Global Change: An Overview

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Human population growth and consumption, energy use, land use changes, and pollution are driving forces of global change. How do these factors impact ecological systems and human societies?

We live in a world where humans are having profound impacts on the global environment. Climate is warming, the populations of many species are in decline, pollution is affecting ecosystems and human health, and human societies now face new risks in terms of sea level changes, disease, food security, and climate extremes.

Scientists who study global environmental change are interested in learning how drivers of environmental change (including human population growth and consumption, energy use, land use changes, and pollution) impact biological systems across many scales — from the level of the individual organism, to populations, communities, and ecosystems (Vitousek 1994). Global environmental change science is therefore a highly multidisciplinary effort, involving physical scientists who study climate, the oceans, the atmosphere, and geology, as well as biologists investigating physiology, evolution, and ecology.

Drivers of Global Change

Human Population and Consumption

Almost 7 billion people now live on Earth. Rapid growth of the human population, especially over the last 300 years, is one of the most remarkable trends in population change ever observed. Demographers project that world population will rise to 9 billion by 2050 and level off somewhere between 9-12 billion people by the end of the century. In many modern societies, more people require more resources, such as crops, seafood, forest products, energy, and minerals and increasingly larger economies to support economic development and rising standards of living. Population growth and the increased demand for natural resources is therefore a major factor driving global environmental change (Figure 1).

Figure 1: Rising human populations and consumption put pressure on natural resources such as marine species.

The population story is more complex, however, because there is not a simple relationship between the number of people and the amount of resources consumed. Affluence, or the wealth per person, and the social norms of consumption are also important. For example, the populations of China and India are roughly 1.32 and 1.14 billion people, respectively — about four times that of the US. However, the energy consumption per person in the US is six times larger than that of a person in China, and 15 times that of a person in India. Because the demand for resources like energy is often greater in wealthy, developed nations like the US, this means that countries with smaller populations can actually have a greater overall environmental impact. Over much of the past century, the US was the largest greenhouse gas emitter because of high levels of affluence and energy consumption. In 2007, China overtook the US in terms of overall CO_2 emissions as a result of economic development, increasing personal wealth, and the demand for consumer goods, including automobiles.

Energy Use/Climate Change

Worldwide, fossil fuels (oil, coal, and natural gas) dominate our energy consumption, accounting for 85% of all energy used. As mentioned previously, the rapid rise of fossil fuels is a relatively recent phenomenon, developing in the nineteenth century with the discovery of oil and the industrialization of economies, and expanding rapidly in the twentieth century with increased economic development and rising populations and affluence. From 1860–1991, energy use per person rose more than 93 fold compared to a world population increase of four fold, indicating that rising affluence and consumption are driving energy demand (Cohen 1995).

Burning fossil fuels releases about 8.5 billion tons of carbon (as CO_2) into the atmosphere each year, causing its concentration to increase and Earth's greenhouse warming to strengthen, which leads to rising global air temperatures. Since 1880, average global air temperature has risen approximately 0.9°C. The top five CO_2-emitting countries/regions are China, US, EU, Russia, and India, which together account for two thirds of global emissions.

Global change scientists use climate models to determine how added greenhouse gases affect changes in air temperature and precipitation. If fossil fuel burning continues at current rates, global temperatures may rise by as much as 4°C by the year 2100 (IPCC 2007). Precipitation changes are expected to lead to increased rainfall in mid-to-high latitude regions, but increased droughts are projected for subtropical regions (IPCC 2007).

Land Use Changes

Landscapes are changing worldwide, as natural land covers like forests, grasslands, and deserts are being converted to human-dominated ecosystems, including cities, agriculture, and forestry (Figure 2). Between 2000-2010, approximately 13 million hectares of land (an area the size of Greece) were converted each year to other land cover types (FAO 2010). Developed regions like the US and Europe experienced significant losses of forest and grassland cover over the past few centuries during phases of economic growth and expansion. More recently, developing nations have experienced similar losses over the past 60 years, with significant forest losses in biologically diverse regions like Southeast Asia, South America, and Western Africa.

