5

Environmental Benefits

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Key Findings

Key findings in this chapter include the following:

Fossil Fuels in the Environment

- Fossil fuels are composed mainly of carbon and hydrogen atoms (and oxygen, in the case of low-grade coal). Carbon and hydrogen appear abundantly throughout the universe and on Earth.

- In addition to mining and drilling, hydrocarbons also enter the environment through natural seepage, industrial and municipal effluent and run-off, leakage from underground storage or wells, and spills and other accidental releases.

- The chemical characteristics of fossil fuels make them uniquely potent sources of fuel. They are more abundant, compact, and reliable, and cheaper and safer to use than other energy sources.

Direct Benefits

- The greater efficiency made possible by technologies powered by fossil fuels makes it possible to meet human needs while using fewer natural resources, thereby benefiting the environment.

- Fossil fuels make it possible for humanity to flourish while still preserving much of the land needed by wildlife to survive.

- The prosperity made possible by fossil fuels has made environmental protection both highly valued and financially possible, producing a world that is cleaner and safer than it would have been in their absence.

Impact on Plants

- Elevated CO_2 improves the productivity of ecosystems both in plant tissues aboveground and in the soils beneath them.

- The effects of elevated CO_2 on plant characteristics are overwhelmingly positive, including increasing rates of photosynthesis and biomass production.

- Atmospheric CO_2 enrichment ameliorates the negative effects of a number of environmental plant stresses including high temperatures, air and soil pollutants, herbivory, nitrogen deprivation, and high levels of soil salinity.

- Exposure to elevated levels of atmospheric CO_2 prompts plants to increase the efficiency of their use of water, enabling them to grow and reproduce where it has previously been too dry for them to exist.

- The productivity of the terrestrial biosphere is increasing in large measure due to the aerial fertilization effect of rising atmospheric CO_2 concentrations.

- The benefits of CO_2 enrichment will continue even if atmospheric CO_2 rises to levels far beyond those forecast by the IPCC.

Impact on Terrestrial Animals

- The IPCC's forecasts of possible extinctions of terrestrial animals are based on computer models that have been falsified by data on temperature changes, other climatic conditions, and real-world changes in wildlife populations.

- Animal species are capable of migrating, evolving, and otherwise adapting to changes in climate that are much greater and more sudden than what is likely to result from the human impact on the global climate.

- Although there likely will be some changes in terrestrial animal population dynamics, few if any will be driven even close to extinction.

Impact on Aquatic Life

- The IPCC's forecasts of dire consequences for life in the world's oceans rely on falsified computer models and are contradicted by real-world observations.

- Aquatic life demonstrates tolerance, adaptation, and even growth and developmental improvements in response to higher temperatures and reduced water pH levels ("acidification").

- The pessimistic projections of the IPCC give way to considerable optimism with respect to the future of the planet's marine life.

Conclusion

- Combustion of fossil fuels has helped and will continue to help plants and animals thrive leading to shrinking deserts, expanded habitat for wildlife, and greater biodiversity.

Introduction

The previous two chapters considered ways the use of fossil fuels[1] benefits humanity. This chapter considers how human use of fossil fuels benefits plants and wildlife. As with the previous chapters, the focus here is on documenting the benefits rather than conducting a cost-benefit analysis. Cost-benefit analyses of climate change, fossil fuels, and regulations aimed at reducing greenhouse gas emissions are conducted in Part 3.

Why consider benefits that do not directly affect humans? Because even economists recognize the limits of a strictly utilitarian ethic. Amartya Sen, a Nobel Prize-winning economist, warned recently against taking "a strictly anthropocentric perspective on the question of the environment" (Sen, 2014). He continues,

> [W]e human beings do not only have needs. We also have values and priorities, about which we can reason. To say that worrying about other species is none of our business is not ethical reasoning, but a refusal to engage in ethical reasoning. … It is hard to see how environmental thinking, which has many different aspects, can be reduced to a concern only with human living standards, given the other concerns we may very reasonably have (*Ibid.*).

Fossil fuels clearly have environmental impacts beyond those directly affecting human health and well-being. Chapter 3 documented the human benefit of increased food production thanks to aerial carbon dioxide (CO_2) fertilization, but not its larger beneficial effects on the biosphere, including effects on forests, terrestrial life, and aquatic life. Chapter 4 explained how fossil fuels powered the technologies that led to great advances in human health, but did not describe how those same technologies make it possible to feed a growing global population without completely displacing wildlife habitat or how other plants and animals respond positively to elevated CO_2 in the atmosphere. This chapter fills those gaps.

In their ambition to condemn fossil fuels, the United Nations' Intergovernmental Panel on Climate Change (IPCC) and many environmental advocacy groups focus entirely on their *negative* environmental effects and studiously ignore their *beneficial* effects. For example, in a news report based on an interview with Andreas Fischlin, "an ecological modeler at the Swiss Federal Institute of Technology in Zurich," Tollefson (2015) claims, "a growing body of research suggests that ecological and economic impacts are already occurring with the 0.8°C of warming that has already occurred. These impacts will increase in severity as temperatures rise. Damage to coral reefs and Arctic ecosystems, as well as more extreme weather, can all be expected well before the 2°C threshold is reached (pp. 14–15)."

Similarly, the American Academy for the Advancement of Science (AAAS) Climate Science Panel claims,

> The overwhelming evidence of human-caused climate change documents both current impacts with significant costs and extraordinary future risks to society and natural systems. The scientific community has convened conferences, published reports, spoken out at forums and proclaimed, through statements by virtually every national scientific academic and relevant major scientific organization – including the American Academy for the Advancement of Science (AAAS) – that climate change puts the well-being of people of all nations at risk (AAAS, n.d., p. 3).

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[1] This report follows conventional usage by using "fossil fuels" to refer to hydrocarbons, principally coal, oil, and natural gas, used by humanity to generate power. We recognize that not all hydrocarbons are derived from animal or plant sources.

In light of the alarming claims made by some scientists working on climate issues and by members of the media covering those issues, readers can be forgiven for assuming climate change produces *no* environmental benefits. This chapter demonstrates that assumption is wrong.

Section 5.1 provides background on carbon chemistry, acid precipitation, hydrogen gas, and carbon in the oceans. Section 5.2 presents the direct benefits of fossil fuels on plants and wildlife. The three main benefits are powering technologies that make it possible to use fewer resources to meet human needs; minimizing the amount of surface space needed to generate the raw minerals, fuel, and food needed to meet human needs; and bringing about the prosperity that leads to environmental protection becoming a positive social value and objective.

Fossil fuels also indirectly benefit the environment by contributing to the rise in atmospheric CO_2 levels experienced during the twentieth century and possibly the warming forecast by climate models for the twenty-first century and beyond. How much warming will occur and how much can be attributed to the combustion of fossil fuels are unsolved scientific puzzles, as explained in Chapter 2. Nevertheless, Section 5.3 considers the impacts of rising atmospheric CO_2 concentrations and *possible* warming and on plants, finding those impacts to be net positive. This extends to rates of photosynthesis and biomass production and the efficiency with which plants utilize water. Section 5.4 considers the impacts of rising CO_2 levels and temperatures on terrestrial animals and once again finds those impacts will be positive: Real-world data indicate warmer temperatures and higher atmospheric CO_2 concentrations would be beneficial, favoring a maintenance or increase in biodiversity.

Section 5.5 reviews laboratory and field studies of the impact of rising CO_2 concentrations and temperatures on aquatic life (corals and fish) and finds tolerance, adaptation, and even growth and developmental improvements. Section 5.6 provides a brief conclusion.

A previous volume in the *Climate Change Reconsidered* series subtitled “Biological Impacts” (NIPCC, 2014) contains summaries of nearly 2,000 peer-reviewed articles addressing in depth issues that are addressed only briefly in this chapter. Figure 5.1, taken from the *Summary for Policymakers* of that volume, summarizes its principal findings. Hundreds of summaries of new scientific research released since 2013 have been added to this chapter.

Figure 5.1
Summary of findings on biological impacts

- **Atmospheric carbon dioxide (CO_2) is not a pollutant.** It is a colorless, odorless, non-toxic, non-irritating, and natural component of the atmosphere. Long-term CO_2 enrichment studies confirm the findings of shorter-term experiments, demonstrating numerous growth-enhancing, water-conserving, and stress-alleviating effects of elevated atmospheric CO_2 on plants growing in both terrestrial and aquatic ecosystems.

- **The ongoing rise in the atmosphere’s CO_2 content is causing a great greening of the Earth.** At locations all across the planet, the historical increase in the atmosphere’s CO_2 concentration has stimulated vegetative productivity. This has occurred in spite of many real and imagined assaults on Earth’s vegetation, including fires, disease, pest outbreaks, deforestation, and climatic change.

- **There is little or no risk of increasing food insecurity due to rising surface temperatures or rising atmospheric CO_2 levels.** Farmers and others who depend on rural livelihoods for income are benefitting from rising agricultural productivity throughout the world, including in parts of Asia and Africa where the need for increased food supplies is most critical. Rising temperatures and atmospheric CO_2 levels play a key role in the realization of such benefits.

- **Terrestrial ecosystems have thrived throughout the world as a result of warming temperatures and rising levels of atmospheric CO_2.** Empirical data pertaining to numerous animal species, including amphibians, birds, butterflies, other insects, reptiles, and mammals, indicate global warming and its myriad ecological effects tend to foster the expansion and preservation of animal habitats, ranges, and populations, or otherwise have no observable impacts. Multiple lines of evidence indicate animal species are adapting and in some cases evolving, to cope with climate change of the modern era.

- **Rising temperatures and atmospheric CO_2 levels do not pose a significant threat to aquatic life.** Many aquatic species have shown considerable tolerance to temperatures and CO_2 values predicted for the next few centuries and many have demonstrated a likelihood of positive responses in empirical studies. Any projected adverse impacts of rising temperatures or declining seawater and freshwater pH levels ("acidification") will be mitigated through behavioural changes during the many decades to centuries it is expected to take for pH levels to fall.

Source: Summary for Policymakers. *Climate Change Reconsidered II: Biological Impacts.* Nongovernmental International Panel on Climate Change (NIPCC). Chicago, IL: The Heartland Institute, 2014.

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5.1 Fossil Fuels in the Environment

> *Fossil fuels are composed mainly of carbon and hydrogen atoms (and oxygen, in the case of low-grade coal). Carbon and hydrogen appear abundantly throughout the universe and on Earth.*

As was observed at the beginning of Chapter 2, many people mistakenly believe they can address the climate change issue without understanding basic climate science. The "science tutorial" offered at the beginning of that chapter provided the science so often missing in popular and even academic writing on the subject. Section 2.1.2.2 discussed carbon chemistry in the context of the carbon cycle. Only a small part of that discussion will be repeated here, as the focus now is on fossil fuels.

5.1.1 Carbon Chemistry

Carbon and hydrogen appear abundantly throughout the universe and on the Earth. Carbon's unique function as the base element for Earth's biosphere derives from it being the lightest element capable of forming four covalent bonds with atoms of most elements in many variations. ("Covalent bonds" involve the sharing of electron pairs and are stronger than bonds involving single electrons.) The resulting molecules can contain from one to millions of carbon atoms. Carbon is so abundant and apt to bond with other atoms that the discipline of chemistry is divided into *organic chemistry*, which studies only carbon-based compounds, and *inorganic chemistry*, which studies all other compounds. Carbon-based compounds comprise the overwhelming majority of the tens of millions of compounds identified by scientists.

Compounds containing carbon atoms typically are combustible; have high melting points, low boiling points, and low solubility in water; and do not conduct electricity. All of these qualities make them good candidates for fuels that can be used to store, transport, and then release energy through combustion. Compounds containing carbon will typically produce carbon dioxide, among other byproducts, when burned.

Hydrogen is the lightest element and the most abundant substance in the universe, composing much of the mass of stars and gas giant planets. On Earth, it is rarely found in its monoatomic state due to its propensity to form covalent bonds with other elements. It is mostly present in hydrocarbons and water. At standard temperature and pressure, hydrogen is a highly combustible gas with a very high gravimetric energy density (energy per unit of weight, e.g. joules per kilogram) but a relatively low volumetric energy density (energy per unit of volume, e.g., joules per liter).

When carbon and hydrogen come together, the carbon provides the "backbone" to which hydrogen bonds, forming long and lightweight molecular chains, circles, and other complex patterns. In general, small linear hydrocarbons will be gases while medium-sized linear hydrocarbons will be liquids. Branched hydrocarbons of intermediate size tend to be waxes with low melting points. Long hydrocarbons tend to be semi-solid or solid. Figure 5.1.1.1 identifies the most common hydrocarbons and their uses.

5.1.2 Fossil Fuels

The main forms of fossil fuels are coal, oil, and natural gas (methane). Each form has in common a basis in hydrocarbons, which are molecules composed of carbon and hydrogen atoms. Types of hydrocarbons include methane, ethylene, and benzene. Coal, oil, and natural gas are made up largely of hydrocarbons, nitrogen, sulfur, and oxygen. The energy produced by burning a fossil fuel comes from breaking the carbon-hydrogen and carbon-carbon bonds and recombining them into carbon-oxygen (CO_2) and hydrogen-oxygen (H_2O) bonds. Because the hydrocarbons in coal have fewer hydrogen-carbon bonds than oil or natural gas, its gravimetric energy density (joules per kg) is less and it produces more CO_2 per unit of weight when burned. There are four types of coal according to their carbon content: anthracite has the most carbon, then bituminous, then subbituminous, then lignite. (See Figure 5.1.2.1.)

