1 Global Warming and Forests in the Anthropocene

> The post-1950 acceleration in the Earth System indicators remains clear. Only beyond the mid-century is there clear evidence for fundamental shifts in the state and functioning of the Earth System that are beyond the range of variability of the Holocene and driven by human activities.
>
> Steffen *et al.*, 2015

> Humans are the only creature in this world who cut the trees, made paper from it and then wrote "SAVE TREES" on it.
>
> Anonymous

1.1 INTRODUCTION

There is considerable interest and concern about global warming and climate change. In response, there is also great interest in the role that tree planting and new forests might play in partial mitigation of global warming and in reducing climate change by cooling the atmosphere now and especially in the future, as carbon dioxide increases. This interest is evident in the very large number of reports and conclusions in widely diverse scientific journals, books, and the popular media. The purpose of this book is to bring together in one place a review of background information and results from sources, primarily reports in scientific journals, about global warming and the role of forests in cooling and warming the atmosphere now and in future projections.

This chapter includes background information and reviews for the Anthropocene, global warming, atmospheric cooling and warming by forests, the influence of deforestation, land-use change, and tree planting.

Cambridge University Press
978-1-108-47178-7 — Trees and Global Warming
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Excerpt
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1.2 GLOBAL WARMING IN THE ANTHROPOCENE EPOCH

Geological time is divided into epochs. The epoch from the end of Northern Hemisphere glaciers and the Ice Age has been deemed the Holocene ("recent whole") Epoch, including the past 10–12 thousand years. During this epoch, agriculture and settlements were developing. Rice culture began about eight thousand years ago. Human populations were small, and life spans were relatively short, so their impacts on the geology and ecology of the Earth were relatively small. Carbon dioxide levels were low and balanced between the atmosphere and the land/forest and ocean sinks. In the last two centuries, however, industrialization, technology, and the demands of a continually growing huge human population for space and resources have changed the relative stability of the Holocene forever. Rapidly accelerating new technology, fossil fuel combustion, air, water, and soil pollution, increasing temperatures, urbanization and mega-cities, industrial agriculture, mass extinctions, and global demand for middle-class lifestyles have caused great changes in the geology and ecology of the Earth (Zalasiewicz *et al.*, 2010; Waters *et al.*, 2016). Combined rapid changes since 1950 have been called the Great Acceleration, particularly in human wants and needs (Steffen *et al.*, 2011, 2015; Friedman, 2016). To satisfy continuing human demand for protein from domestic animals, Harari (2015) estimates that humans maintain populations of approximately 1 billion of each of sheep, pigs, and cattle, and approximately 25 billion chickens. The total of 28 billion animals is about four times the size of the human population. Sheep and cattle require extensive pasturelands. All require large quantities of food, often grain. Either through metabolism or microbial decomposition of feces, carbon dioxide and methane and other gases are released to the atmosphere. China has been using urbanization and mega-cities to relocate and house its huge population. Nineteen more mega-city/clusters are planned, with one planned to house 150 million people (The Economist, 2018). All of this places an enormous burden on natural regulation of carbon dioxide in the atmosphere, the land mass, and the oceans.

In 1974, Margulis and Lovelock proposed the Gaia Hypothesis that the Earth is capable of environmental self-regulation. This included atmospheric homeostasis by and for the atmosphere. They meant that the planet functions well by itself and can remediate any changes, both natural and human-caused. There is renewed interest in whether global warming and climate change are consistent with the Gaia Hypothesis in terms of self-regulation of the Earth. Conversely, global warming and climate change may be a response and self-regulating mechanism by the Earth.

Continuing population growth, and resulting human activities, needs, and desires, however, are affecting the geophysical and biological regulation of the Earth. Humans are now playing an increasingly central role in regulating the atmosphere and climate of the Earth. Recognizing this, Nobel Laureate Paul Crutzen proposed a new epoch, as he felt that the Holocene was no longer operational. He called it the Anthropocene Epoch (Crutzen and Stoermer, 2000). The geoscience community is divided on the validity and adoption of the new epoch. It would seem, however, that the Anthropocene is here.