Figure 2: An example of tropical deforestation in the Amazon Basin of South America

This satellite image shows that logging happens most commonly along roads where tree harvesters gain easy access to the forests.

Land use changes affect the biosphere in several ways. They often reduce native habitat, making it increasingly difficult for species to survive. Some land use changes, such as deforestation and agriculture, remove native vegetation and diminish carbon uptake by photosynthesis as well as hasten soil decomposition, leading to additional greenhouse gas release. Almost 20% of the global CO_2 released to the atmosphere (1.5–2 billion tons of carbon) is thought to come from deforestation.

Pollution

One of the byproducts of economic development has been the production of pollution — products and waste materials that are harmful to human and ecological health. The rise of pollution corresponds to the increased use of petroleum in the twentieth century, as new synthetic products such as plastics, pesticides, solvents, and other chemicals, were developed and became central to our lives. Many air pollutants, including nitrogen and sulfur oxides, fine particulates, lead, carbon monoxide, and ground-level ozone come from coal and oil consumption by power plants and automobiles. Heavy metals, such as mercury, lead, cadmium, and arsenic, are produced from mining, the burning of fossil fuels, and the manufacture of certain products like metals, paints, and batteries.

Aquatic ecosystems such as rivers, lakes, and coastal oceans have traditionally been used for pollution disposal from industry and sewage treatment plants, but they have also been subject to unintentional runoff from upland watersheds, such as nitrogen and phosphorus loss from agricultural soils and home septic systems as well as plastics washed into rivers and oceans from storm sewer systems. We often don’t think of nutrients like nitrogen and phosphorus as pollutants. However, humans now add more nitrogen to the biosphere through fertilizers than is added naturally each year by all of the nitrogen-fixing bacteria on the planet (Vitousek 1994). The Pacific and Atlantic oceans now have garbage patches full of plastic that are possibly as large as the continental US. These are strong indicators of global change — humanity now dominates the global movement of nitrogen and other materials on Earth.

Organismal/Population Responses

Population Declines/Extinction

Human consumption of animals is impacting species worldwide. Over the past 2000 years, the spread of human societies throughout islands in the Pacific Ocean led to the overhunting of many bird species. As many as 2000 species may have gone extinct, representing 20% of all known bird species, and an extinction rate 100–1000 times greater than natural rate of species loss over geological history (Pimm *et al.* 1995, Steadman 1995). As a result of industrialized fishing, the populations of many seafood species, including marlins, tunas, swordfish, codfish, sailfish, and sharks have declined 80–90%, pushed to the brink of extinction over the past half century (Baum *et al.* 2004, Myers & Worm 2003). The rise of the “bushmeat trade” in tropical forests is leading to a decline in threatened and endangered primate species where hunters gain easy access to forests by logging roads.

Climate change is another threat affecting populations. Corals are tropical marine animals related to jellyfish that harbor unicellular photosynthetic algal symbionts, which help the corals acquire energy. The combination of high solar radiation and rising temperatures is causing corals to "bleach," whereby they expel their algae. Some corals never recover from this kind of disturbance. Bleaching events are increasing in frequency in many important coral systems in the world (Hoegh-Guldberg 1999). Corals and many other marine organisms build calcium carbonate ($CaCO_3$) shells or external skeletons from seawater. Increased CO_2 in the atmosphere is dissolving into oceans, making seawater more acidic, and causing the $CaCO_3$ to dissolve. The combined effects of bleaching and ocean acidification have led many marine scientists to predict the significant decline of coral reefs worldwide (Hoegh-Guldberg *et al.* 2007). The Great Barrier Reef in Australia — the largest biological structure on earth — may be largely dead by 2050 (Figure 3).

Figure 3: Satellite image of the Great Barrier Reef, a 2600-km long constellation of reefs and islands off the northeast coastline of Australia.