Considerable attention has been devoted to studying the possibility that some part of the world's supply of "fossil fuels" is produced by deep biospheres within the geosphere. Gold (1992, 1999) proposed that microbial life is common there and plays an important role in geochemical cycles, particularly in the carbon cycle. Kolesnikov *et al.* (2009) established experimentally that ethane and heavier hydrocarbons can be synthesized under conditions of the upper mantle, but it is as yet unknown how this may affect estimates of supplies of hydrocarbon-based fuels. According to Colman *et al.* (2017), "Despite 25 years of intense study, key questions remain on life in the deep subsurface, including whether it is endemic and the extent of its involvement in the anaerobic formation and degradation of hydrocarbons. Emergent data from cultivation and next-generation sequencing approaches continue to provide promising new hints to answer these questions."

Hydrocarbons affect the natural environment when they are burned by releasing CO_2 and H_2O into the air. When burned, the sulfur and nitrogen in fossil fuels combine with oxygen to produce sulfur dioxide (SO_2) and nitrogen oxides (NO_x). Sulfur dioxide and produce sulfuric and nitric acid, respectively, which can reduce the pH of rainwater (Cassidy and Frey, n.d.). Coal generally has more of these substances and natural gas has less. Coal also has some mineral content, typically quartz, pyrite, clay minerals, and calcite.

Hydrocarbons also enter the environment through natural seepage (Kvenvolden and Cooper, 2003), industrial and municipal effluent and run-off, leakage from underground storage or wells, and spills and other accidental releases. In some cases these releases harm plants and wildlife and endanger human health. According to Aminzadeh *et al.* (2013), "Hydrocarbon seepage can have profound local effects that may be widespread, causing vast blighted areas. The seeps that form the Buzau mounds in the Carpathian foreland of Romania are built by repeated acidic mudflows that form large blighted and barren areas," citing Baciu (2007) (p. 4). See Varjani (2017) and Chandra *et al.* (2013) for discussions of human health threats and many citations. This topic is addressed further in Chapter 8.

5.1.3 Acid Precipitation

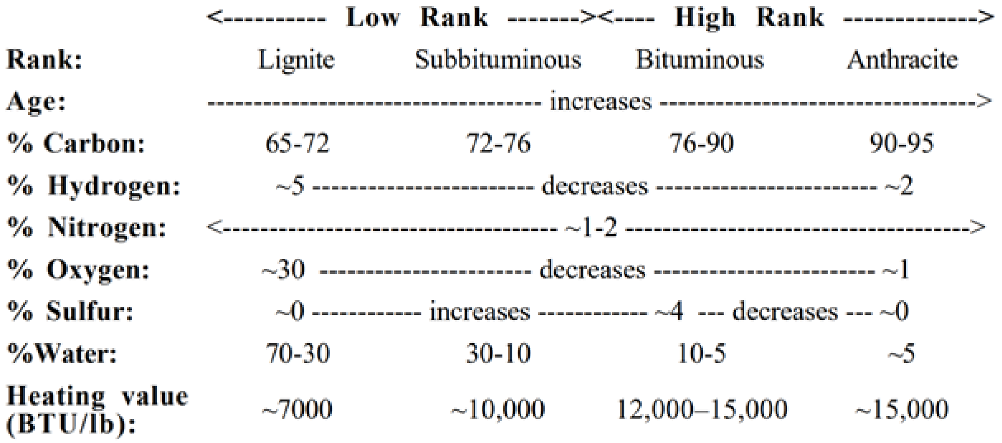
The reduced pH of rainwater due to sulfur dioxide and nitrogen oxide emissions from the burning of fossil fuels, popularly referred to as "acid rain," was once thought to be dangerously acidifying soils and surface waters in the United States and around the world. The U.S. National Acid Precipitation Assessment Project (NAPAP, 1991), a project involving hundreds of scientists working in small groups over a period of 10 years at a cost of $550 million, found those concerns were unjustified. NAPAP found "there is no evidence of an overall or pervasive decline of forests in the United States and Canada due to acid deposition or any other stress" and "there is no case of forest decline in which acidic deposition is known to be a predominant cause" (Compendium of Summaries, p. 135).

Figure 5.1.1.1
Common hydrocarbons and their uses

Name	Number of Carbon Atoms	Uses
Methane	1	Fuel in electrical generation. Produces least amount of carbon dioxide.
Ethane	2	Used in the production of ethylene, which is utilized in various chemical applications.
Propane	3	Generally used for heating and cooking.
Butane	4	Generally used in lighters and in aerosol cans.
Pentane	5	Can be used as solvents in the laboratory and in the production of polystyrene.
Hexane	6	Used to produce glue for shoes, leather products, and in roofing.
Heptane	7	The major component of gasoline.
Octane	8	An additive to gasoline that, particularly in its branched forms, reduces knock.
Nonane	9	A component of fuel, particularly diesel.
Decane	10	A component of gasoline, but generally more important in jet fuel and diesel.

Hydrocarbons longer than 10 carbon atoms in length are generally broken down through the process known as “cracking” to yield molecules with lengths of 10 atoms or less. *Source:* Petroleum.co.uk, 2018.

Figure 5.1.2.1
Variation of selected coal properties with coal rank



	<---------- **Low Rank** ------->		<---- **High Rank** ------------->	
Rank:	Lignite	Subbituminous	Bituminous	Anthracite
Age:	---------------------------------- increases --------------------------------->			
% Carbon:	65-72	72-76	76-90	90-95
% Hydrogen:	~5 ----------------------- decreases ----------------------- ~2			
% Nitrogen:	<---------------------------------- ~1-2 ----------------------------------->			
% Oxygen:	~30 ---------------------- decreases ------------------------ ~1			
% Sulfur:	~0 ----------- increases ------------ ~4 --- decreases --- ~0			
%Water:	70-30	30-10	10-5	~5
Heating value (BTU/lb):	~7000	~10,000	12,000–15,000	~15,000

Source: Radovic, 1997, Figure 7-3, p. 117.

NAPAP also found acidic deposition to be a threat to sensitive species of fish in only a few bodies of water and a small contributor relative to other factors, including logging and development. Remediation with lime is an inexpensive solution in such cases. A follow-up report issued in 1998 similarly found "Most forest ecosystems in the East, South, and West are not currently known to be adversely impacted by sulphur and nitrogen deposition" (NAPAP, 1998).

European researchers arrived at similar conclusions. For example, Elfving *et al*. (1996) found "in the Swedish National Forest Inventory (NFI), a steady increase in the estimated productivity of forest land has been noticed since inventory was begun in 1923. Young stands generally indicate higher site indices than old stands at equal site conditions. For spruce, this rise of site index has been estimated at 0.05–0.11 $m.year^{-1}$, with the highest value in the south." The authors also noted "the increasing atmospheric deposition of nitrogen is suspected to have the biggest influence" on rising forest productivity, meaning the positive effects of "acid rain" were outweighing the possible negative effects.

While "acid rain" was probably never a significant environmental threat, the dramatic reductions in SO_2 and NO_2 emissions in the United States and globally since the 1980s mean it has even less impact on the environment today. For additional commentary on the topic, see Goklany (1999), Aldrich (2003), Lomborg (2004), Menz and Seip (2004), Burns (2011), and Ridley (2012).

5.1.4 Hydrogen Gas

Pure hydrogen without carbon or the contaminants found in fossil fuels can be burned to generate energy, but it has serious disadvantages as a fuel. Hydrogen gas (H_2) is highly flammable and will explode at concentrations ranging from 4% to 75% by volume in the presence of a flame or a spark. Pure hydrogen-oxygen flames are invisible to the naked eye, making detection of a burning hydrogen leak difficult. Because hydrogen is so light, it is usually stored under pressure, introducing more cost, weight, and risk, and this is difficult to do because hydrogen embrittles many metals. While a typical automobile gas tank holds 15 gallons of gasoline weighing 90 pounds, the corresponding hydrogen tank would need to hold 60 gallons and would need to be insulated, but the fuel would weigh only 34 pounds (McCarthy, 2005).

Pure hydrogen can be obtained from methane through a process called reforming, or from water through electrolysis. However, the energy required to do either exceeds the amount of energy released when the hydrogen is burned. Current industrial electrolysis processes have effective electrical efficiency of approximately 70% to 80%, meaning they require 50 to 55 kWh of electricity to produce enough hydrogen to carry about 40 kWh of power (Christopher and Dimitrios, 2012). When the energy required to store and transport the fuel is considered, the process is even less efficient. Unless a non-fossil fuel is used to generate the electricity needed for reforming or electrolysis, using hydrogen as a fuel would not reduce carbon dioxide or other emissions generated by burning fossil fuels.

5.1.5 Carbon in the Oceans

The human contribution of oil to oceans during oil production or shipping gets extensive media attention but is small relative to natural seepage. The U.S. National Research Council found "spillage from vessels in U.S. waters during the 1990s declined significantly as compared to the prior decade and now represents less than 2% of the petroleum discharges into U.S. waters" and "only 1% of the oil discharges in North American waters is related to the extraction of petroleum" (NRC, 2003). Roberts and Feng note, "Hydrocarbons have been synonymous with the Gulf of Mexico (GOM) since early Spanish explorers wrote about the occurrence of sea surface slicks and tar balls on beaches" (Roberts and Feng, 2013, p. 43).

Because fossil fuels are carbon-based and therefore part of the carbon cycle, accidental releases or spills simply return the fuels' component parts to carbon reservoirs in different chemical forms. This often has the effect of minimizing the harm they could cause by coming into contact with plants or animals, including humans. Petroleum is typically reformed by biodegradation, dispersion, dissolution, emulsification, evaporation, photo-oxidation, resurfacing, sinking, and tar-ball formation.

Of these processes, biodegradation plays the biggest role. Hydrocarbons are energy-rich, making them inviting targets for bacteria and fungus. Atlas (1995) writes, "Hydrocarbon-utilizing micro-organisms are ubiquitously distributed in the marine environment following oil spills. These micro-organisms naturally biodegrade numerous contaminating petroleum hydrocarbons, thereby cleansing the oceans of oil pollutants" (Atlas, 1995). Aminzadeh *et al.* note, "Many marine seeps likewise have changed environments dominated by biota that can tolerate and exploit the seep. Some of these communities may be locally inhabited by very adept methanotrophs and paradoxically thrive, producing mounds similar to reefs. Fossil communities such as the Burgess Shale fauna (Friedman, 2010) have been thought to be associated with seeps (Johnston *et al.*, 2010)" (Aminzadeh, 2013.).

Varjani reported, "Petroleum hydrocarbon pollutants degradation by bacterial species has been well documented and metabolic pathways have been elucidated (Leahy and Colwell, 1990; Hendrickx *et al.*, 2006; Abbasian *et al.*, 2015; Meckenstock *et al.*, 2016; Wilkes *et al.*, 2016)" (Varjani, 2017, p. 282). Varjani's review of the literature found 38 microorganisms have been shown to biodegrade one or more of the four fractures of crude oil (saturates, aromatics, resins, and asphaltenes).

Because the efficiency and effectiveness of biodegradation is sometimes limited by the availability of indigenous colonies of bacteria and fungi or minerals needed for their replication, human intervention in the form of seeding bacterial populations and adding fertilizer can speed up and complete the biodegradation process. This process of bioremediation has been demonstrated to be successful in many different environments (Farhadian *et al.*, 2008; Chandra *et al.*, 2013; Ron and Rosenberg, 2014; Hu *et al.*, 2017).

5.1.6 Conclusion

Carbon chemistry explains why fossil fuels are preferred over other chemical compounds as sources of energy. Kiefer (2013) writes,

> Carbon transforms hydrogen from a diffuse and explosive gas that will only become liquid at -423° F [-253° C] into an easily handled, room-temperature liquid with 63% more hydrogen atoms per gallon than pure liquid hydrogen, 3.5 times the volumetric energy density (joules per gallon), and the ideal characteristics of a combustion fuel. … A perfect combustion fuel possesses the desirable characteristics of easy storage and transport, inertness and low toxicity for safe handling, measured and adjustable volatility for easy mixing with air, stability across a broad range of environmental temperatures and pressures, and high energy density. Because of sweeping advantages across all these parameters, liquid hydrocarbons have risen to dominate the global economy (p. 117).

In summary, the chemical characteristics of carbon and hydrogen, the main components of fossil fuels, make fossil fuels uniquely potent sources of fuel. They are more abundant, compact, reliable, and cheaper and safer to use than other energy sources. While it is possible to use hydrogen to transmit energy without the "backbone" provided by carbon, it is inefficient, expensive, and dangerous compared to carbon-based fuels. Acid rain, once thought to be a serious environmental threat, is no longer considered one. Human contributions of oil to the oceans via leakage and spills are trivial in relation to natural sources and quickly disperse and biodegrade. The damage caused by oil spills is a net cost of using oil, but not a major environmental problem.