1.3 CLEANER AIR AND GLOBAL WARMING

Global warming began with human utilization of fire for cooking and heating. Fuel combustion progressed rapidly with the Industrial Revolution and has accelerated to the present day. The rate began to increase with rapid industrialization, population growth, and deforestation during and after World War II. This resulted in largely unregulated emissions of sulfate and other chemical aerosols and gases to the atmosphere. During that time, pollution levels of atmospheric sulfate and other chemical aerosols and gases reflected much of the incoming shortwave solar energy (sunlight) back to space. This meant that less sunlight penetrated below the pollution layer, and the air was cooler. There was less returning near-infrared radiation to be trapped by the pollution layer at night. Night temperatures were cooler than they would have been if the pollution layer had not reflected much sunlight back to space. This also resulted in reductions in atmospheric visibility and a prevailing condition known as "global dimming."

Following several episodes of high pollutant effects on human health, in the 1970s clean air quality standards were adopted, and aerosol pollution levels began to decline significantly. Cleaner air meant "global brightening" with more incoming solar radiation and more retention of outgoing infrared radiation resulting in a warmer atmosphere. Mercado *et al.* (2009) estimated that global dimming provided more diffusive uniform distribution of light to interiors of trees as well as the tops of tree canopies, and increased photosynthesis by 25% from 1960 to 1999. It has been estimated that it has only been since 1990 that the impacts of the enhanced greenhouse effect and global warming and climate change have emerged and have been recognized (Wild *et al.*, 2007). The Law of Unintended Consequences at work.

Warming in the Arctic region is progressing faster than in other regions. The reasons for this are not completely evident, but reduction of global dimming may be a cause. The clean air acts of the 1970s resulted in reduction in airborne particulates from pollution emissions, particularly sulfate aerosols, in the Northern Hemisphere, resulting in stronger incoming solar radiation. Acosta-Navarro *et al.* (2016) used air quality data from the 1980s and simulation modeling to determine how increased solar radiation might affect Arctic warming. Simulated summer warming was attributed to increased solar radiation and increasing input of heat from the ocean and the atmosphere. Sea ice reduction resulted in heat transfer from the ocean to the atmosphere. This increased Arctic warming in the fall and winter.

1.3.1 *James Hansen's Testimony 1988*

On 23 June 1988, Dr. James E. Hansen, Director of NASA's Goddard Institute for Space Studies at Columbia University in New York, testified by invitation at a meeting of the US Senate Committee on

Energy and Natural Resources in Washington, DC. His presentation was entitled: "The Greenhouse Effect: Impacts on Current Global Temperature and Regional Heat Waves" (Hansen, 1988). The presentation was of profound importance, summarized in his three main conclusions:

- Number one, the Earth is warmer in 1988 than at any time in the history of instrumental measurements.
- Number two, the global warming is now large enough that we can ascribe with a high degree of confidence a cause and effect relationship to the greenhouse effect.
- Number three, our computer climate simulations indicate that the greenhouse effect is already large enough to begin to affect the probability of extreme events, such as summer heat waves.

Hansen confirmed that global warming and climate change were real and were here now. This introduced a controversial subject into the national conversation, where it remains controversial today. Hansen's testimony caused a sensation, and he was deemed by many in academia, government, and the general public to be mistaken and a doomsayer. Climate change denial began to hamper efforts to mitigate global warming and climate change, and this continues 30 years later. By 2016, however, 90–100% of climate scientists who publish believed that humans are the cause of recent global warming (Cook *et al.*, 2016).

Using a climate model, Hansen *et al.* (2005) proposed that greenhouse gases and aerosols had caused an imbalance in the energy of the Earth. They concluded that the Earth was absorbing more energy from the sun (0.85 ± 0.5 watts per square meter) than it was returning to space. They confirmed this by measuring heat increase in the ocean for a 10-year period. The implications of this included that, without atmospheric composition change, a global warming of approximately 0.6 °C was expected.

Since Hansen's testimony in 1988, many changes in temperature and climate have been observed and recorded. Using data from NOAA, and interviews, Borenstein and Forster (2018) have reported some of these changes. Carbon dioxide increased to over 400 parts per million (ppm) and continues to rise. The greenhouse effect increased, and as a result, the world is much warmer. Average temperatures have increased by approximately 1.6 °C in the United States. When North America and Europe are combined, the average increase is approximately 1.89 °C. The increases in temperature vary by region, with the average increase in South Central Colorado being approximately 2.3 °C. Storms and rainfall are increasing, resulting in property damage and flooding. Wildfires and droughts are increasing. Arctic ice loss is raising ocean levels and decreasing albedo (that is, reducing the ratio of reflected light to incident light), causing warming. Warming is amplifying and increasing the incidence of natural climatic events. NASA (2018) agree that naturally varying climate is being influenced by human-caused warming. They indicate climate changes that are occurring now and make predictions about future effects. These include lengthening of frost-free growing seasons, more droughts and heat waves, hurricanes becoming stronger and more intense, and both sea-level rise by 1–4 ft and the Arctic becoming ice-free by 2100. These climatic changes are caused by global warming.