Land use changes are diminishing the habitat of species worldwide. In the United States, urbanization, agriculture, tourism, ranching, and roads are leading causes of species endangerment (Czech *et al.* 2000). The greater prairie chicken in the American Midwest is a classic example. This species lives in native tallgrass prairie ecosystems, which were eliminated as settlers converted them to agricultural fields and cities from 1850-1870. In Illinois, for example, tallgrass prairies declined in abundance from 8.5 million hectares to 985 hectares, supporting only two populations of 46 birds by the 1990s (Westemeier *et al.* 1998). In heavily deforested tropical regions like Singapore in Southeast Asia, around 40% of native butterfly, bird, fish, and mammal species have gone extinct as a result of deforestation (Brook *et al.* 2003).

Pollution has caused diverse impacts on species populations. Some chemical pollutants, such as the pesticide DDT, have been discovered to disrupt animal hormone systems, causing reproductive failure in many bird, fish, and reptile species. Nitrogen and phosphorus runoff from agricultural fields travels to lakes and down rivers to coastal oceans, where nutrient-poor waters become fertilized with excess nutrients. This results in a population explosion of phytoplankton, which, when they die, creates an abundant food source for bacteria. As bacteria consume the decaying algae, they also use up the oxygen supply in the water, creating anoxic (no oxygen) or hypoxic (low oxygen) conditions. We call this ecosystem response to nutrient pollution "eutrophication." Animal species such as fish, crabs, and oysters, which require abundant oxygen to survive, die off under these conditions. Indeed, the mouths of most of the world's major river systems are now classified as "dead zones" (Diaz and Rosenberg 2008).

Phenology Changes and Range Shifts

Organisms can respond to environmental change by moving to new locations that are physiological suitable. This is a concern with respect to climate warming, as suitable ranges for species are now moving northwards. There is evidence that tree species, such as spruce, have been shifting northwards in latitude and upwards in altitude in response to global warming. Warming is also changing the seasons, with the earlier arrival of spring causing some bird and butterfly species to migrate northwards earlier in the year, as well as some plant species to bloom earlier (Walther *et al.* 2002)

Adaptation/Evolution

Human alterations to the environment are causing some species to become evolutionarily adapted to new conditions (Visser 2008). Because people generally harvest large plants and animals that often produce the most offspring, selection favors early reproductive maturity and organisms with smaller body sizes (Darimont *et al.* 2009). This could lead to lower reproduction, species fitness, and cause populations to decline faster than expected. Other long-term studies of bird populations offer insights into how climate change affects fitness. As temperature warms and spring comes earlier in the year, insect populations (a food source for birds) peak sooner, creating a selective force on bird populations that favors individuals who lay their eggs earlier in the year. Studies testing this hypothesis have found that some bird populations do not adapt egg laying to warming, leading to lower fitness (Visser *et al.* 1998), whereas other studies have found rapid changes in egg laying that keep up with shifting insect populations (Charmantier *et al.* 2008). Some scientists argue that many species will not be able to adapt fast enough to new environmental conditions, possibly leading to 15-37% of species going extinct (Thomas *et al.* 2004).

Community Responses

Human-altered environments are often characterized by deliberate or accidental changes in species interactions. Food webs are intricate feeding relationships, and when the abundance of one species increases or decreases, this change has the potential to ripple throughout the rest of the community. For example, the introduction of a new species, such as a predator, can have detrimental effects to communities with species that have evolved in the absence of predators. The brown tree snake is an example of a particularly devastating species that was accidentally introduced to the Pacific island of Guam following World War

II. Within decades of introduction, this species drove half of the native reptiles, two thirds of the mammals, and three fourths of the bird species to extinction.

