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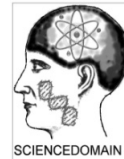
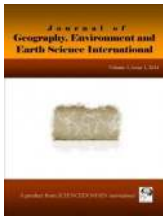


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The Impact of Climate Change on Select Ecosystems

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Authors' contributions

This work was carried out in collaboration between both authors. Authors MS and RS designed the study, wrote the first draft of the manuscript and managed the literature searches. Authors RS and MS revised the final manuscript. Both authors read and approved the final manuscript.

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ABSTRACT

Terrestrial and marine environments are experiencing pronounced changes. As species and their ecosystems undergo rising temperatures, varying precipitation patterns and alterations in their chemistry and phenology, there is a great deal of added stress on many organisms. Many species attempting to adapt to a rapidly changing climate are forced to migrate or to become extinct. Forest communities are changing in composition as well as migrating northward. Often, roads, cities, and other forms of development physically impede migration. Some species are not able to migrate at the pace with which their ecosystems are warming. In some forest communities, southern boundaries are migrating northward faster than northern boundaries are migrating northward which decreases the overall size of the forest and the amount of habitat available for the species therein. Some insects, like the pine beetle, thrive in warmer conditions providing significant challenges for their hosts. The oceans are warming, global circulation patterns are weakening, overturning is thwarted as there is greater stratification, and there is increased acidification. Coral reefs and other ecosystems which provide food and shelter for a whole host of other species are bleaching worldwide. The amount of carbon humans add to the atmosphere each year globally continues to climb. Currently, we add approximately 35 gigatons of carbon dioxide (CO₂) equivalent to the

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atmosphere annually, and we have moved from approximately 280 parts per million (ppm) of CO₂ prior to the Industrial Revolution to 398 ppm in 2014, which was the hottest year on record. The best atmospheric scientists agree that we should keep temperatures below the tipping point of 2° Celsius (C) in order to avert an ecosystems disaster. The purpose of this paper is to present some of the negative scenarios that have been proposed since researchers first realized that warming was inevitable by comparing early forecasts with the latest impacts.

Keywords: Climate change; global warming; ecosystem; IPCC; deforestation; acidification.

1. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC), established in 1988 and comprised of hundreds of eminent scientists from numerous countries has concluded that the warmest years in the history of record keeping have taken place since 1980, stating that the "balance of evidence suggests that there is a discernible human influence on global climate" [1]. Prior to the IPCC's findings, there were intense debates as to whether global warming was actually taking place. Early global climate models from the 1960s and 1970s had predicted relatively large increases in average temperatures. When these rising temperatures did not occur, the models were criticized and many believed that global warming was another doomsday scenario of environmentalists determined to slow industrial development and economic growth.

However, one problem with early climate models was the underestimation of the effect of aerosols in the atmosphere. These high altitude pollutants tend to reflect solar radiation while promoting the condensation of water vapor into clouds, which also reflect solar radiation yielding a cooling effect witnessed primarily in the Northern Hemisphere. Once this cooling effect was entered into newer model calculations, the predictions fell more in line with reality [2]. Also, with the passage of numerous clean air acts, the volume of aerosols was reduced and global temperatures started to rise.

As a result, locations from the equator toward the poles commenced to undergo higher temperature profiles leading to melting glaciers, rising sea levels, and an increase in extreme events such as floods, heat waves, and droughts [3]. Based on a global warming scenario consisting of a 1°C to 3°C increase by the year 2100, the IPCC concluded that these events "will put the most stress on those systems that are already affected by pollution, increasing resource demands, and non-sustainable management

practices" [4]. While the potential impacts are difficult to quantify because of a lack of knowledge concerning the complete connections between climate change and ecosystems, this review is an examination of select scenarios for the future.

