculture Available at: www-naweb.iaea.org/nafa/index.html (Accessed on 01/05/11)

Foster, D.R., Knight, D.H. & Franklin, J.F. 1998. Landscape patterns and legacies resulting from large, infrequent forest disturbances. *Ecosystems*, 1(6): 497–510.

Franklin, J., Drake, D.R., McConkey, K.R., Tonga, F. & Smith, L.B. 2004. The effects of Cyclone Waka on the structure of lowland tropical rain forest in Vava'u, Tonga. *Journal of Tropical Ecology*, 20: 409–420.

Fujita, T.T. 1971. Proposed characterization of tornadoes and hurricanes by area and intensity. Satellite and Mesometeorology Research Paper 91. Department of Geophysical Sciences, University of Chicago, Chicago, IL.

Gardiner, B., Blennow, K., Carnus, J-M., Fleischer, P., Ingemarson, F., Landmann, G., Lindner, M., Marzano, M., Nicoll, B., Orazio, C., Peyron, J-L., Reviron, M-P., Schelhaas, M-J., Schuck, A., Spielmann, M. & Usbeck, T. 2010. Destructive Storms in European Forests: *Past and Forthcoming Impacts*. Final report to European Commission - DG Environment.

Guthrie, R.H. 2002. The effects of logging on frequency and distribution of landslides in three watersheds on Vancouver Island, British Columbia. *Geomorphology*, 43: 273– 292.

Grishin, S.Y. 2009. Forest die-off under the impact of burning pyroclastic surge on the Shiveluch Volcano (Kamchatka, 2005). *Russian Journal of Ecology*, 40(2): 146–148.

Halpern, C.B. & Harmon, M.E. 1983. Early plant succession on the Muddy River mudflow, Mount St. Helens. *American Midland Naturalist*, 110: 97–106.

Halpern, C.B., Frenzen, P.M., Means, J.E., Franklin, J.F. 1990. Plant succession in areas of scorched and blown-down forest after the 1980 eruption of Mount St. Helens, Washington. *Journal of Vegetation Science*, 1: 181–194.

Hansen, J., Sato, M., Ruedy, R., Lacis, A., Asamoah, K., Borenstein, S., Brown, E., Cairns, B., Caliri, G., Campbell, M., Curran, B., de Castro, S., Druyan, L., Fox, M., Johnson, C., Lerner, J., McCormick, M.P., Miller, R.L., Minnis, P., Morrison, A., Pandolfo, L., Ramberran, I., Zaucker, F., Robinson, M., Russell, P., Shah, K., Stone, P., Tegen, I., Thomason, L., Wilder, J. & Wilson, H. 1996. A Pinatubo climate modeling investigation. *In*: Fiocco, G., Fua, D. & Visconti, G., eds., The Mount Pinatubo Eruption: Effects on the Atmosphere and Climate, pp. 233-272. NATO ASI Series Vol. 42, Springer-Verlag.

Hanson, P.J. & Weltzin, J.F. 2000. Drought disturbance from climate change: response of United States forests. *Science of The Total Environment*, 262(3): 205–220.

Hensel, P. & Proffitt, C.E. 2002. Hurricane Mitch: acute impacts on mangrove forest structure and an evaluation of recovery trajectories: executive summary: USGS Open File Report 03-182.

Hogg, E.H. & Bernier, P.Y. 2005. Climate change impacts on drought-prone forests in western Canada. *For. Chron*., 81: 675–682.

Hogg, E.H., Brandt, J.P. & Michaelian, M. 2008. Impacts of a regional drought on the productivity, dieback and biomass of western Canadian aspen forests. *Can. J. For. Res*., 38(6): 1373–1384.

Hooper, M.C., Arii, K. & Lechowicz, M.J. 2001. Impact of a major ice storm on an old-growth hardwood forest. *Canadian Journal of Botany*, 79: 70–75.