Record-breaking high temperatures were recorded in 2014, 2015, and 2016 and were attributed to human activities (Mann *et al.*, 2016; 2017; Kennedy *et al.*, 2017). El Nino events increase air temperatures, and one contributed to increased temperatures in 2015 (Betts *et al.*, 2016). Also in 2015, the global carbon dioxide level increased above 400 ppm for the first time, to 400.9 ppm. Betts *et al.* (2016) predicted that the level would remain above 400 ppm. On 19 July 2018, the global average carbon dioxide concentration was 409.32 ppm. King (2017) examined temperature records from 1861–2005 and found record high temperatures in 17 years. They concluded that without global warming, only seven high temperature incidents would have occurred.

There is a direct relationship between the amount of carbon dioxide emitted and global warming. Allowing for net heat flux and carbon capture by the ocean, and carbon dioxide uptake by forests, atmospheric warming is caused by increased radiative forcing from remaining anthropogenic carbon dioxide. Today's global warming results from the beginning of significant anthropogenic carbon dioxide emissions in the 1800s (Goodwin *et al.*, 2015). Continually increasing levels of carbon dioxide make it highly unlikely that the atmospheric temperature increase can be kept at less than 2 °C or at 1.5 °C as proposed by the Paris Climate Agreement (Huntingford and Mercado, 2016). A forecast of future atmospheric temperature increases to 2100 ranged from 2.0 °C to 4.9 °C with a median of 3.2 °C (Rafferty *et al.*, 2017). Anthropogenic carbon dioxide was previously considered to remain in the atmosphere for no longer than 100 years. It is evident now that carbon dioxide will remain in the atmosphere for 1000 years or longer (Archer *et al.*, 2009; Soloman *et al.*, 2009). As Mason Inman (2008) declared, carbon is forever. This complicates efforts to keep atmospheric temperature at or below 1.5 °C.

Additional coverage of the greenhouse effect, global warming, and the carbon cycle can be found in Chapter 2, "The Gases That Cause the Greenhouse Effect", and in Chapter 3: Carbon and Photochemical Oxidant Cycles.

1.4 Trees and Forests: Cooling and Warming the Atmosphere

Hansen (1988) was able to use data obtained by Keeling from his continuous carbon dioxide monitoring station at Mauna Loa, Hawaii, beginning in 1960. Over time, Keeling documented that carbon dioxide concentrations in the Northern Hemisphere decreased during the summer months and increased during the winter months. He attributed the summer decrease in atmospheric carbon dioxide to uptake of carbon dioxide by vegetation during photosynthesis (Keeling *et al.*, 1996). Graven *et al.* (2013) examined data from 1960 onward and verified enhanced seasonal changes in carbon dioxide concentrations. As carbon dioxide levels increased, the seasonal changes in carbon dioxide continued to grow, implying that summer vegetation growth must be increasing to enable the seasonal changes. This led to a conclusion that increasingly elevating anthropogenic carbon dioxide might act as a global fertilizing agent, increasing terrestrial vegetation, primarily forests, and resulting in partial mitigation of warming caused by anthropogenic carbon dioxide.

1.4.1 Cooling and Warming

Way *et al.* (2015) have concluded that we have considerable knowledge about the effects of elevated carbon dioxide on most plant physiological responses at the leaf level, but transferring these results to whole trees is an area of great uncertainty. Most of what we know beyond the leaf level comes from experiments with small or young trees under varying ambient conditions and very high carbon dioxide levels. The development of sophisticated and specific satellite imagery and many climate and statistical models were required to proceed further to determine the possible role of trees and forests in atmospheric cooling and warming. Mao *et al.* (2016) used satellite imagery to detect what they termed clear evidence of significant Earth greening for the past 30 years.