2. WARMER WATERS

Among the most publicized impacts of global warming are rising sea levels. Although estimates are highly variable, it is reported that during the 20th century sea levels rose by 5 to 10 inches as result of global warming [5]. Writing in American Demographics, Edmondson cited the IPCC's conservative 1995 report which states that "global warming is most likely to contribute to a 6-inch increase in sea levels by 2050 and an increase of about 14 inches by 2100" [6]. The warming causes the thermal expansion of ocean waters which contributes to a rise in sea level. In the latest assessment, the IPCC reports that from 1901 to 2010, global mean sea level rose by 0.19 meters and that global sea level will continue to rise during the 21st century [7].

The geographic distribution of sea level change derived through modelling generally takes into account variations in heat uptake and varying amounts of thermal expansion, changes in wind stress at the sea surface, ocean circulation, and subduction. The model results are dissimilar at the local level and the degree of confidence in making predictions from them is low. However, at the regional and basin scale, there is a greater degree of similarity in the outcomes of the simulations. Certain regions show a rise in sea level that is significantly higher than the global average, and in several regions the rise is more than twice the global average. Nicholls et al. [8] suggest that 22% of all coastal wetlands could be lost as a result of rising sea levels by the year 2080, and that the Caribbean Islands as well as those of the Pacific and Indian Oceans will experience the greatest relative increase in frequent flood events.

2.1 Aquatic Ecosystems

As the world's oceans continue to warm, the higher specific heat of water causes them to warm at a slower rate than the atmosphere. The increase in the average global temperature over the past century has been less than it would have been had the oceans not been absorbing approximately 93% of the additional heat by warming to depths of as much as 3000 meters [9]. However, the more intense heating of the surface waters enhances the stratification of thermal layers. This increased stratification inhibits the natural overturning that occurs in the ocean. Therefore, nutrient-rich waters from the deep do not reach the surface in the quantities they have historically. Increasing temperatures and accompanying amplified stratification have been shown to cause a decrease in dissolved oxygen levels, thus increasing the size of the oxygen minimum zones (OMZs). The OMZs favor small anaerobic bacteria and other microbes while reducing the habitable extent of larger, oxygen-dependent marine organisms which either move to suitable geographic zones, if they are able, or they suffocate [10].

2.1.1 Acidification

Not only have the oceans been masking the effects of global warming, they have been soaking up approximately 26% of anthropogenic CO₂. The excess CO₂ lowers the pH and carbonate ion concentrations and is referred to as ocean acidification. Human produced CO₂ has lowered the global ocean pH by 0.1 units since the beginning of the Industrial Revolution in the United States. The increased warming and acidification of the world's oceans are affecting marine ecosystems at various speeds and scales. Increasing temperatures result in a shift in a species' abundance, geographic range, migration routes, and its phenology. Those calcifying organisms producing shells, exoskeletons, and eventually reefs from calcium carbonate (CaCO₃) are most vulnerable to increased acidification as it causes the mineral to dissolve [11].

Calcifying species, including corals, clams, sea urchins, muscles, barnacles, and some planktons, depend on precise pH levels and chemical conditions to build their shells and other structures. These species are absolutely essential for marine ecosystems as they provide shelter in nurseries for juvenile fish, food for

predators, and natural fortresses against storms. However, a global inventory of Earth's coral reefs estimates that already nearly 60% are at risk due to the actions of humans [12], and 90% of all living reefs have been damaged to some extent by coral bleaching [13]. During the next 30-50 years, coral bleaching likely will impact the reefs of the Caribbean to the greatest extent [14].

A new study published in the journal *Environmental Science and Technology* analyzed the impacts of increasing levels of ocean acidity on communities' reproduction, growth, and survival [15]. The study used the IPCC Fifth Assessment Report to illustrate a range of possible scenarios pertaining to varying levels of CO₂ emissions. The IPCC derived various emission scenarios based on societal choices, population growth, technologies, and energy sources using CO₂ equivalent metrics to make predictions about future warming. The researchers chose the best and worst case scenarios of emissions, or Representative Concentration Pathways (RCPs) RCP 4.5 and RCP 8.5, respectively, to project the potential impacts on marine ecosystems by 2100.