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5.2 Direct Benefits

Fossil fuels benefit the environment directly in three ways. First, they power the technologies that dramatically improve the efficiency with which natural resources are used, thereby reducing the impact of human activities on nature. One attempt to measure this benefit found the impact of global human consumption on the environment was reduced 32% from 1900 to 2006 due to technological advances (Goklany, 2009).

Second, fossil fuels save land for wildlife. They do this in three ways. The first is via the application of technology already mentioned. The use of fossil fuels to create ammonia fertilizer, to power tractors and other farm machinery, and to speed the transport of perishable food products to processing plants and markets allowed humanity's nutrition needs to be met with fewer acres under cultivation. According to Goklany (2009), technology reduced the impact of population and affluence on the amount of cropland used in the United States by 95%. In other words, fossil fuels erased all but 5% of the increased use of land that human population growth and prosperity otherwise would have required.

Fossil fuels also save land for wildlife by being more power-dense than alternative sources of energy, thus requiring less surface area than wind or solar power to produce equal amounts of energy to meet human needs. According to one estimate, using windmills to produce the same amount of energy as is currently produced globally by fossil fuels would require 14.4 million onshore turbines requiring some 570 million acres, an area equal to 25% of the entire land area of the United States (30% of the lower 48 states) (Driessen, 2017).

Fossil fuels also save land for wildlife by increasing the level of carbon dioxide (CO_2) in the atmosphere, which acts as fertilizer for crops, increasing yields and making it possible to meet the nutritional needs of a growing human population without converting yet more forests and grasslands into cropland. As documented below, assuming the 120 ppm increase in atmospheric CO_2 concentration since the beginning of the Industrial Revolution was caused by the burning of fossil fuels, fossil fuels increased agricultural production per unit of land area by 70% for C_3 cereals, 28% for C_4 cereals, 33% for fruits and melons, 62% for legumes, 67% for root and tuber crops, and 51% for vegetables (Idso *et al.*, 2003, p. 18). As the atmosphere's CO_2 content continues to rise, agricultural land use efficiency will rise with it.

The third direct benefit of fossil fuels is the impact prosperity has on the willingness of people to pay to protect the environment. Once a society attains a level of prosperity sufficient to meet its basic physical needs, the willingness of citizens to spend and sacrifice for a better environment rises more than twice as fast as per-capita income (Coursey, 1992), leading to greater investments over time in safe and clean drinking water, sanitary handling of human and animal wastes, and other measures of environmental protection. As Bryce (2014) writes,

> It's only by creating wealth that we will be able to support the scientists, tinkerers and entrepreneurs who will come up with the new technologies we need. It's only by getting richer that we will be able to afford the adaptive measures we may need to take in the decades ahead as we adjust to the Earth's ever-changing climate. It is only by using more energy, not less, that we will be able to provide more clean water and better sanitation to the poorest of the poor" (p. 54).

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5.2.1 Efficiency

> *The greater efficiency made possible by technologies powered by fossil fuels makes it possible to meet human needs while using fewer natural resources, thereby benefiting the environment.*

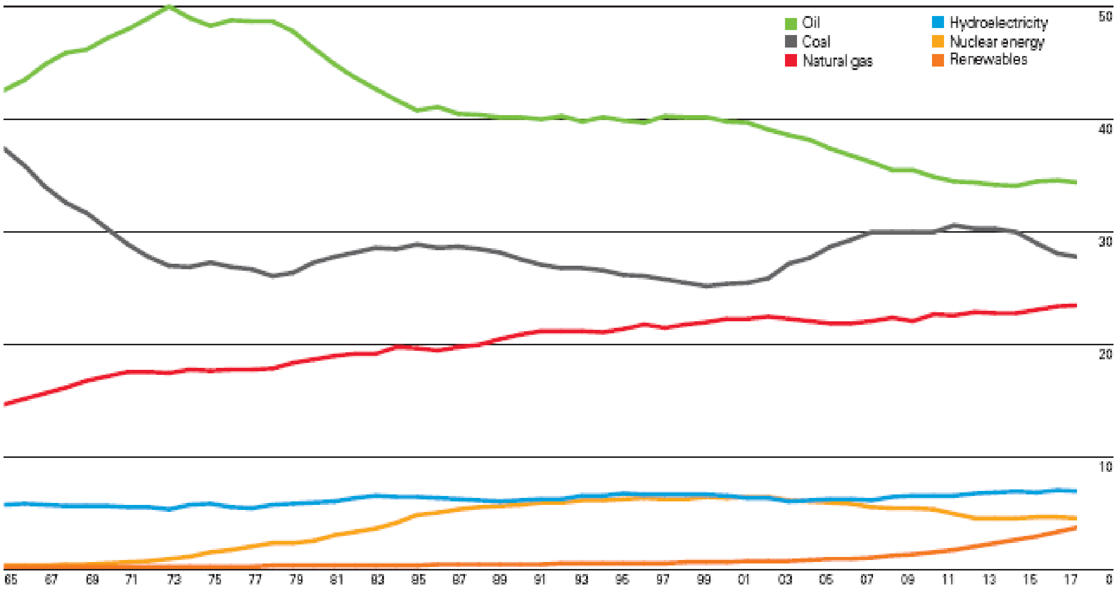
Fossil fuels power the technologies used to protect the environment. Chapters 3 and 4 documented how those technologies contribute to human prosperity and human health. This chapter shows how those technologies make it possible to protect and clean the air and water of both manmade and natural pollutants, leading to benefits not only for humanity but for nearly all other forms of life.

"Without cheap supplies of electricity produced from coal, the ongoing revolution in information technology, as well as the age of biotech and nanotech, simply wouldn't be possible. Electricity accelerates the trend toward objects and systems that are Smaller Faster Lighter Denser Cheaper," writes Bryce (2014, p. 191). "If oil didn't exist, we would have to invent it. No other substance comes close to oil when it comes to energy density, ease of handling, and flexibility. Those properties explain why oil provides more energy to the global economy than any other fuel" (*Ibid.*, p. 173). Figure 5.2.1.1 illustrates the dominance of oil, coal, and natural gas in meeting the world's energy needs.

The market system spurs innovation and efficient use of natural resources required to produce consumer goods and services, thereby indirectly leading to protection of the environment (see Chapter 1, Section 1.2.6 and Goklany, 1999; Huber, 1999, Chapter 4; Bradley, 2000; Baumol, 2002). Producers benefit when they use fewer resources because their costs decline. They also benefit, as do their customers, by developing new technologies that increase the value of the output from the resources they use.

The history of the three Industrial Revolutions briefly told in Chapter 3 reveals how central fossil fuels and especially coal were to economic progress in the past, continue to be today, and will be for the foreseeable future. McNeill (2000) writes,

Figure 5.2.1.1
Shares of global primary energy consumption by fuel



Oil remains the world's dominant fuel, making up just over a third of all energy consumed. In 2017 oil's market share declined slightly, following two years of growth. Coal's market share fell to 27.6%, the lowest level since 2004. Natural gas accounted for a record 23.4% of global primary energy consumption, while renewable power hit a new high of 3.6%.

Source: BP, 2018, p. 11.

> No other century – no millennium – in human history can compare with the twentieth for its growth in energy use. We have probably deployed more energy since 1900 than in all of human history before 1900. My very rough calculation suggests that the world in the twentieth century used 10 times as much energy as in the thousand years before 1900 A.D. In the 100 centuries between the dawn of agriculture and 1900, people used only about two-thirds as much energy as in the twentieth century.

Many authors have documented the remarkable pace of growth in human population, energy use, and well-being in the twentieth century and its impact on the environment (Cronon, 1992; Schlereth, 1992; Avery, 2000; Norton Green, 2008; McNeill and Engelke, 2016; Gordon, 2016). While these authors document the negative as well as positive impacts of fossil fuels on the environment, the positive effects are dominant. Gordon (2016) observed, "When the electric elevator allowed buildings to extend vertically instead of horizontally, the very nature of land use was changed and urban density was created" (p. 4). Cities are "greener," in some ways, than less-dense population patterns due to their smaller footprint and lower per-capita use of many resources (Owen, 2004; Brand, 2010). Gordon also noted, "And so it was with motor vehicles replacing horses as a primary form of intra-urban transportation; no longer did society have to allocate a quarter of its agricultural land to support the feeding of the horses or maintain a sizable labor force for removing their waste" (*Ibid.*).

By reducing the demand for wood for use as a fuel and by increasing the productivity of land used for agriculture, fossil fuels allowed more land to remain as forests or even return to forests. Mather and Needle (1998) described the transition in the United States as follows:

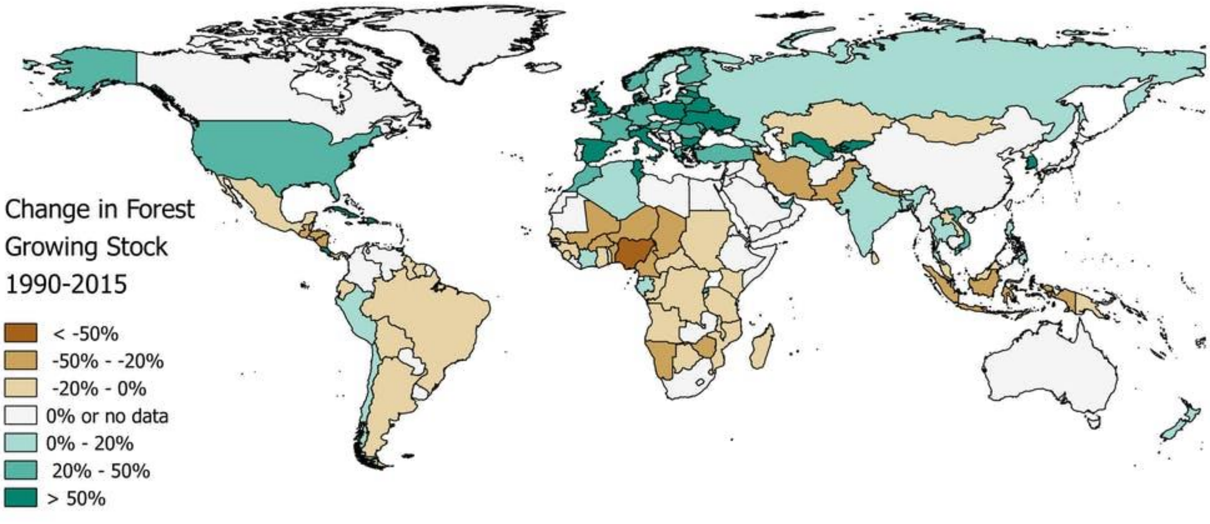
> Perhaps the most striking example of the process, however, is from the United States. Here, as elsewhere, the process has operated at a number of scales and is closely linked to reforestation. Within the south, for example, cropland has been increasingly concentrated on areas of high quality land. A 'process of natural selection' has led to the concentration of cropland on the better land and the vacating by agriculture of the poorer land. The areas of greatest abandonment of land coincided with major environmental limitations, such as steep slopes and infertile soils, which limited the range of operations in which the farmers could engage. More generally, large areas of relatively poor land in New England were abandoned as better land in the Mid-West and other parts of the country was opened up. Much of the abandoned land in New England (and in the South) subsequently reverted to forest. The result was that, by 1980, the percentage of the land area of Maine under forest was 90, compared with 74 in the mid-1800s. In New Hampshire, the corresponding figures for these dates were 86 and 50%: in Vermont 76 and 35% (p. 122)

This process continues today. According to the Food and Agriculture Organization of the United Nations, in 2015 net forest area increased or was unchanged from the previous year in 12 of the agency's 15 regions and unchanged globally (FAO, 2018, Figure 26). The three regions that saw declines were Southeast Asia, North Africa, and landlocked developing countries, all areas experiencing poverty and/or civil strife. In contrast to these poor countries, Kauppi *et al.* (2018) report "a universal turnaround has been detected in many countries of the World from shrinking to expanding forests" during the 25-year period 1990 to 2015, which they depict in the figure reproduced as Figure 5.2.1.2.

According to Kauppi *et al,* the most rapid expansion of forests is occurring in nations with the highest life expectancy, education, and per-capita income indicators, as recorded in national scores on the United Nations Human Development Index. The authors say "This indicates that forest resources of nations have improved along with progress in human well-being. Highly developed countries apply modern agricultural methods on good farmlands and abandon marginal lands, which become available for forest expansion. Developed countries invest in sustainable programs of forest management and nature protection." Significantly, they add, "Our findings are significant for predicting the future of the terrestrial carbon sink. They suggest that the large sink of carbon recently observed in forests of the World will persist, if the well-being of people continues to improve" (*Ibid.*)

Jesse Ausubel, head of the Program for the Human Environment at Rockefeller University, has written extensively on how modern technology made

Figure 5.2.1.2
Change in Forest Growing Stock, 1990 – 2015



Source: Kauppi *et al.*, 2018.

possible by electricity and the fossil fuels that produce it has led to a "dematerialization" of modern civilization, the steady reduction in natural resources required to produce each unit of income or wealth (see, e.g., Ausubel, 1996; Wernick *et al.*, 1996; Wernick and Ausubel, 2014). In 2008, Ausubel and Paul E. Waggoner of the Connecticut Agricultural Experiment Station in New Haven observed, "During past years, dematerialization and declining intensity of impact have ameliorated a range of humanity's environmental impacts, from the carbon emission attending energy use to the cropland and fertilizer attending food production, and the use of wood" (Ausubel and Waggoner, 2008).