Imaizumi, F., Sidle, R.C. & Kamei, R. 2008. Effects of forest harvesting on the occurrence of landslides and debris flows in steep terrain of central Japan. *Earth Surface Processes and Landforms*, 33: 827–840.

International Atomic Energy Agency (IAEA). 2002. Modelling the migration and accumulation of radionuclides in forest ecosystems. Report of the Forest Working Group of the Biosphere Modelling and Assessment (BIOMASS) Programme, Theme 3. Vienna. Available at: www-pub.iaea.org/MTCD/publications/PDF/Biomass1_web.pdf

IAEA. 2006. Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience. Report of the Chernobyl Forum Expert Group 'Environment'. Vienna.

International Federation of Red Cross and Red Crescent Societies (IFRC & RCS). 2010. *World Disasters Report – Focus on urban risk.* Geneva.

International Food Safety Authorities Network (INFOSAN). 2011. Information on nuclear accidents and radioactive contamination of foods. Information Note 30 March 2011. World Health Organization and FAO.

International Hurricane Research Center (IHRC). 2011. IHRC Web site. Available at: www.ihc.fiu.edu/index.htm (Accessed 07/03/11)

International Tsunami Information Center (ITIC). 2011. ITIC Web site. Available at: http://itic.ioc-unesco.org (Accessed 07/03/11)

International Union for Conservation of Nature (IUCN). 2006. *Earthquake in Pakistan: An Assessment of Environmental Risks and Needs*. Based on IUCN Field Missions to NWFP and AJK, November 19–26 and December 4–7, 2005. Pakistan.

Irland, L.C. 2000. Ice storms and forest impacts. *Science of The Total Environment*, 262(3): 231–242.

Johnson, E.A. 1987. The relative importance of snow avalanche disturbance and thinning on canopy plant populations. *Ecology*, 68, 43–53.

Jump, A.S., Mátyás, C. & Peñuelas, J. 2009. The altitude-for-latitude disparity in the range retractions of woody species. *Trends in Ecology and Evolution*, 24: 694–701.

Kajimoto, T., Daimaru, H., Okamoto, T., Otani, T. & Onodera, H. 2004. Effects of snow avalanche disturbance on regeneration of subalpine *Abies mariesii* forest, northern Japan. *Arctic, Antarctic, and Alpine Research*, 36, 436–445.

Karnosky, D.F., Percy, K.E., Xiang, B., Callan, B., Noormets, A., Mankovska, B., Hopkin, A., Sober, J., Jones, W., Dickson R.E. & Isebrands, J.G. 2002. Interacting elevated CO_2 and tropospheric O_3 predisposes aspen (*Populus tremuloides* Michx.) to infection by rust (*Melampsora medusae f.sp. tremuloidae*). *Global Change Biology*, 8: 329–338.

Karnosky, D.F., Pregitzer, K.S., Zak, D.R., Kubiske, M.E., Hendrey, G.R., Weinstein, D., Nosal, M. & Percy, K.E. 2005. Scaling ozone responses of forest trees to the ecosystem level in a changing climate. *Plant, Cell and Environment*, 28: 965–981.

Kauffman, J.B. & Cole, T.G. 2010. Micronesian mangrove forest structure and tree responses to a severe typhoon. *Wetlands*, 30: 1077–1084.

Khan, A., Khan, M.A., Said, A., Ali, Z., Khan, H., Ahmad, N. & Garstang, R. 2010. Rapid assessment of flood impact on the environment in selected affected areas of Pakistan. Pakistan Wetlands Programme and UNDP Pakistan.

Kupfer, J.A., Myers, A.T., McLane, S.E. & Melton, G.N. 2008. Patterns of forest damage in a southern Mississippi landscape caused by Hurricane Katrina. *Ecosystems*, 11: 45–60.

Laurance, W.F. & Curran, T.J. 2008. Impacts of wind disturbance on fragmented tropical forests: A review and synthesis. *Austral Ecology*, 33: 399–408.

Lugo, A.E. 2008. Visible and invisible effects of hurricanes on forest ecosystems: an international review. *Austral Ecology*, 33, 368–398.