In the worst case scenario (high emissions of CO₂) between 21-32% of calcifying species would be significantly impacted. In the low emission scenario, between 7-12% of the species would be affected. The average ocean acidity levels for the low emission scenario would decrease from a pH of 8.1 to 7.95, while in the high emission scenario, wherein economies rely heavily of fossil fuel-based energy, the average ocean acidity would decline to a pH of 7.80 [15]. While there remains a great deal of uncertainty regarding how different organisms will respond to a certain level of change, what could be a minor impact to some species could move another species closer to extinction.

2.1.2 Coastal storms

The rise in global temperatures is also projected to increase the number and intensity of tropical storms along the coasts. The result might be severe outbreaks of violent weather which could potentially damage coastal forests through heavy winds and flooding, possibly resetting ecosystems to early successional phases [16]. Poiani and Johnson note that such "potential changes in wetland hydrology and vegetation could result in a dramatic decline in the quality of habitat for breeding birds" [17].

Mangrove forests and salt marshes are integral components of coastal ecosystems providing feeding grounds and protective vegetative cover for numerous species of juvenile fish. However, many of these habitats are being degraded by development and forms of exploitation and will be further stressed by rising sea levels. According to the IPCC, 62% of the mangrove forests in Puerto Rico have been eradicated as a result of anthropogenic activity [18]. Due to the inability to migrate rapidly enough, Jamaica's Port Royal mangrove forest could be totally decimated by rising sea levels. Consequently, the loss of mangrove forests and salt marshes could degrade entire coastal ecosystems and destroy the habitat of numerous species of local wildlife, which is the primary cause of species extinction [19].

3. WARMER LANDS

As the continents continue to warm, isotherms will be drawn closer to the poles. Knox and Schearing conclude that climatic change could cause regional wind patterns to shift, which would be accompanied by an increase in wind speed intensity [20]. Such shifts could impact existing rain shadow effects in some regions causing more precipitation on the windward side of mountain ranges while creating even drier conditions on the leeward sides [21]. Fire patterns are likely to be altered as well which could affect a variety of plant species, even those that are fire resistant or require the presence of fire to regenerate. A study by Flannigan and Van Wagner based on a doubling of CO₂ levels reveals that wildfires in Canada would undergo a 46% increase in seasonal severity [22].

3.1 Terrestrial Ecosystems

There are unique species such as the bristlecone pine (*Pinus longaeva*) and the giant sequoia (*Sequoiadendron giganteum*) which have maintained their present locations for thousands of years despite substantial climatic change. However, for many species of vegetation, temperature differences of a few degrees or a slight variation in rainfall pattern may determine whether a particular species survives or becomes extinct. Unlike earlier climatic events, such as that following the last Ice Age which slowly took place over long periods of time, these changes are expected to occur suddenly [23]. Because climate and vegetation are so strongly associated, it is assumed that such rapid changes in climate will affect plant distributions

and result in altering the makeup of natural communities [24]. History has shown that most species respond individually to climatic change and not as communities. Those individuals that have the ability to migrate will likely do so, resulting in a number of new associations. In addition to differences in migration rates, community types will be altered and new associations will be created due to changes in disturbance regimes and competition [25].

Many species attempting to adapt to this rapidly changing climate will be forced to migrate at rates of speed beyond their abilities, which may be the greatest of all potential threats to biodiversity. Evidence from the fossil pollen record reveals the migration rates of various species since the end of the last glacial period. According to a benchmark study by the Environmental Protection Agency (EPA), beech and maples migrate at a rate of 10 to 20 km per century, hemlock migrate at 20 to 25 km per century, and pine and oak species migrate at 30 to 40 km per century [26]. However, some researchers have suggested that within the next century plant species may be forced to shift as much as 500 km, which is well beyond the migration rates of many species [27]. Both plant and animal communities at high elevations and in high latitudes may have no place to migrate and could be lost completely. Walker et al. [28] report alpine ecosystems are "thought to be particularly sensitive to climate change".