Ausubel and Waggoner asked whether the trend was ending or would continue. They found that from 1980 to 2006, the carbon intensity of the Chinese economy declined to 40% of its 1980 level. "Without the dematerialization from 1980–2006 by Chinese consumers, actual national energy use in 2006 would have been 180% greater," they write. "Reversing China's 26-year dematerialization would increase the entire global energy consumption by fully 28%." The authors found dematerialization taking place in both an early period (1980–1995) and a more recent period (1995–2006) globally and for the United States, China, and India. They write,

> Although the average global consumer enjoyed 45% more affluence in 2006 than in 1980, each only consumed 22% more crops and 13% more energy. The richer consumer actually used 20% less wood, a saving of 0.67 minus 0.53 m^3 per person or 39 board feet. The evidence … also shows persistently declining intensity of the impact of crop production on land and fertilizer use and persistence of declining French carbon emissions per energy production (*Ibid.*).

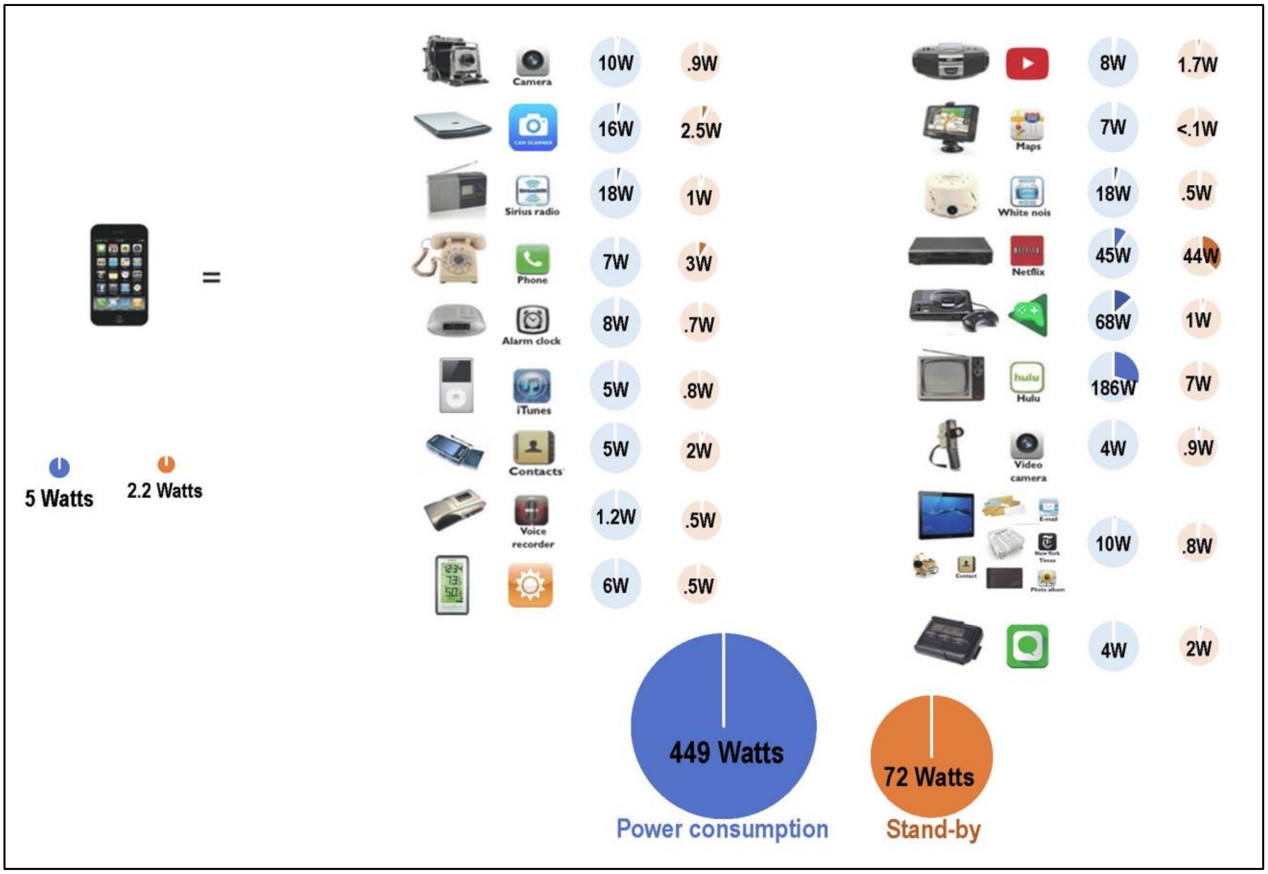
"The USA dematerialized steadily near 2%/year throughout the 25 years. ... Its intensity of impact did not decrease," the two authors report. In conclusion, they write,

> The dematerialization of crop, fertilizer and wood use plus the decarbonization of carbon emission per GDP continue. And although a declining intensity of impact is hard to find for energy, it continues for other phenomena. The declining intensities continue assisting the journey across sustainability's dual dimensions of present prosperity without compromising the future environment (*Ibid.*).

Vaclav Smil, professor emeritus in the faculty of environment at the University of Manitoba in Winnipeg, Manitoba, Canada, also has written extensively on dematerialization. In 2013 he estimated that a dollar's worth of value produced today in the United States requires about 2.5 ounces of raw material, whereas a dollar's worth of value (adjusted for inflation) would have required 10 ounces of raw material in 1920. He estimated that since 1900, the energy required to produce a ton of steel and nitrogen fertilizer has fallen by 80% and a ton of aluminum and cement by 70% (Smil, 2013).

An example of dematerialization at work is the extraordinary energy savings made possible by the widespread use of cellphones. Tupy (2012) has documented how one smart phone saves 444 watts of power consumption by doing the work of at least nine devices previously used. A graphic illustrating his findings appears as Figure 5.2.1.3.

Figure 5.2.1.3
Dematerialization at work: One smart phone saves 444 watts of power consumption



A single smart phone, pictured on the left, consumes 5 Watts of power and requires 2.2 Watts of stand-by power to produce the work of 18 devices consuming 449 Watts and requiring 72 Watts of stand-by power. Power and energy use data based on Lawrence Berkeley Laboratory standby statistics and other industry sources. Graphic courtesy of Nuno Bento, IIASA, 2017. *Source:* Adapted from Tupy, 2012.

IPAT Equation and T-Factor

A formula commonly used to estimate the environmental impact of human activities (Ehrlich and Holdren, 1971) is:

$$\mathbf{I = P \times A \times T}$$

where I is environmental impact, P is human population, A is per-capita affluence or wealth (commonly denoted as per-capita Gross Domestic Product (GDP)) and T is technological innovation. Following Goklany (1999, 2009), we can see that since A = GDP/P, the equation can be simplified as:

$$\mathbf{I = GDP \times T}$$

The technological change (ΔT) from an initial time (t_i) to final time (t_f) is therefore:

$$\mathbf{T = I/GDP}$$

The impact of technological innovation is therefore:

$$\mathbf{\Delta T = \Delta(I/GDP)}$$

If population, affluence, their product (GDP), and the technology-factor are all normalized to unity at t_i, then:

$$\mathbf{\Delta T = (I_f /GDP_f) - 1}$$

where subscript f denotes the value at the end of the period.

Indur Goklany, a writer on technology and science who served as a contributor to and reviewer of IPCC reports as well as chief of the technical assessment division of the National Commission on Air Quality and a consultant in the Office of Policy, Planning, and Evaluation at EPA, calls this final equation the “T-factor.” The smaller the T-factor, the more efficiently natural resources are being used. Goklany used this measure to show how new technology is making possible giant steps forward in environmental protection.

The T-factor for sulfur dioxide (SO_2) emissions – a pollutant produced largely from fossil fuel combustion at power plants and other industrial facilities – in the United States between 1900 and 1997 was 0.084, “which means that $1 of economic activity produced 0.084 times as much SO_2 in 1997 as it did in 1900,” a dramatic reduction (Goklany, 1999, p. 72). Similarly, the T-factor for volatile organic compounds (VOCs) was 0.094 and for nitrogen oxide (NO_x), 0.374. Between 1940 and 1997, the T-factor for particulate matter (PM_{10}) was 0.034 and for carbon monoxide, 0.121.The T-factor for lead emissions between 1970 and 1997 was 0.008.Emissions levels for all of these pollutants have continued to fall since 1997.

More recently, Goklany (2009) estimated the T-factors for habitat converted to cropland, water withdrawal, air pollution, death from extreme weather events, and carbon dioxide emissions in the United States, other countries, and globally. Goklany summarized the impact of technology on carbon dioxide (CO_2) emissions:

> [F]or the U.S., despite a 27-fold increase in consumption (i.e., GDP) since 1900, CO_2 emissions increased 8-fold. This translates into a 67% reduction in impact per unit of consumption (i.e., the T-factor, which is also the carbon intensity of the economy) during this period, or a 1.1% reduction per year in the carbon intensity between 1900 and 2004. Since 1950, however, U.S. carbon intensity has declined at an annual rate of 1.7%. Arguably, CO_2 emissions might have been lower, but for the hurdles faced by nuclear power.
>
> Globally, consumption increased 21-fold since 1900, while CO_2 increased 13-fold because technology reduced the impact cumulatively by 32% or 0.4% per year. Both U.S. and global carbon intensity increased until the early decades of the 20th century. Since 1950, global carbon intensity has declined at the rate of 0.9% per year (Goklany, 2009, p. 18).

Some of Goklany’s other findings include:

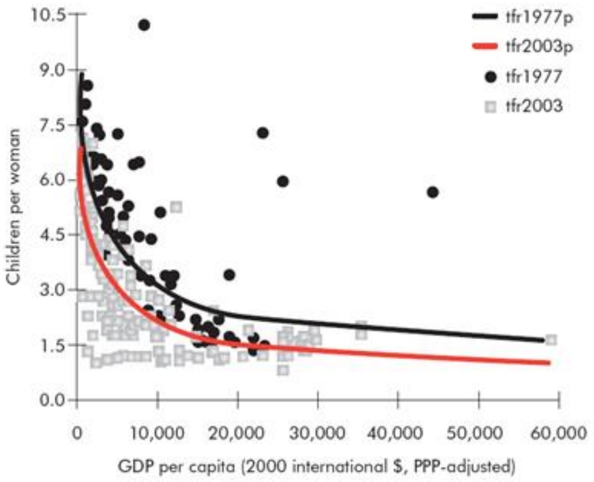
- Technological change reduced the amount of land that would have been converted from habitat to cropland globally by 84.3% from 1950 to 2005, and by 95% in the United States from 1910 to 2006.

- Technology reduced air pollution in the United States by between 70.5% and 99.8%, depending on the pollutant and time period.

- Globally, technology reduced the number of deaths due to climate-related disasters by 95.3% from 1900/09 to 1997/2006 despite a 300% rise in world population in this period (*Ibid.*, Table 2, pp. 22–23).

The T-factor is so powerful it dominates the IPAT equation. The greater productivity, prosperity, and economic opportunities created by technological advances encourage smaller family sizes, resulting in slower population growth or even a negative population growth rate. Goklany plots total fertility rate (TFR) versus per-capita income, demonstrating the close negative correlation. (See Figure 5.2.1.4.) He concludes, "Thus, in the IPAT equation, P is not independent of A and T: sooner or later, as a nation grows richer, its population growth rate falls (e.g., World Bank 1984), which might lead to a cleaner environment (Goklany 1995, 1998, 2007b)" (Goklany, 2009, p. 7).

Figure 5.2.1.4
Total fertility rate (tfr) vs. per-capita income, 1977–2003



Source: Goklany, 2007a.

In summary, the human impact on the environment is smaller than it would otherwise be thanks to the technologies fueled by fossil fuels. "Dematerialization" made possible by electricity and advanced technologies means fewer raw materials must be mined and processed to meet a growing population's demand for goods and services.

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5.2.2 Saving Land for Wildlife

> *Fossil fuels make it possible for humanity to flourish while still preserving much of the land needed by wildlife to survive.*

Fossil fuels benefit the environment by minimizing the amount of surface space needed to generate the raw materials, fuel, and food needed to meet human needs. If it were not for fossil fuels, the human need for surface space would crowd out habitat for many species of plants and animals. Fossil fuels save land for wildlife in three ways: by being more energy-dense than alternative fuels, thereby reducing the amount of surface space needed to meet the demand for energy; by making possible the "Green Revolution" dramatically reducing the acreage needed to feed the planet's growing population; and via aerial fertilization, the "greening of the Earth" that occurs when plants benefit from the CO_2 produced when fossil fuels are burned.

Fossil fuels save land for wildlife because of their exceptional power density, a concept explained in Chapter 3, Section 3.4.1. A natural gas well is nearly 50 times more power-dense than a wind turbine, more than 100 times as dense as a biomass-fueled power plant and 1,000 times as dense as corn ethanol (Bryce, 2010, p. 93). Coal has an energy density 50% to 75% that of oil, still far superior to solar, wind, and biofuels (Layton, 2008; Smil, 2010).