Less-dramatic changes in food webs can occur with changes in species abundance. For example, in the Yellowstone National Park region (Wyoming, US), settlers in the nineteenth century extirpated wolves to make way for cattle ranching. The removal of one of the apex predators in the community initiated what is called a "trophic cascade." Wolves in this region feed on herbivores like elk and moose. With the loss of predators, the herbivore population exploded, causing them to over browse one of their primary food sources — willow trees (Berger *et al.* 2001). The resulting decline in willows had a negative impact on two thirds of the bird species that used willows for nesting and perching. Thus, changes at the top of the food web tricked down through the rest of the community, with unanticipated impacts on trees and birds. Interestingly, restoration of the Yellowstone ecosystem through the reintroduction of wolves in the 1990s has reversed many of these changes. In tropical regions, decreasing forested habitat has been shown to eliminate top predators that need large home ranges for acquiring food, thereby setting off similar trophic cascades whereby herbivores become abundant and the plant community is negatively affected (Terborgh *et al.* 2001). These kinds of trophic cascades are also experienced in marine habitats. The loss of top predators, such as sharks, from overfishing has led to an increase in lower-trophic-level predators, such as sting rays, which have decreased food sources like scallops (Myers *et al.* 2007).

Changing climate presents another mechanism by which community interactions can be altered. As species migrate to new ranges that are physiologically suitable, new mixes of species will produce new community structures. The consequences of these changes are poorly understood.

Ecosystem Responses

Ecosystems are important in terms of understanding the causes and impacts of global change. We saw previously how the addition of carbon from fossil fuels enhanced earth's greenhouse effect, raising global air temperature. We also saw how modification of the nitrogen cycle through the use of fertilizers and nutrient runoff from agricultural fields can also cause global changes like eutrophication and anoxia in aquatic ecosystems.

Increased magnitudes of carbon and nitrogen cycles and raising temperatures can have important further impacts on ecosystems. Elevated CO_2 causes photosynthesis in the biosphere to increase. Scientists are working on determining whether the additional growth of forests may soak up enough CO_2 in plant biomass to help mitigate the rise in atmospheric CO_2 from fossil fuels, but over a decade of research suggests that this is not happening. Nitrogen added to the biosphere ultimately cycles through ecosystems and becomes gaseous nitrous oxide (N_2O). Increased atmospheric N_2O concentrations has three negative implications for ecosystems: it represents a loss of nitrogen from soils, which lowers soil fertility, it is a greenhouse gas that is 150-300 times more powerful in terms of global warming potential compared to CO_2, and it destroys stratospheric ozone that protects life on earth from harmful ultraviolet radiation.

Warming temperatures are affecting the surface of the Earth in ways that are themselves amplifying warming through a positive feedback loop. For example, as Arctic sea ice thaws and snow cover on land decreases in duration, the high reflectivity (albedo) of snow and ice is replaced by darker ocean water or land surfaces that absorb solar radiation and makes high latitudes warm even more. As high-latitude forests in the boreal biome migrate northwards into regions that were previously tundra, the dark forest canopies of evergreen conifers tower above the snow-covered, barren landscapes, causing the albedo to decline and surface temperatures to warm (Chapin *et al.* 2005). These are what are called ecosystem-climate positive feedbacks that accelerate the rate of warming.

Impacts on Human Society

Global change scientists are interested in understanding several potential impacts of climate warming on human societies, including human health, natural disturbances, and food security.

Health

Climate change and pollution pose a number of potential risks. One of the most commonly cited examples is the potential spread and rise of infectious diseases, such as the mosquito-borne tropical diseases, malaria and Dengue fever. Warming temperatures are expected to increase the geographic range suitable for the mosquito species that transmit these diseases, and some scientists have warned that this could mean a spread of tropical diseases into areas that traditionally do not experience them, such as North America (Kuhn *et al.* 2005). However, other scientists have argued that the range of malaria actually contracted during twentieth-century warming (Gething *et al.* 2010). The reason, they argue, is that control measures, such as insecticides, bed nets, and medical treatments, are being deployed effectively to combat the diseases. Exposure to extreme heat is another risk to societies. The heat waves of 1995 in Chicago and 2003 in France caused 700 and 14,800 deaths, respectively. Poor sanitation increases the risk of cholera and other diarrheal diseases where floods contaminate water supplies with untreated sewage. The risk of these diseases rises with the increased occurrence of extreme precipitation events. Other causes of concern include increased respiratory illnesses resulting from ground-level ozone (smog) and fine particulates from vehicle exhaust and indoor cooking fires in urban and suburban areas.