Boundaries between forest and tundra ecosystems as well as tree lines are expected to advance in altitude and latitude in response to climate warming. Danby and Hik examined recent tree lines at six sites in the Canadian Yukon and found that tree line elevation increased significantly during the early to mid-20th century [29]. Kaplan and New reveal that a 2°C increase in global temperatures would raise the mean annual temperature over the Arctic between 3.2°C and 6.6°C causing the tundra ecosystem to move northward reducing dwarf-shrub tundra habitat by 60% [30].

Most European regions can anticipate being negatively affected by climate change, which will pose challenges to many economic sectors. Global warming is likely to amplify regional disparities in natural resources with the vast majority of ecosystems having difficulty adapting to climate change. Rebetez and Dobbstein report that Scots pine stands in the inner-alpine valleys of the Alps are dying off, and nearly 50% of the

Scots pine population in Switzerland has already perished since 1995 due to the fact that Switzerland's temperature has increased at more than twice the global average with most of the warming taking place during the last 20 years [31]. An analysis of the response of alpine plant species distribution to various climatic and land-use scenarios found that alpine plant species with restricted habitat availability above the tree line will experience severe fragmentation and habitat loss [32]. The future threat to the forests of Europe due to climate change is predicted to be highest in Scandinavia and Eastern Europe [33].

Interestingly, the Northern forests that cover much of North America, Europe, and Asia, should be getting greener. Over the past century temperatures have gone up and the length of the growing season has increased, nearly doubling in sections of Alaska. With CO₂ on the rise, plants should be thriving. However, Goetz et al. tracked changes between 1982 and 2003 and found the forest was getting browner instead of greener as expected [34]. Angert et al. [35] tracked the health of forests along the interior of Alaska from 1982 to 2002 and noticed that after 1994, the CO₂ uptake declined during the growing season, hinting that forest growth had slowed during the past decade.

3.1.1 Anthropogenic deforestation

Numerous studies have verified that anthropogenic deforestation has an influence on local and regional climate and could very well play a role in global warming. Palm et al. [36] suggest that 25% of the net annual CO₂ emissions are the result of clearing tropical forests. Gbetnkou reports on deforestation in Cameroon and the associated negative impacts including drought, desertification, and the disappearance of plant and animal species [37]. Fearnside states that the rate of deforestation in Amazonian has rapidly increased since 1991 with 70% of the clearing due to cattle ranching, which has led to a decline in biodiversity, weakening of the hydrologic cycle, and enhanced global warming [38].

Seasonally dry and tropical regions will experience decreased crop productivity with local temperature increases of just 1°C to 2°C while increases in temperature and associated decreases in soil water are projected to lead to a gradual transition from tropical forest to savanna in eastern Amazonia by the middle of the 21st

century. Notaro and Vavrus conclude that additional global warming is expected due to the disruption of the hydrologic cycle through reduced evapotranspiration, which will result in drying and reduced forest cover over Amazonia, South Africa, and Australia [39].

3.1.2 Insect deforestation

Tiny winged beetles, approximately one-half inch long, have been removing unhealthy trees in North American forests for a long time. They have been key contributors to the health of conifer ecosystems as they prevent groves from becoming overcrowded. But in recent decades, they have been responsible for what is probably the largest impact on forest from insects on record. The current infestation is approximately 10 times the size of past events. The prominence of protracted droughts and shorter winters has allowed the bark beetles to kill billions of trees. Of the 850 million acres of forests in the United States, bark beetles have decimated some 46 million acres. The bark beetles are making their way through American forests from Mexico up the ridge of the Rockies and north to the Yukon, sometimes bringing down as many as 100,000 trees a day [40].

The trees themselves are not the only species affected by the beetle outbreak. The white bark pine trees produce an important food source for grizzly bears, Clark's nutcrackers, red squirrels, and other animals in the Yellowstone area who have now run out of pine cones. In America's west, real estate agents have watched home prices decline precipitously from the contamination of their view. Hikers, campers, and skiers have witnessed the demise of their forested recreation areas. The beetles are expected to move into higher elevations and eat into larger tracts of American forests as temperatures continue to climb and the beetle continues to proliferate.