Power density benefits the environment because "energy sources with high power densities have the least deleterious effect on open space" (Bryce 2010, p. 92). Bryce estimates replacing U.S. coal-fired generation capacity in 2011 (300 gigawatts) with wind turbines at 1 watt per square meter would have required 300 billion square meters, or roughly 116,000 square miles (Bryce, 2014, pp. 217–218). Driessen (2017), using a number of conservative assumptions, estimated using windmills to produce the same amount of energy as is currently produced globally by fossil fuels would require 14.4 million onshore turbines requiring some 570 million acres (890,625 square miles), an area equal to 25% of the entire land area of the United States (30% of the lower 48 states).

Smil (2016) conducted a detailed tally of the land used by different energy systems around the world. He estimated that in 2010, new renewable energy sources (solar PV, wind, and liquid biofuels) required 270,000 km^2 of land to produce just 130 GW of power. Fossil fuels, thermal, and hydroelectricity generation claimed roughly 230,000 km^2 of land to deliver 14.34 TW of power, *110 times as much power on approximately 15% less land.* Fossil fuels, thermal, and hydropower required less than 0.2% of the Earth's ice-free land and nearly half that was surface area covered by water for reservoirs (pp. 211–212).

A study of the use of biofuels to replace fossil fuels conducted by the UK's Energy Research Centre and published in 2011 found that replacing half of current global primary energy supply with biofuels would require an area ranging from twice to ten times the size of France. Replacing the entire current global energy supply would require …

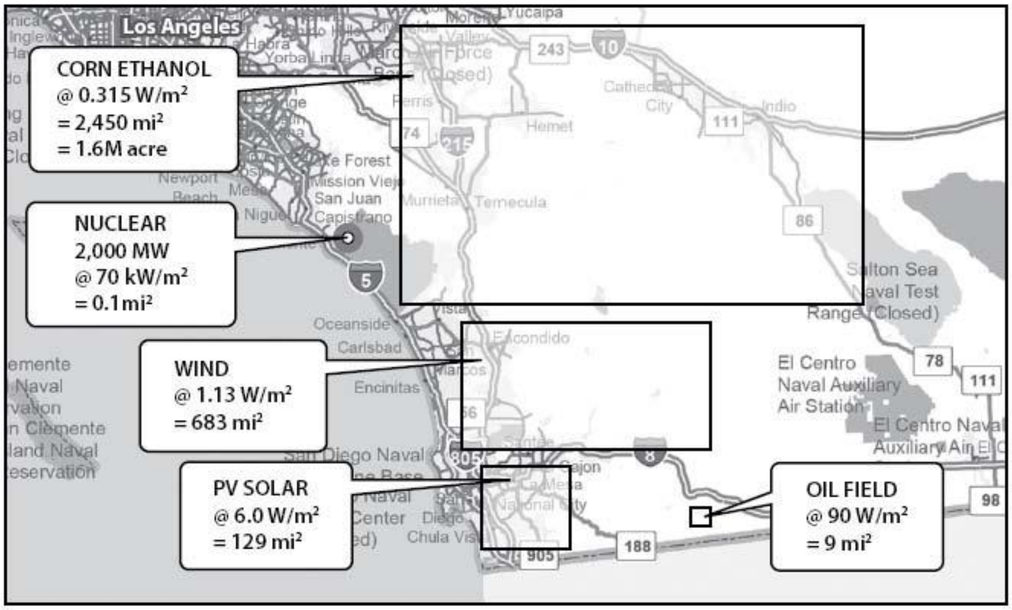
> an area of high yielding agricultural land the size of China. … In addition these estimates assume that an area of grassland and marginal land larger than India (>0.5Gha) is converted to energy crops. The area of land allocated to energy crops could occupy over 10% of the world's land mass, equivalent to the existing global area used to grow arable crops. For most of the estimates in this band a high meat diet could only be accommodated with extensive deforestation (Slade *et al.*, 2011, p. vii).

Kiefer (2013) calculated that replacing the energy used by the United States each year just for transportation "would require more than 700 million acres of corn. This is 37% of the total area of the continental United States, more than all 565 million acres of forest and more than triple the current amount of annually harvested cropland. Soy biodiesel would require 3.2 billion acres – one billion more than all U.S. territory including Alaska" (*Ibid.*). The figure Kiefer used to illustrate the difference power density makes in the amount of land required to produce 2,000 MW appears in Figure 5.2.2.1.

If any energy source other than fossil fuels (or nuclear) had been used to fuel the enormous growth in human population and prosperity in the twentieth century, the ecological consequences would have been disastrous. Wildlife would have been crowded out to make way for millions of windmills or millions of square miles of corn or soy planted to fuel cars, trucks, ships, and airplanes.

The second way fossil fuels save land for wildlife is by making possible the Green Revolution described in Chapter 3, Section 3.3.1. The discovery in 1909 of a process by which natural gas and atmospheric nitrogen could be converted into ammonia, now widely used as fertilizer, was only one of many technological innovations that improved farm productivity. Recall that Goklany (2009), in the

Figure 5.2.2.1
Area required by different fuels to produce 2,000 MW of power



Source: Kiefer, 2013, p. 131.

T-factor analysis described in the previous section, applied his formula to cropland in the United States. He found a T-factor of 0.05 in 2006 relative to 1910, meaning technology reduced the impact of increases in population and affluence on the amount of cropland used by 95% since 1910. In other words, advances in technology alone erased all but 5% of the effect of population growth and increased affluence. Farmers in the United States were able to feed a growing and increasingly affluent population without significantly increasing the amount of land they needed

Savage (2011) estimated in 2011 that using organic farming methods to produce the 2008 U.S. yield of all crops would have required an additional 121.7 million acres of cropland, 39% more than was actually in production that year. That cropland "would be the equivalent of all the current cropland acres in Iowa, Illinois, North Dakota, Florida, Kansas, and Minnesota combined" (*Ibid.*). While not all of the superior yield of non-organic crops is due to ammonia fertilizers, much of it is and most of the pesticides and herbicides that explain the remainder of the high yield are produced from petroleum and natural gas.

Ausubel, Wernick, and Waggoner calculated the land spared in India thanks to the Green Revolution just for growing one crop, wheat, was 65 MHa (million hectares), "an area the size of France or four Iowas" (Ausubel *et al*., 2013). Their graph showing how "the land sparing continued into the twentieth century" appears below as Figure 5.2.2.2. Similarly, they report the amount of land devoted to growing corn in China doubled from 1960 to 2010 while each harvested hectare became four-and-a-half times more productive, sparing some 120 MHa.

Ausubel and his coauthors propose a formula similar to the IPAT formula described in Section 5.2.1 to predict how many acres of land must be taken for crop production:

$$\boldsymbol{im} = \textbf{Impact} = \mathbf{P \times A \times C_1 \times C_2 \times T}$$

where

im = cropland (in hectares) taken
P = population (persons)
A = affluence (in GDP per capita)
C_1 = dietary response to affluence (in kilocalories/GDP)
C_2 = FAO's Production Index Number/kcal)
T = Technology (hectares divided by crop PINs)

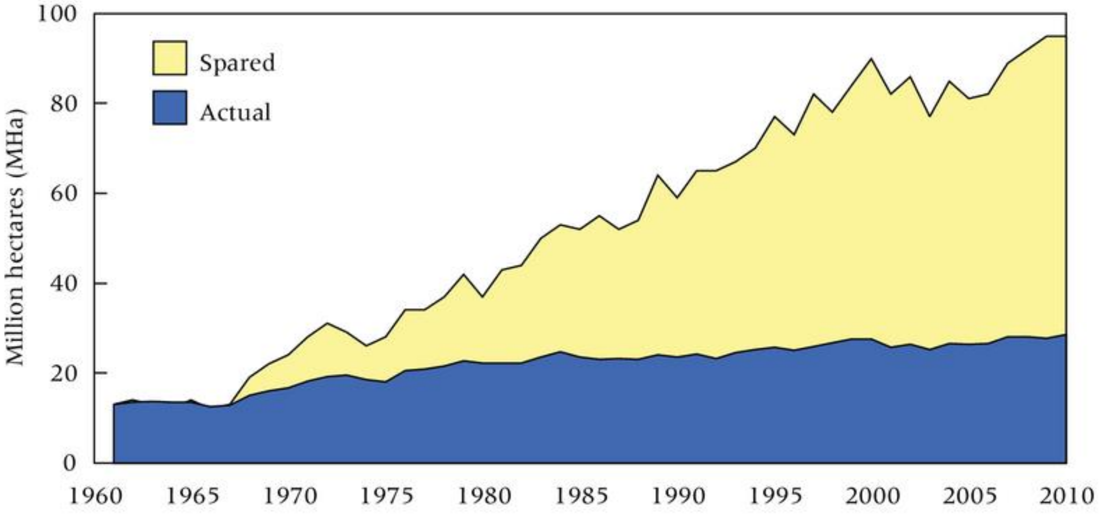
In the ImPACT formula, rising population and affluence can increase the amount of land moved from habitat or other uses and devoted to cropland, while technology reduces that shift by increasing efficiency. Changes in consumer behavior (C_1 and C_2) can either increase or decrease the need for more land under cultivation. Declining $C_{1,}$ as shown in Figure 5.2.2.3, reveals how "in country after country after calories exceed minimum levels, caloric intake rises, slows, and may eventually level off as affluence grows" (p. 226).

Ausubel and his coauthors find dematerialization of food is occurring globally and is likely to continue. In the authors' ImPACT formula, *im* = -0.02 for the period 2010 to 2060. The trend is driven partly by the tendency of people to reduce their consumption of meat relative to their income once a threshold of prosperity is reached and partly by the increasing productivity of the world's farmers, who are likely to increase crop outputs/hectare by about 2% per year. "[T]he number of hectares of cropland has barely changed since 1990," they report. Using conservative estimates of trends, they predict "by 2060, some 146 MHa of land could be restored to Nature, an area equal to one and a half times the size of Egypt, two and a half times France, or ten times Iowa" (Ausubel *et al*., 2013).

The third way fossil fuels save land for wildlife is via the aerial fertilization effect described in Chapter 3, Section 3.4 and in greater detail in Section 5.3 below. As noted by Huang *et al*. (2002), human populations "have encroached on almost all of the world's frontiers, leaving little new land that is cultivatable." And in consequence of humanity's ongoing usurpation of this most basic of natural resources, Raven (2002) noted "species-area relationships, taken worldwide in relation to habitat destruction, lead to projections of the loss of fully two-thirds of all species on Earth by the end of this century." Fortunately, humanity has a powerful ally in the ongoing rise in the atmosphere's CO_2 content resulting, research shows, from the human combustion of fossil fuels. Since CO_2 is the basic "food" of essentially all terrestrial plants, the more of it there is in the atmosphere, the bigger and better they grow. Section 5.3 summarizes extensive research in support of this finding.

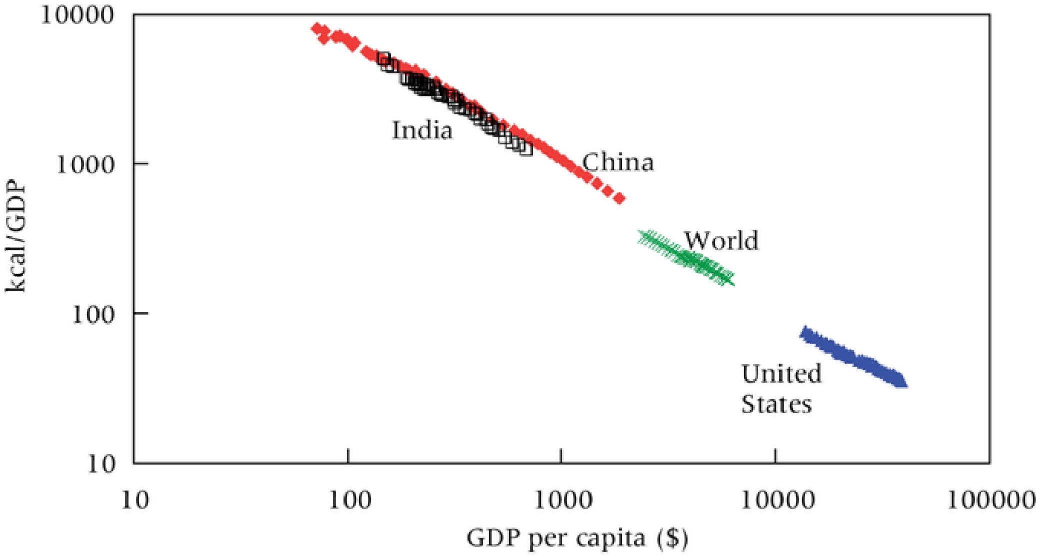
Since the start of the Industrial Revolution, it can be calculated on the basis of the work of Mayeux *et al*. (1997) and Idso and Idso (2000) that the 120 ppm increase in atmospheric CO_2 concentration increased agricultural production per unit land area by 70%

Figure 5.2.2.2
Actual and potential land used for wheat production in India, 1961–2010



Upper segment shows the hectares farmers would have tilled to produce the actual harvest had yields stayed at the 1960 level. *Source:* Ausubel *et al.*, 2013, citing FAO, 2012.