Magnusson, W.E., Lima, A.P. & de Lima, O. 1996. Group lightning mortality of trees in a Neotropical forest. *Journal of Tropical Ecology*, 12: 899–903.

Marske, K.A., Ivie, M.A. & Hilton, G.M. 2007. Effects of volcanic ash on the forest canopy insects of Montserrat, West Indies. *Environmental Entomology*, 36(4): 817–25.

Martin, T.J. & Ogden, J. 2006. Wind damage and response in New Zealand forests: a review. *New Zealand Journal of Ecology*, 30(3): 295–310.

Millennium Ecosystem Assessment (MEA). 2005. *Ecosystems and human well-being: Current state and trends.* Millennium Ecosystem Assessment Series Vol. 1. Island Press, Washington DC.

Ministerial Conference on the Protection of Forests in Europe (MCPFE). 2007. *State of Europe's Forests 2007: the MCPFE report on sustainable forest management in Europe.* Jointly prepared by (MCPFE) Liaison Unit Warsaw, United Nations Economic Commission for Europe (UNECE), and Food and Agriculture Organization of the United Nations (FAO). Warsaw.

Munck, I.A., Bennett, C.M., Camilli, K.S. & Nowak, R.S. 2010. Long-term impact of de-icing salts on tree health in the Lake Tahoe Basin: Environmental influences and interactions with insects and diseases. *Forest Ecology and Management*, 260(7): 1218–1229.

National Oceanic and Atmospheric Administration (NOAA). 2010. *Oil spills in mangroves: planning and response considerations*. Hoff, R. (ed). Washington, DC. Available at: response.restoration.noaa.gov/book_shelf/34_mangrove_complete.pdf

NOAA. 2011. Hurricane Research Division. Available at: www.aoml.noaa.gov/hrd/tcfaq/A1.html (Accessed 05/03/11)

NOAA/National Weather Service (NWS). 2011. Storm Prediction Centre - Monthly and Annual U.S. Tornado Summaries. Available at: www.spc.noaa.gov/climo/online/monthly/newm.html

Nykänen, M-L., Peltola, H., Quine, C., Kellomäki, S. & Broadgate, M. 1997. Factors affecting snow damage of trees with particular reference to European conditions. *Silva Fennica*, 31(2): 193–213.

Office for the Coordination of Humanitarian Affairs (OCHA). 2011. Southern Africa Flood and Cyclone Situation Update #13. Issued by the Regional Office for Southern & Eastern Africa (ROSEA). Available at: reliefweb.int/sites/reliefweb.int/files/reliefweb_pdf/node-400015.pdf

Oswalt, S.N. & Oswalt, C.M. 2008. Relationships between common forest metrics and realized impacts of Hurricane Katrina on forest resources in Mississippi. *Forest Ecology and Management*, 255: 1692–1700.

Päätalo, M-L. 1998. Factors influencing occurrence and impacts of fires in northern European forests. *Silva Fennica*, 32(2): 185–202.

Park Williams, A., Allen, C.D., Millar, C.I., Swetnam, T.W., Michaelsen, J., Still, C.J. & Leavitt, S.W. 2010. Forest responses to increasing aridity and warmth in the southwestern United States. *PNAS*, 107(50): 21289–21294.

Patel, E.R. 2007. Logging of rare rosewood and palisandre (*Dalbergia* spp.) within Marojejy National Park, Madagascar. *Madagascar Conservation & Development*, 2(1): 103–112.

Peñuelas, J., Lloret, F. & Montoya, R. 2001. Severe drought effects on Mediterranean woody flora in Spain. *Forest Science*, 47: 214–218.

Peterson, C.J. 2000. Catastrophic wind damage to North American forests and the potential impact of climate change. *Science of The Total Environment*, 262(3): 287–311.

Peterson, C.J. 2007. Consistent influence of tree diameter and species on damage in nine eastern North America tornado blowdowns. *Forest Ecology and Management*, 250: 96–108.