Sun *et al.* (2017) used data from the new sophisticated OCO-2 satellite to detect real-time induced chlorophyll fluorescence associated with gross primary production (GPP) and detect increased global vegetation attributed directly to photosynthesis. Using models and satellite data, Zeng *et al.* (2017) concluded that leaf area index had increased for global vegetation for the last 30 years. This index estimates the leaf area on trees (canopies in this case) in relation to land surface area, and thus estimates how much tree cover there is. This indicated to them that the slow increase in Earth greening had reduced the expected global land surface temperature by 0.09 °C since 1982. Seventy percent of the effect was attributed to evapotranspiration. Satellite data do not always distinguish between forms of vegetation, most of which is assumed to be likely to be trees.

Extensive modeling was done to estimate the effects of global land-use change on forests and cooling and warming. Gibbard *et al.*

(2005) modeled whether global transformation of grassland and cropland to trees would result in warming from lower tree albedo or cooling from increased transpiration. Their conclusion was that total replacement with trees would result in a global average temperature increase of 1.3 °C. Replacement of trees with grasslands would result in an average 0.4 °C cooling. Bala *et al.* (2007) modeled the effects of large-scale deforestation and concluded that increased albedo would result in a net cooling effect. Unger (2014) concluded that wide-scale forest reduction would result in atmospheric cooling. Trees release biogenic volatile organic compounds (BVOCs) which participate in prolonging the life of methane and other greenhouse gases. Reduction of BVOCs would result in atmospheric cooling.

In an extensive and widely cited review, Bonan (2008) examined results from climate model simulations and flux tower measurements in relation to cooling and warming by tropical, temperate, and boreal forests at different latitudes. Low albedo in tropical forests is offset by evapotranspiration, resulting in air cooling and promotion of precipitation. Air cooling may be global in effect. Depending on conditions, tropical forests are either carbon-neutral or carbon sinks. Boreal forests have low albedo which causes warming, weak cooling, and moderate carbon sequestration. Temperate forest trees have lower albedo than grasslands or croplands. Eastern US temperate forests may warm temperatures in the summer, which can be offset by increased evapotranspiration. Carbon sequestration is strong, especially in mature forests. Li *et al.* (2015) used satellite observations to determine atmospheric cooling and warming in forests of the world. Similar to Bonan (2008), they estimated that tropical forests cool in all seasons, whereas temperate forests provide moderate cooling in summer and some warming in winter. Boreal forests cool in summer with overall annual net warming. Spracklen *et al.* (2008), however, consider that the low albedo of boreal forests can result in an overall cooling effect. BVOCs from trees (primarily conifers) cause cloud condensation nuclei to form, resulting in clouds and cooling.

1.4.2 Transpiration and Cooling

Atmospheric temperature and climate are influenced by intensity of reflectance by albedo and by the terrestrial water flux. Evapotranspiration by forests is essential to the global water cycle. Heat, necessary for converting liquid water to a gas, provides latent heat flux. Forests provide abundant latent heat flux (Ban-Weiss *et al.*, 2011). Jasechko *et al.* (2013) determined that 80–90% of evapotranspiration is transpiration from vegetation. Anything that affects transpiration will affect atmospheric cooling. Transpiration will be used in place of evapotranspiration here. Leggett and Ball (2018) observed long-term temperature trends and concluded that most were lower than those predicted by most simulation models for the effects of elevated carbon dioxide. They concluded that there was a "temperature gap" and attributed it to the influence of transpiration.

Much attention has focused on estimating the possible effects of elevated future carbon dioxide on growth, carbon sequestration, and atmosphere temperature. Early experiments established that elevated carbon dioxide closes stomata or decreases stomatal aperture and conductance, which decreases transpiration (Long, 2012). Cao *et al.* (2010) modeled the influence of doubled carbon dioxide concentration on stomatal conductance and canopy transpiration. Their results indicated that canopy transpiration was decreased by 8%, resulting in increased land surface temperature. Elevated carbon dioxide was determined to depress transpiration more than elevated temperature in the future (Kirschbaum and McMillan, 2018).

Field experiments with elevated carbon dioxide resulted in large photosynthesis-caused increases in growth of young trees. It was assumed that this growth acceleration would continue (Long, 2012). Many of the increases in tree growth were not sustained, owing to acclimation and to limitations of soil nutrients, particularly nitrogen and phosphorus.

Fernandez-Martinez *et al.* (2015) consider that availability of soil nutrients is the key to regulating global forest carbon balance.