Natural Disturbances

Changing climate has the potential to increase risks from sea level rise, extreme storm events, and drought. About 25% of the world's population lives with 100 km of the coast. In 2007, the IPCC projected an 18-59 cm sea level rise by 2100, but many scientists argue that this range is too low, and that sea level rise could be as great as 1-6 m (Kopp et al 2009, Jevrejeva *et al.* 2010). People living in low lying regions, such as Bangladesh and Pacific island nations (e.g., Tuvalu and the Maldives) are already experiencing the effects of salt water incursion in their agricultural fields and fresh water supplies. Arctic Inuit communities are battling the loss of coastal villages as a result of increased storm surges from sea level rise.

Extreme precipitation events may become more common in mid-to-high latitude regions, consistent with the prediction that warmer air temperatures, as a result of climate warming, will increase the moisture content of the atmosphere (IPCC 2007). Besides catastrophic flooding and associated property damage (Figure 4), extreme storms are a concern for infrastructure, with cities now faced with the prospect of significant costs associated with roads, dams, and levees being washed out by floods.

Figure 4: Flood damage in Nashville, TN from heavy rainfall on May 1-2, 2010
Parts of Middle Tennessee received more than 19 inches (49 cm) of rainfall in two days. Floods this severe are expected only once per 1000 years but may become more commonplace in a warmer world.

Meanwhile, drought is gripping subtropical regions worldwide, and precipitation is expected to decline in these regions over the twenty-first century (IPCC 2007). The American Southwest has been experiencing drought conditions since 1999, a duration comparable to other severe historical droughts such as the Dust Bowl of the 1930s in the American Great Plains. Warming is also diminishing the snow packs of the Rocky and Sierra Mountains, further decreasing water supplies to major metropolitan areas. Australia has also experienced severe dryness over the past decade. Droughts in climatically sensitive subtropical regions, such as sub Saharan Africa pose risks for food security for a number of African nations.

Global change scientists have also investigated whether tropical cyclones (hurricanes) are becoming more frequent or severe with climate change. Although observational and modeling studies suggest that hurricanes may become stronger in the future as a result of warmer sea surface temperatures, there is little evidence to suggest that they are becoming more common (Knutson *et al.* 2010).

Food Security

Food security is the ability of people to have access to sufficient, nutritious food. Although we currently grow enough food to feed the global human population, a population rising to 9 billion by 2050, combined with climate changes, will strain the capacity of some regions to feed people, thereby raising the risks of food insecurity (Godfray *et al.* 2010).

Water is very important to food security because it is one of the key determinants of crop yield, and changing climate has the potential to alter precipitation around the world. It takes approximately 1000 tons of water to produce a kilogram of grain, and 2–7 kilograms of grain are required per kilogram of livestock weight gain (Brown 2008), suggesting that food production, and meat production in particular, requires substantial inputs of water from precipitation. Where precipitation is insufficient, irrigation, and the diversion of rivers, lakes, or groundwater is required to supplement rainfall.

Figure 5: Time-lapse photos of the Aral Sea showing significant water loss due to irrigation projects in central Asia during the late twentieh century

The world faces several challenges with respect to water and food security. Warming temperatures and decreased precipitation may cause crop yields to decline, particularly in southern Asia and Africa, leading to rising food prices and increased difficulty in gaining access to food (Parry et al 2005, Lobell *et al.* 2008). In some of the world's largest grain producing regions, such as the American Southern Great Plains and the North China Plain, groundwater aquifers are being depleted by as much as 10 feet (3 m) per year as irrigation is outpacing recharge by precipitation (Brown 2008). Collapse of these aquifers would impact globally significant grain supplies. Poorly designed irrigation systems can also destroy important aquatic ecosystems, such as the Aral Sea in Asia, which was once one of the largest lakes in the world but has shrunk to 10% of its original size due to water diversion for agricultural irrigation (Figure 5). Population growth and rising affluence in developing nations and the growing demand for meat further exacerbates water demands.

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