There have been more than 50 bills introduced in the U.S. Congress since 2001 to increase the amount of timber that is cut, in part to address the bark beetle problem. The legislators have worked with the U.S. Forest Service, which is responsible for 80% of the country's woodlands, to remove numerous trees to reduce competition. The few trees that remain are presumably better able to resist the beetles. However, some foresters believe the actions are misguided and counterproductive. The massive cutting of trees often removes more trees than the beetles [40].

From 2000 to 2012, bark beetles destroyed enough trees to cover the entire state of Colorado. Normally, a healthy tree can defend itself against invading beetles by deploying chemicals and flushing them out with a sticky resin. But heat and drought thwart a tree's ability to fight since the lack of water means less resin. In certain areas of the Rocky Mountain West, the mid-2000s was the hottest and driest period in 800 years. Insects serve as the canary in the coal mine for their larger environment [41].

Typically, beetle invasions are kept in check when they either run out of trees or when long, cold winters freeze the larvae. Some larvae normally survive as they produce a type of natural antifreeze. However, the beetles thrive in warm weather. In 2008, a group of biologists at the University of Colorado documented pine beetles flying and boring into trees in June, a full month earlier than previous records indicate. Amid warmer springs, the beetle's season of flight had doubled. This result in the beetles maturing and laying eggs, followed by another generation of their offspring maturing and laying eggs within a single summer [41].

As the mountain pine beetles run out of lodge pole pines to eat in the United States, in 2011 they made their first leap into a brand new species of tree, the jack pine, in Alberta. The jack pine has not evolved a defense and they do not fight back. The capacity of the beetles to invade a new species means the insects could begin their march eastward across Canada's boreal forest, then go south into the white, red, and jack pines of Minnesota and the Great Lakes area, and finally move south to the woods of the East Coast. During the past year, the spruce beetle decimated five times the amount of acreage in Colorado as it did in 2009. And in the last decade, scientists observed that for the first time on record the southern pine beetle was seen in New Jersey and subsequently on Long Island [42].

4. CONCLUSION

The overwhelming evidence for global warming is unequivocal with nightmare scenarios that include melting glaciers, sea ice, and permafrost, as well as rising sea levels, higher storm surges, an increase in the acidity of the world's oceans, and greater frequencies of severe weather accompanied by more floods, droughts, and wild fires. In the most recent Summary for Policymakers, the IPCC warns the "global

temperature change for the end of the 21st century is likely to exceed 1.5°C relative to 1850 to 1900" [43]. This group of scientists as well as many others in the field agrees that global warming should not exceed 2°C above pre-industrial temperatures. Global average temperatures are currently 0.8°C above pre-industrial levels. However, the CO₂ that enters the atmosphere today has a residence time of approximately a century and will continue to heat the planet. Additionally, the amount of heat absorbed by the world's oceans will eventually be released back into the atmosphere compounding the warming.

The next United Nations Climate Summit will be held in Paris beginning on September 23rd, 2015. We recommend that world leaders adopt binding carbon cutting strategies to avoid exceeding the tipping point of 2°C. Passing the tipping point means that positive feedback loops, such as melting Arctic sea ice and melting permafrost that releases methane, could throw the climate system into unpredictable, runaway cycles. The quota for the amount of carbon that can be emitted between now and 2100 in order to keep the temperatures below the tipping point will be met in just 30 years if we continue to emit at current rates. Further, it is estimated that two-thirds of known fossil fuels reserves need to be kept in the ground to avoid passing the tipping point. Both the costs of carbon pollution and the incentives to produce clean energy-based economies of the future need to increase at a rate and of a magnitude similar to that which is at stake with the problems of climate change and its impacts on Earth ecosystems and inhabitants.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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