Figure 5.2.2.3
Dematerialization of food, 1961–2007



Graph shows kcal/GDP – as a function of calories consumed divided by GDP for China, India, the United States, and the world – consistently declines with rise in per-capita GDP from 1961 to 2007 over a range of incomes and cultures. *Source:* Ausubel *et al.*, 2013, Figure 6, p. 227, citing FAO, 2012 and World Bank, 2012.

for C_3 cereals, 28% for C_4 cereals, 33% for fruits and melons, 62% for legumes, 67% for root and tuber crops, and 51% for vegetables. A nominal doubling of the atmosphere's CO_2 concentration will raise the productivity of Earth's herbaceous plants by 30% to 50% (Kimball, 1983; Idso and Idso, 1994), while the productivity of its woody plants will rise by 50% to 80% (Saxe *et al*. 1998; Idso and Kimball, 2001). As the atmosphere's CO_2 content continues to rise, so too will crop yields per acre rise, meaning we will need less land to raise the food we need, giving wildlife the space it needs to live. This is a substantial and underappreciated benefit of humanity's use of fossil fuels.

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5.2.3 Prosperity

> *The prosperity made possible by fossil fuels has made environmental protection both highly valued and financially possible, producing a world that is cleaner and safer than it would have been in their absence.*

The contribution of fossil fuels to human prosperity was documented in detail in Chapter 3. While there are many claims that human prosperity fueled environmental destruction (e.g., Heinberg, 2007; NRDC, 2008), data show the opposite has been true. As Bailey (2015) writes,

> It is in rich democratic capitalist countries that the air and water are becoming cleaner, forests are expanding, food is abundant, education is universal, and women's rights respected. Whatever slows down economic

> growth also slows down environmental improvement. By vastly increasing knowledge and pursuing technological progress, past generations met their needs and vastly increased the ability of our generation to meet our needs. We should do no less for future generations (p. 72).

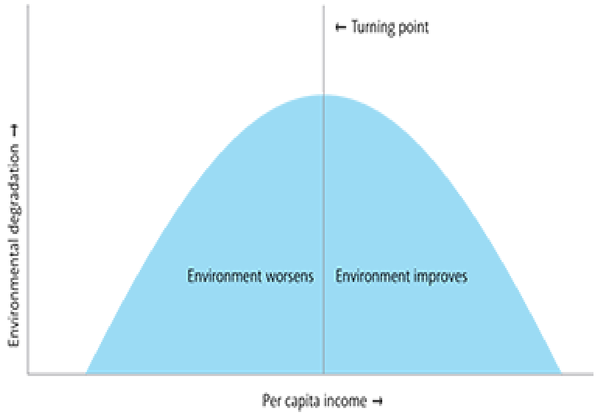
Similarly, Bryce (2014) writes,

> The pessimistic worldview ignores an undeniable truth: more people are living longer, healthier, freer, more peaceful, lives than at any time in human history. … The plain reality is that things are getting better, a lot better, for tens of millions of people all around the world. Dozens of factors can be cited for the improving conditions of humankind. But the simplest explanation is that innovation is allowing us to do more with less. We are continually making things and processes Smaller Faster Lighter Denser Cheaper (pp. xxi–xxii).

As fossil fuels create global prosperity, more care is taken to protect the environment and more humans are protected from air and water pollution, food contaminated with bacteria or toxic substances, contagious diseases, and accidental death from floods and other natural risks (Ausubel, 1996; Avery, 2000; Goklany, 2007; Epstein, 2014; Moore and Hartnett White, 2016). Fossil fuels may contribute to rising levels of air and water pollution in the early stages of a society's economic growth, but even during the worst period those risks pale compared to the risks of life without fossil fuels described by Goklany and other historians in Chapter 3. Over time, those same fuels make it possible to *clean* air and water of both manmade and natural pollutants, leading to a cleaner and safer environment, demonstrated by the Environmental Kuznets Curves (EKCs) described in Chapter 1, Section 1.3.3 and reproduced here as Figure 5.2.3.1 and by government data on air quality in the United States reported in Chapter 6.

Developed countries and even many developing countries are on the downward slope of the right side of EKCs as measured by emissions of pollutants that pose potential threats to human health. The trend toward a cleaner and safer world has been documented by many of the scholars previously cited in this chapter, but see specifically Julian Simon (1980, 1982, 1995, 1996); Julian Simon and Herman Kahn (1984); Vaclav Smil (2005, 2006); and Indur Goklany (2007, 2012). More recent academic studies documenting EKCs for carbon dioxide emissions include Shahbaz *et al.* (2012), Tiwari *et al.* (2013), Osabuohien *et al.* (2014), Apergis and Ozturk (2015), and Sarkodie (2018).

Figure 5.2.3.1
A typical Environmental Kuznets Curve



Source: Ho and Wang, 2015, p. 42.

Between 1970 and 2017, for example, U.S. emissions of six air pollutants (particulates, ozone, lead, carbon monoxide, nitrous oxide, and sulfur dioxide) declined by 73%. Those reductions occurred even as U.S. gross domestic product (GDP) grew 262%, energy consumption rose 44%, miles traveled rose 189%, and the nation's population increased 59% (EPA, 2018). The graphic used by the U.S. Environmental Protection Agency (EPA) to illustrate these trends is reproduced as Figure 5.2.3.2 below.

Steven Hayward, currently a fellow in law and economics at the American Enterprise Institute, began producing with various coauthors an annual "Index of Environmental Indicators" in 1994 reporting the latest data on environmental quality in the United States and worldwide. In 2011, observing that much of the data his team was reporting was now available online, he replaced the annual index with an "Almanac of Environmental Trends," a website that could be frequently updated. In the first (and only) print edition of Hayward's almanac (Hayward, 2011), he summarized progress on air quality in the United States as follows:

- "The improvement in air quality is the greatest public policy success story of the last generation."
- "Virtually the entire nation has achieved clean air standards for four of the six main pollutants regulated under the Clean Air Act. The exceptions are ozone and particulates."
- "In the cases of ozone and particulates, the areas of the nation with the highest pollution levels have shown the greatest magnitude of improvement."
- "The chief factor in the reduction of air pollution has been technology. Regulations played a prominent role in some innovations, but many were the result of market forces and economic growth."
- "The long-term trend of improving air quality is sure to continue."

Concerning water quality, Hayward presented the following summary:

> Although water quality has improved substantially over the past 40 years, the federal government lacks good nationwide monitoring programs for assessing many basic water quality issues. Partly, this is due to the complexity and diversity of water pollution problems, which make a uniform national program methodologically difficult. Partial datasets and snapshots of particular areas provide a sense of where the main challenges remain.
>
> Total water use in the United States has been flat for the last 30 years, even as population, food production, and the economy have continued to grow. In general the U.S. has improved water use efficiency by about 30% over the last 35 years.

On "toxic chemicals and other environmental health risks," Hayward reported:

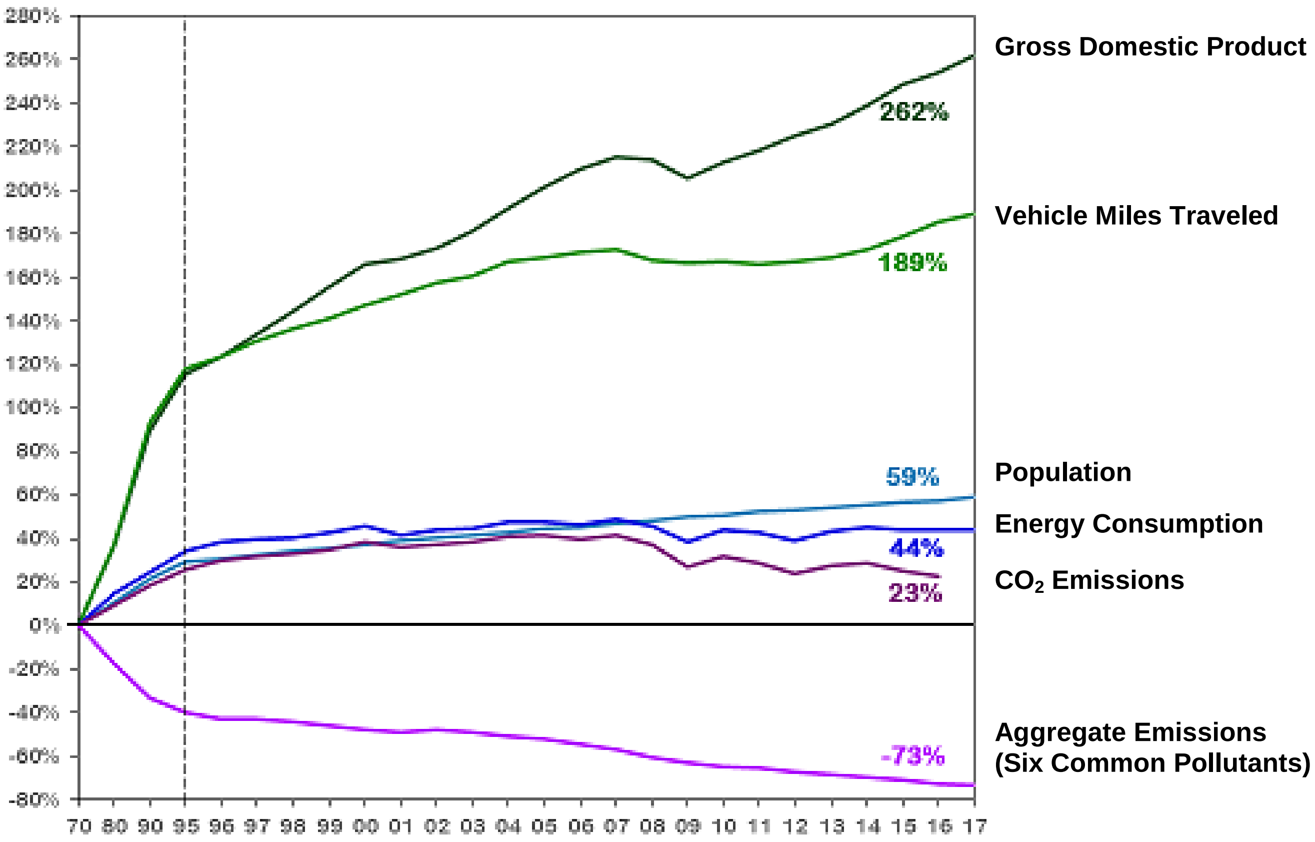
- "The total amount of toxic chemicals used in American industry is steadily declining – a measure of resource efficiency."
- "Hazardous waste is declining. After a slow start, human exposure to toxic chemicals at Superfund sites has declined by more than 50% over the last decade."
- "Levels of most heavy metals and synthetic chemicals in human blood, tissue, and urine samples are either very low or declining."
- "Dioxin compounds in the environment have declined more than 90% over the last two decades."
- "After rising steadily for several decades, cancer rates peaked in the early 1990s and have been declining."

Hayward attributes this remarkable improvement in environmental quality mainly to technology and markets, not to government regulations. He writes,

> The chief drivers of environmental improvement are economic growth, constantly increasing resource efficiency, technological innovation in pollution control, and the deepening of environmental values among the American public that have translated to changed behavior and consumer preferences. Government regulation has played a vital role, to be sure, but in the grand scheme of things regulation can be understood as a lagging indicator, often achieving results at needlessly high cost, and sometimes failing completely (p. 2).

While the environmental record of the United States stands out even among developed countries for its successes, the story is similar if not the same in all but communist and formerly communist countries. There is little doubt but that the prosperity made possible by fossil fuels has made environmental protection both highly valued and financially possible, producing a world that is cleaner and safer than it would have been in their absence.

Figure 5.2.3.2
Trends in prosperity vs. emissions of CO_2 and pollutants in the United States, 1970–2017.



Source: EPA, 2018.

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5.3 Impact on Plants

A major environmental benefit produced by the combustion of fossil fuels is an entirely unintended consequence: the beneficial effects on plant life of elevated levels of carbon dioxide (CO_2) in the atmosphere. As reported in Chapter 2, long-term studies confirm the findings of shorter-term experiments, demonstrating numerous growth-enhancing, water-conserving, and stress-alleviating effects of elevated atmospheric CO_2 on plants growing in both terrestrial and aquatic ecosystems.

At locations across the planet, the increase in the atmosphere's CO_2 concentration has stimulated vegetative productivity in spite of many real and imagined assaults on Earth's vegetation, including fires, disease, pest outbreaks, deforestation, and climatic change. Farmers and others who depend on rural livelihoods for income are benefitting from the consequent rising agricultural productivity throughout the world, including in Africa and Asia where the need for increased food supplies is most critical.

This section presents a literature review of the effects of rising CO_2 levels on ecosystems, then plants under stress and plant water use efficiency. The final section looks at the future impacts of higher CO_2 levels on plants, including effects on food production, biodiversity, and extinction rates. The studies summarized here are nearly all based on observational data – real-world experiments and field research – and not computer models, which often are programmed to predict negative effects.