Pierson, T.C., Janda, R.J., Thouret, J-C., & Borrero, C.A. 1990. Perturbation and melting of snow and ice by the 13 November 1985 eruption of Nevado del Ruiz, Colombia, and consequent mobilization, flow, and deposition of lahars. *Journal of Volcanology and Geothermal Research*, 41: 17–66.

Raffa, K.F., Aukema, B.H., Bentz, B.J., Carroll, A.L., Hicke, J.A., Turner, M.G. & Romme, W.H. 2008. Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. *Bioscience*, 58: 501–517.

Resco de Dios, V., Fischer, C. & Colinas, C. 2007. Climate change effects on Mediterranean forests and preventive measures. *New Forests*, 33: 29–40.

Restrepo, C., Walker, L.R., Shiels, A.B., Bussmann, R., Claessens, L., Fisch, S., Lozano, P., Negi, G., Paolini, L., Poveda, G., Ramos-Scharrón, C., Richter, M. & Velázquez, E. 2009. Landsliding and its multiscale influence on mountainscapes. *BioScience*, 59: 685–698.

Riesen, T.K. 2002. Radiocaesium in forests: A review on most recent research. *Environmental Review*, 10: 79–90.

Risk Management Solutions (RMS). 2007. The Great Storm of 1987. Available at: www.rms.com/Publications/Great_Storm_of_1987.pdf

Salisbury, H.E. 1989. *The Great Black Dragon Fire: A Chinese Inferno*. Little, Brown and Company, Boston MA, USA.

Schelhaas, M.J., Nabuurs, G.J. & Schuck, A. 2003. Natural disturbances in the European forests in the 19th and 20th centuries. *Global Change Biology*, 9(11): 1620–1633.

Schuster, R.L. & Highland, L.M. 2001. Socioeconomic and environmental impacts of landslides in the Western Hemisphere. U.S. Geological Survey Open-File Report 01-0276.

Schuster, R.L. & Highland, L.M. 2004. Impact of landslides and innovative landslide-mitigation measures on the natural environment. International Conference on Slope Engineering, Hong Kong, China, 8-10 December 2003. Keynote address, Proceedings 29. Available at: pubs.usgs.gov/op/HongKongJuly/HongKongJuly21sm.pdf

Seidl, R., Fernandes, P.M., Fonseca, T.F., Gillet, F., Jöhnsson, A.M., Merganičová, K., Netherer, S., Arpaci, A., Bontemps, J.D., Bugmann, H., González-Olabarria, J.R., Lasch, P., Meredieu, C., Moreira, F., Schelhaas, M. & Mohren, G.M.J. 2011. Modelling natural disturbances in forest ecosystems: a review. *Ecological Modelling*, 222(4): 903–924.

Sidle, R. 2005. Influence of forest harvesting activities on debris avalanches and flows. In: Jakob, M. & Hungr, O. eds. Debris-flow hazards and related phenomena, pp. 387-409. Praxis, Springer Berlin Heidelberg.

Sivakumar, M.V.K., Motha, R.P. & Das, H.P. (eds.) 2005. *Natural disasters and extreme events in agriculture: impacts and mitigation.* Springer-Verlag Berlin Heidelberg, New York.

Srinivasa, H. & Nakagawa, Y. 2008. Environmental implications for disaster preparedness: Lessons learnt from the Indian Ocean Tsunami. *Journal of Environmental Management*, 89: 4–13.

Stanturf, J.A., Goodrick, S.L. & Outcalt, K.W. 2007. Disturbance and coastal forests: A strategic approach to forest management in hurricane impact zones. *Forest Ecology and Management*, 250: 119–135.

State Forestry Administration. 2008. *Blizzard damage on forestry in China*. Translation of report prepared by State Forestry Administration, China.

Teague, B., McClead, R. & Pascoe, S. 2009. *2009 Victorian Bushfire Royal Commission Interim Report.* Australia: Government Printer for the State of Victoria.