5.3.1 Introduction

As early as 1804, de Saussure showed that peas exposed to high CO_2 concentrations grew better than control plants in ambient air. Work conducted in the early 1900s significantly increased the number of species in which a growth-enhancing effect of atmospheric CO_2 enrichment was observed to occur (Demoussy, 1902–1904; Cummings and Jones, 1918). By the time a group of scientists convened at Duke University in 1977 for a workshop on Anticipated Plant Responses to Global Carbon Dioxide Enrichment, an annotated bibliography of

590 scientific studies dealing with CO_2 effects on vegetation had been prepared (Strain, 1978). This body of research demonstrated increased levels of atmospheric CO_2 generally produce increases in plant photosynthesis, decreases in plant water loss by transpiration, increases in leaf area, and increases in plant branch and fruit numbers, to name but a few of the most commonly reported benefits.

Five years later, at the International Conference on Rising Atmospheric Carbon Dioxide and Plant Productivity, it was concluded a doubling of the atmosphere's CO_2 concentration likely would lead to a 50% increase in photosynthesis in C_3 plants, a doubling of water use efficiency in both C_3 and C_4 plants, significant increases in nitrogen fixation in almost all biological systems and an increase in the ability of plants to adapt to a variety of environmental stresses (Lemon, 1983). In the years since, many other studies have been conducted on hundreds of plant species, repeatedly confirming the growth-enhancing, water-saving, and stress-alleviating advantages of elevated atmospheric CO_2 concentrations on Earth's plants and soils (Idso and Idso, 2011).

The sections below update the literature review conducted for Chapter 1 of the previous volume in the *Climate Change Reconsidered* series titled *Biological Impacts* (NIPCC, 2014). The key findings of that chapter are presented in Figure 5.3.1.1. That report also included two appendices with tables summarizing more than 5,500 individual plant photosynthetic and biomass responses to CO_2-enriched air reported in the scientific literature, finding nearly all plants experience increases in these two parameters at higher levels of CO_2.

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Figure 5.3.1.1
Key findings: CO_2, plants, and soils

- Results obtained under 3,586 separate sets of experimental conditions conducted on 549 plant species reveal nearly all plants experience increases in dry weight or biomass in response to atmospheric CO_2 enrichment. Additional results obtained under 2,094 separate experimental conditions conducted on 472 plant species reveal nearly all plants experience increases in their rates of photosynthesis in response to atmospheric CO_2 enrichment.
- Long-term CO_2 enrichment studies confirm the findings of shorter-term experiments, demonstrating that the growth-enhancing, water-conserving, and stress-alleviating effects of elevated atmospheric CO_2 likely persist throughout plant lifetimes.
- Forest productivity and growth rates throughout the world have increased gradually since the Industrial Revolution in concert with and in response to the historical increase in the atmosphere's CO_2 concentration. Therefore, as the atmosphere's CO_2 concentration continues to rise, forests will likely respond by exhibiting significant increases in biomass production and they likely will grow more robustly and significantly expand their ranges.

- Modest increases in air temperature tend to increase carbon storage in forests and their soils. Thus, old-growth forests can be significant carbon sinks and their capacity to sequester carbon in the future will be enhanced as the atmosphere's CO_2 content continues to rise.
- As the atmosphere's CO_2 concentration increases, the productivity of grassland species will increase even under unfavorable growing conditions characterized by less-than-adequate soil moisture, inadequate soil nutrition, elevated air temperature, and physical stress imposed by herbivory.
- The thawing of permafrost caused by increases in air temperature will likely not transform peatlands from carbon sinks to carbon sources. Instead, rapid terrestrialization likely will act to intensify carbon-sink conditions.
- Rising atmospheric CO_2 concentrations likely will enhance the productivity and carbon sequestering ability of Earth's wetlands. In addition, elevated CO_2 may help some coastal wetlands counterbalance the negative impacts of rising seas.
- Rising atmospheric CO_2 concentrations likely will allow greater numbers of beneficial bacteria (that help sequester carbon and nitrogen) to exist within soils and anaerobic water environments, thereby benefitting both terrestrial and aquatic ecosystems.
- The aerial fertilization effect of atmospheric CO_2 enrichment likely will result in greater soil carbon stores due to increased carbon input to soils, even in nutrient-poor soils and in spite of predicted increases in temperature. The carbon-sequestering capability of Earth's vegetation likely will act as a brake on the rate-of-rise of the atmosphere's CO_2 content and thereby help to mute the effects of human CO_2 emissions on global temperatures.
- The historical increase in the atmosphere's CO_2 content has significantly reduced the erosion of valuable topsoil over the past several decades; the continuing increase in atmospheric CO_2 can maintain this trend and perhaps even accelerate it for the foreseeable future.

Source: Chapter 1. "CO_2, Plants, and Soils." *Climate Change Reconsidered II: Biological Impacts.* Nongovernmental International Panel on Climate Change (NIPCC). Chicago, IL: The Heartland Institute, 2014.

5.3.2 Ecosystem Effects

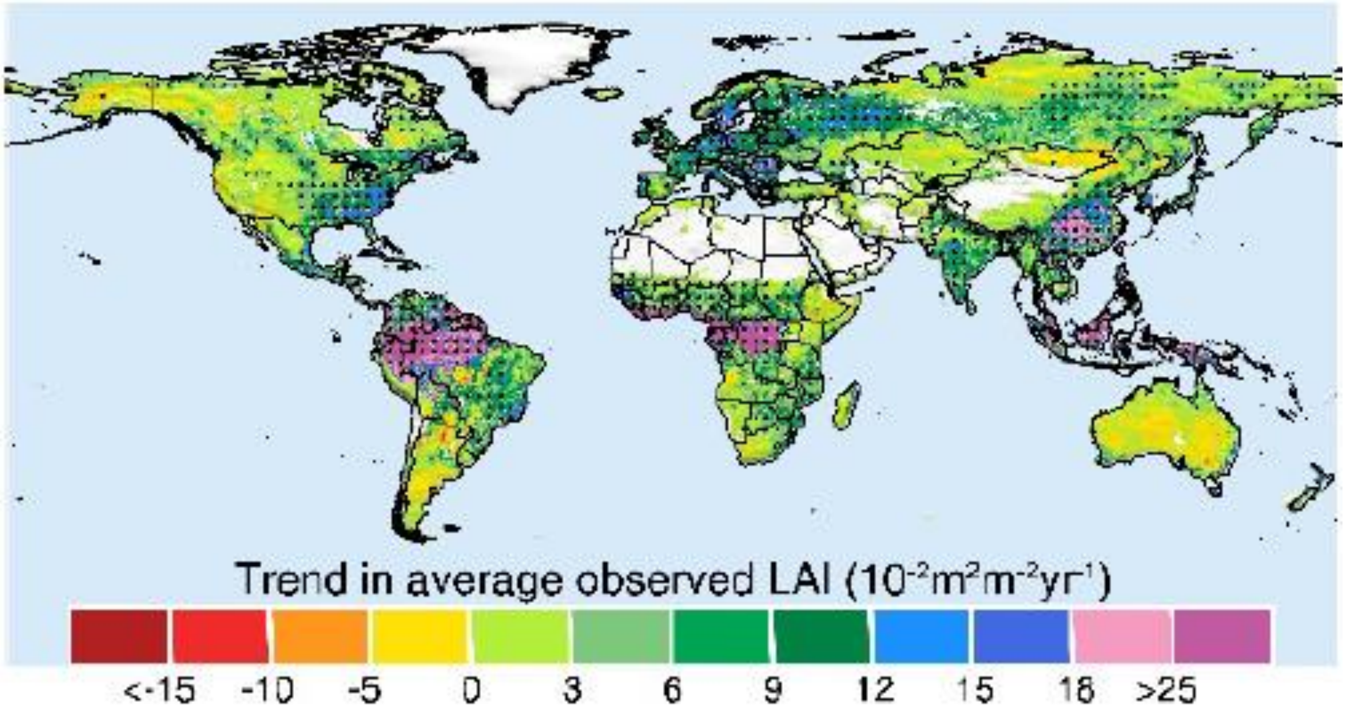
Elevated CO_2 improves the productivity of ecosystems both in plant tissues aboveground and in the soils beneath them.

Zhu *et al.* (2016), in an article in *Nature Climate Change* titled "Greening of the Earth and its drivers," discussed global changes in leaf area index (LAI) associated with increasing atmospheric CO_2 concentrations. They reported,

> We show a persistent and widespread increase of growing season integrated LAI (greening) [from 1982 to 2009] over 25% to 50% of the global vegetated area, whereas less than 4% of the globe shows decreasing LAI (browning). Factorial simulations with multiple global ecosystem models suggest that CO_2 fertilization effects explain 70% of the observed greening trend, followed by nitrogen deposition (9%), climate change (8%) and land cover change (LCC) (4%).

Zhu *et al.* illustrated their findings with the figure reproduced as Figure 5.3.2.1 below. Similarly, Li *et al*. (2017) studied 2,196 globally distributed databases containing observations of net primary production (NPP) – the net carbon that is fixed (sequestered) by a given plant community or ecosystem – as well as five environmental variables thought to most impact NPP trends (precipitation, air temperature, leaf area index, fraction of photosynthetically active radiation, and atmospheric CO_2 concentration). They analyzed the spatiotemporal patterns of global NPP over the past half century (1961–2010) and found global NPP increased significantly, from 54.95 Pg C yr^{-1} in 1961 to 66.75 Pg C yr^{-1} in 2010, representing a linear increase of 21.5% over the period. They report,

Figure 5.3.2.1
Greening of the Earth, 1982 to 2009, trend in average observed leaf area index (LAI)



Source: Zhu *et al.,* 2016.

"atmospheric CO_2 concentration was found to be the dominant factor that controlled the interannual variability and to be the major contribution (45.3%) of global NPP." Leaf area index was the second most important factor, contributing an additional 21.8%, followed by climate change (precipitation and air temperature together) and the fraction of photosynthetically active radiation, which accounted for the remaining 18.3% and 14.6% increase in NPP, respectively.

Cheng *et al*. (2017) present similar findings with respect to global terrestrial carbon uptake (i.e., gross primary production, or GPP). Using a combination of ground-based and remotely sensed land and atmospheric observations, they estimated changes in global GPP, water use efficiency (WUE), and evapotranspiration (E) over the period 1982–2011. They estimate global GPP has increased by 0.83 ± 0.26 Pg C per year, or a total of 24.9 Pg C over the past three decades. They also report 82% of the global vegetated land area shows positive trends in GPP despite "the large-scale occurrence of droughts and disturbances over the study period." Similarly, ecosystem WUE was found to increase in 90% of the world's vegetative areas and there was a high correlation between the spatial trends in these two parameters.

According to Cheng *et al.*, global WUE "increased at a mean rate of 13.7 ± 4.3 mg C mm^{-1} H_2O per year from 1982 to 2011 ($p < 0.001$), which is about 0.7 ± 0.2% per year of mean annual WUE." Global E experienced a non-significant very small increase of 0.06 ± 0.13% per year. Thus, both WUE and E were found to "positively contribute to the estimated increase in GPP," though the contribution from WUE accounted for 90% of the total GPP trend. Cheng *et al*. conclude the "estimated increase in global GPP under climate change and rising atmospheric CO_2 conditions over the past 30 years is taking place at no cost of using proportionally more water, but it is largely driven by the increase in carbon uptake per unit of water use, i.e. WUE."

Cheng *et al*. conclude their results show "terrestrial GPP has increased significantly and is primarily associated with [an] increase in WUE, which in turn is largely driven by rising atmospheric

CO_2 concentrations and [an] increase in leaf area index." They add, "the most important driver for the increases in GPP and WUE from 1982 to 2011 is rising atmospheric CO_2," noting a 10% increase in atmospheric CO_2 induces an approximate 8% increase in global GPP and a 14% increase in global WUE.

Numerous studies have focused on the impact of elevated CO_2 or surface temperature increases on specific ecosystems. We can begin this literature review in the alpine regions of Switzerland, where Rammig *et al.* (2010) monitored climatic conditions and plant growth for nearly a decade at 17 snow meteorological stations in the region. They used their empirical research to project what plant growth would be if the onset of springtime growth were to begin 17 days earlier, as predicted by the gridded output of a set of regional climate models.

Rammig *et al.* found "plant height and biomass production were expected to increase by 77% and 45%, respectively," evidence of a dramatic benefit from warming. In some cases "projections of biomass production over a season resulted in changes of up to two-fold." Thus, future warming, if it occurs, would likely benefit plants located in areas like the Alps, where low temperatures, snow cover, and permafrost now limit their ability to grow to their full potential.

Similarly, Kullman (2010a) monitored subalpine/alpine vegetation in the Swedish Scandes (Scandinavian Mountains), deriving "tentative projections of landscape transformations in a potentially warmer future" based on "actual observations and paleoecological data (Kullman and Kjallgren, 2006; Kullman 2006)." He notes post-Little Ice Age warming has halted "a multi-millennial trend of plant cover retrogression" and "floristic and faunal impoverishment, all imposed by progressive and deterministic neoglacial climate cooling." He reports the "upper range margin rise of trees and low-altitude (boreal) plant species, expansion of alpine grasslands and dwarf-shrub heaths are the modal biotic adjustments during the past few decades, after a century of substantial climate warming." He writes, "alpine plant life is proliferating, biodiversity is on the rise and the mountain world appears more productive and inviting than ever." In contrast to model predictions, he notes, "no single alpine plant species has become extinct, neither in Scandinavia nor in any other part of the world in response to climate warming over the past century," citing, in addition to his own studies, the work of Pauli *et al*. (2001, 2007), Theurillat and Guisan (2001), and Birks (2008).