Tripartite Core Group (TCG). 2008. *Post-Nargis Joint Assessment*. A report prepared by the Tripartite Core Group comprised of representatives of the Government of the Union of Myanmar, the United Nations and Association of Southeast Asian Nations (ASEAN) with support of the humanitarian and development community.

Turner, M.G. 2010. Disturbance and landscape dynamics in a changing world. *Ecology*, 91(10): 2833–2849.

Turner, M.G., Dale, V.H. & Everham, III, E.H. 1997. Fires, hurricanes, and volcanoes: comparing large disturbances. *BioScience*, 47(11): 758–768.

United Nations Convention to Combat Desertification (UNCCD). 2002. *Global Alarm: Dust and sandstorms from the world's drylands.* Edited by: Youlin, Y., Squires, V. and Qi, L. Available at: www.unccd.int/publicinfo/duststorms/globalAlarm-eng.pdf

United Nations Educational, Scientific and Cultural Organization (UNESCO). 2011. World Heritage Convention Web site. Available at: whc.unesco.org/en/list/798 (Accessed 31/05/11)

United Nations Environment Programme (UNEP). 2005. After the tsunami: rapid environmental assessment report. Available at: www.unep.org/tsunami/reports/TSUNAMI_report_complete.pdf

UNEP. 2011. UNEP Year Book 2011: Emerging issues in our global environment. United Nations Environment Programme, Nairobi. Available at: www.unep.org/yearbook/2011

United States Geological Survey (USGS). 2005. The cataclysmic 1991 eruption of Mount Pinatubo, Philippines. USGS Fact Sheet 113-97. Available at: pubs.usgs.gov/fs/1997/fs113-97/ (updated 28/02/05)

USGS. 2011. Volcano Hazards Program. Available at: volcanoes.usgs.gov (Accessed 08/05/11)

Usbeck, T., Wohlgemuth, T., Dobbertin, M., Pfister, C., Bürgi, A. & Rebetez, M. 2010. Increasing storm damage to forests in Swizerland from 1858 to 2007. *Agricultural and Forest Meteorology*, 150: 47–55.

van Mantgem, P.J., Stephenson, N.L., Byrne, J.C., Daniels, L.D., Franklin, J.F., Fulé , P.Z., Harmon, M.E., Larson, A.J., Smith, J.M., Taylor, A.H. & Veblen, T.T. 2009. Widespread increase of tree mortality rates in the western United States. *Science*, 323: 521–524.

Vittoz, P., Stewart, G.H. & Duncan, R.P. 2001. Earthquake impacts in old-growth *Nothofagus* forests in New Zealand. *Journal of Vegetation Science*, 12: 417–426.

Whittaker, R.J., Bush, M.B. & Richards, K. 1989. Plant recolonization and vegetation succession on the Krakatau Islands, Indonesia. *Ecological Monographs*, 59: 59–123.

Williams, J., Albright, D., Hoffmann, A.A., Eritsov, A., Moore, P.F., Carlos Mendes De Morais, J., Leonard, M., San Miguel-Ayanz, J., Xanthopoulos, G. & Van Lierop., P. 2011. Findings and implications from a coarse-scale global assessment of recent selected mega-fires. Paper presented at the 5th International Wildland Fire Conference, Sun City, South Africa, 9–13 May 2011.

World Meteorological Organization (WMO). 2011. WMO Web site. Available at: www.wmo.int (accessed 06/03/11)

Xu, W., Wang, X., Ouyang, Z., Zhang, J., Li, Z., Xiao, Y. & Zheng, H. 2009. Conservation of giant panda habitat in South Minshan, China, after the May 2008 earthquake. *Frontiers in Ecology and the Environment*, 7(7): 353–358.

Zabka M. & Nentwig W. 2002. The Krakatau islands (Indonesia) as a model area for zoogeographical study, a Salticidae (Arachnida: Araneae) perspective. *Annals Zoologici (Warszawa)*, 52: 465–474.

Zhao, M. & Running, S.W. 2010. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science*, 329(5994): 940–943.