Kullman concludes, "continued modest warming over the present century will likely be beneficial to alpine biodiversity, geological stability, resilience, sustainable reindeer husbandry and aesthetic landscape qualities."

In a second 2010 publication on the status of alpine communities in the Swedish Scandes, Kullman (2010b) notes in a modestly warming world "plant species diversity will further increase, both in remaining treeless alpine areas and emerging forest outliers on the former alpine tundra," and that this "new alpine landscape may come to support a previously unseen mosaic of richly flowering and luxuriant plant communities of early Holocene character," citing the works of Smith (1920), Iversen (1973), and Birks (2008).

Kullman explains "many alpine species are extremely tolerant of high temperatures *per se*," citing Dahl (1998) and Birks (2008), as indicated "by their prospering and spread along roadsides far below the treeline, where emerging trees and shrubs are regularly mechanically exterminated (Kullman, 2006; Westerstrom, 2008)." And he notes "another argument against the much-discussed option of pending mass-extinction of alpine species in a warmer future is that some alpine and arctic plant species contain a variety of ecotypes, pre-adapted to quite variable microclimatic and edaphic conditions, which could buffer against extinction in a possibly warmer future (Crawford, 2008)." In addition, he writes this view is supported "by the fact that in the early Holocene, alpine plants survived, reproduced and spread in accordance with higher and more rapidly rising temperatures than those projected for the future by climate models (Oldfield, 2005; Birks, 2008)."

"Over all," Kullman concludes, "continued warming throughout the present century would be potentially and predominantly advantageous for alpine flora and vegetation."

Capers and Stone (2011) "studied a community in western Maine, comparing the frequency and abundance of alpine plants in 2009 with frequency and abundance recorded in 1976" by Stone (1980). The 2009 survey, they write, "recorded an increase in total species richness of the community with the addition of four lower montane species that had not been recorded previously." They also "found no evidence that species with high-arctic distributions had declined more than other species." The changes they recorded are, they write, "consistent with those reported in tundra communities around the world."

Two teams of researchers looked at the possible impact on arid landscapes of more periods of drought or heavy rainfall, which some computer models forecast will accompany warming surface temperatures. D'Odorico and Bhattachan (2012) note "dryland ecosystems are particularly affected by relatively intense hydroclimatic fluctuations," citing Reynolds *et al*. (2007), and they say "there is some concern that the interannual variability of precipitation in dryland regions might increase in the future thereby enhancing the occurrence of severe water stress conditions in ecosystems and societies." To explore this concern further, D'Odorico and Bhattachan studied "some of the current patterns of hydrologic variability in drylands around the world," reviewing "the major effects of hydrologic fluctuations on ecosystem resilience, maintenance of biodiversity and food security." They report the preponderance of the investigations they reviewed indicated random hydrologic fluctuations may in fact *enhance* the resilience of dryland ecosystems by eliminating threshold-like responses to external drivers. They conclude dryland ecosystem resilience is "enhanced by environmental variability through the maintenance of relatively high levels of biodiversity, which may allow dryland ecosystems to recover after severe disturbances, including those induced by extreme hydroclimatic events."

Also considering what to expect in a CO_2-enriched and warmer world in which precipitation could be more variable, Salguero-Gomez *et al.* (2012) write, "a far-too-often overlooked fact is that desert flora have evolved a set of unique structures and mechanisms to withstand extensive periods of drought," among which are "succulence (Smith *et al*., 1997), deep roots (Canadell *et al*., 1996), modified metabolic pathways (Dodd *et al*., 2002), high modularity (Schenk *et al*., 2008) and bet hedging mechanisms such as seed dormancy (Angert *et al*., 2010) or extreme longevity (Bowers *et al*., 1995)."

Salguero-Gomez *et al*. examined the effects of precipitation on populations of two desert plant species, coupling "robust climatic projections, including variable precipitation, with stochastic, stage-structured models constructed from long-term demographic data sets of the short-lived *Cryptantha flava* in the Colorado Plateau Desert (USA) and the annual *Carrichtera annua* in the Negev Desert (Israel)." They found "a surprising pattern of increased population growth for both study species when [they] compared population dynamics in the future to current conditions, consistent with increasing precipitation in Utah, USA and despite decreasing precipitation in Israel."

Salguero-Gomez *et al*. say their study "contributes two notable exceptions to the accepted view that short-lived species, regardless of habitat, are particularly vulnerable to climate change," emphasizing their findings "challenge the commonly held perception based on correlative approaches (e.g. bioclimatic envelope approaches) suggesting that desert organisms may be particularly vulnerable to climate change."

Polley *et al.* (2012) "grew communities of perennial forb and C_4 grass species for five years along a field CO_2 gradient (250–500 ppm) in central Texas (USA) on each of three soil types, including upland and lowland clay soils and a sandy soil." They measured a number of plant physiological properties, processes and ecosystem aboveground net primary productivity (ANPP). They found CO_2 enrichment from 280 to 480 ppm "increased community ANPP by 0–117% among years and soils and increased the contribution of the tallgrass species *Sorghastrum nutans* (Indian grass) to community ANPP on each of the three soil types," noting the "CO_2-induced changes in ANPP and *Sorghastrum* abundance were linked." They report, "by favoring a mesic C_4 tall grass, CO_2 enrichment approximately doubled the initial enhancement of community ANPP on two clay soils." As a result, they conclude "CO_2-stimulation of grassland productivity may be significantly underestimated if feedbacks from plant community change are not considered."

Kullman (2014) analyzed plant species richness on several alpine summits in the southern Swedish Scandes between 2004/2006 and 2012, which "experienced consistent summer and winter cooling and finalized with a cold and snow rich summer 2012." He reports "plant species richness on high alpine summits decreased by 25–46% between 2004/2006 and 2012" and "most of the lost species have their main distribution in subalpine forest and the low-alpine region." He also noted they "advanced upslope and colonized the summit areas in response to warmer climate between the 1950s and early 2000s." He noted "despite the reduction in species numbers, the summit floras are still richer than in the 1950s," and "substantial and consistent climate cooling (summer and winter) during a decade preceded the recent floristic demise." He concludes, "taken together," the findings "highlight a large capability of certain alpine plant species to track their ecological niches as climate fluctuates on annual to decadal scales."

In 1985, Bert Drake, a scientist at the Smithsonian Environmental Research Center in

Edgewater, Maryland, chose a Chesapeake Bay wetland sustaining both pure and mixed stands of the C_4 grass *Spartina patens* and the C_3 sedge *Scirpus olneyi* for an open-top chamber study of the effects of full-day (24-hour) atmospheric CO_2 enrichment to 340 ppm above the then-ambient concentration of the same value. In a paper published 28 years later in *Global Change Biology*, Drake (2014) summarized some of the important findings of this undertaking. The Chesapeake Bay study offers "strong evidence that shoot and root biomass and net ecosystem production increased significantly." He infers – from the fact that methane emission (Dacey *et al*., 1994) and nitrogen fixation (Dakora and Drake, 2000) were also stimulated by elevated CO_2 and that inputs of soil carbon also increased – that "ecosystems will accumulate additional carbon as atmospheric CO_2 continues to rise, as suggested by Luo *et al*. (2006)."

Drake also writes that the long duration of the Chesapeake Bay wetland study allows for a test of "the idea that some process, such as progressive nitrogen limitation, may constrain ecosystem responses to elevated CO_2 in native ecosystems." His findings, as well as those of Norby *et al*. (2005) and Norby and Zak (2011), imply, as he notes, that quite to the contrary, Earth's ecosystems will continue to accumulate carbon as the atmosphere's CO_2 content continues to rise.

Ruzicka *et al.* (2015) studied talus slopes (the pile of rocks that accumulates at the base of a cliff, chute, or slope) "inhabited by isolated populations of boreal and alpine plants and invertebrates," citing previous research on the subject by Ruzicka (2011), Ruzicka *et al.* (2012), and Nekola (1999). They measured, over a period of five years, air temperatures of low-elevation talus slopes at three locations in the North Bohemia region of the Czech Republic. They found "the talus microclimate can be sufficiently resistant to an increase of mean annual atmospheric temperature by 3°C, retaining a sufficient number of freezing days during the winter season." They conclude, "based on our data, we can justifiably suppose that even such an extent of warming in the future (an increase of mean annual atmospheric temperature by 3°C) will not endanger the cold talus ecosystems."

In 1997, two field sites were established in alpine meadows at the Haibei Research Station in Haibei, Quinghai, China. Control and experimental plots were established to examine the impact of simulated warming (1–2°C above control plots) on plant species diversity. After four years of warming, it was determined that warm plots lost an average of 11 to 19 species (~40%) relative to control plots (Klein, 2003; Klein *et al*., 2004). In more recent work, Zhang *et al*. (2017) contend a four-year period is "too short to detect the role colonization and re-establishment may play in community re-assembly," as such processes are known to take place over decades and not years.

Zhang *et al.* resampled the plots after 18 years of simulated warming, in order to see if the shorter-term findings were indeed premature. They found the initial warming-induced decline in species diversity "had rebounded to initial levels, on a par with control plots," concluding, "the long-term impacts of continued global warming are [likely] to result in highly dynamic processes of community reassembly and turnover that do not necessarily lead to a net decline in local diversity," adding that "short-term experiments may be insufficient to capture the temporal variability in community diversity and composition in response to climate change."

O'Leary *et al*. (2017) surveyed publications of 97 expert researchers who had studied six major types of coastal biogenic ecosystems in order to identify "bright spots of resilience" in the face of climate change. They report 80% of the researchers found resilience in the ecosystems they studied, with resilience "observed in all ecosystem types and at multiple locations worldwide." They conclude these findings suggest "coastal ecosystems may still hold great potential to persist in the face of climate change and that local- to regional-scale management can help buffer global climatic impacts."

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5.3.3 Plants under Stress

> *Atmospheric CO_2 enrichment ameliorates the negative effects of a number of environmental plant stresses including high temperatures, air and soil pollutants, herbivory, nitrogen deprivation, and high levels of soil salinity.*

According to the IPCC, a warmer future will introduce new sources of stress on the biological world, including increases in forest fires, droughts, and extreme heat events. The IPCC fails to ask whether the higher levels of atmospheric CO_2 its models also predict will aid or hinder the ability of plants to cope with these challenges. Had it looked, the IPCC would have discovered an extensive body of research showing how atmospheric CO_2 enrichment ameliorates the negative effects of a number of environmental plant stresses. For example, increased ambient CO_2 improves water use efficiency (discussed in detail in Section 5.3.4) of plants by allowing more CO_2 to enter the photosynthetic tissue per unit of time, thereby enhancing the rate of photosynthesis (carboxylation) while water loss is kept at a constant level or even reduced as plants' stomata are open for less time. This well-documented biological process is absent from many computer models that assume climate change has negative effects on agriculture.

This section updates the literature review that appeared in Chapter 3 of *Climate Change Reconsidered II: Biological Impacts* (NIPCC, 2014). The key findings of the previous report appear in Figure 5.3.3.1.

Koutavas (2013) studied tree growth rings to investigate potential growth-climate relationships, developing growth indices from cores extracted from 23 living Greek fir (*Aibes cephalonica*) trees for the period AD 1820–2007. He reports the growth of the trees historically has been "limited by growing-

Figure 5.3.3.1
Key Findings: Impacts on plants under stress

- Atmospheric CO_2 enrichment (henceforth referred to as "rising CO_2") exerts a greater positive influence on diseased as opposed to healthy plants because it significantly ameliorates the negative effects of stresses imposed on plants by pathogenic invaders.
- Rising CO_2 helps many plants use water more efficiently, helping them overcome stressful conditions imposed by drought or other less-than-optimum soil moisture conditions.
- Enhanced rates of plant photosynthesis and biomass production from rising CO_2 will not be diminished by any surface temperature increase that might accompany it in the future. In fact, if ambient air temperatures rise concurrently, the growth-promoting effects of atmospheric CO_2 enrichment will likely rise even more.
- Although rising CO_2 increases the growth of many weeds, the fraction helped is not as large as that experienced by non-weeds. Thus, CO_2 enrichment of the air may provide non-weeds with greater protection against weed-induced decreases in productivity.
- Rising CO_2 improves plants' abilities to withstand the deleterious effects of heavy metals where they are present in soils at otherwise-toxic levels.
- Rising CO_2 reduces the frequency and severity of herbivory against crops and trees by increasing production of natural substances that repel insects, leading to the production of more symmetrical leaves that are less susceptible to attacks by herbivores and making trees more capable of surviving severe defoliation.
- Rising CO_2 increases net photosynthesis and biomass production by many agricultural crops, grasses, and grassland species even when soil nitrogen concentrations tend to limit their growth. Additional CO_2-induced carbon input to the soil stimulates microbial decomposition and thus leads to more available soil nitrogen, thereby challenging the progressive nitrogen limitation hypothesis.
- Rising CO_2 typically reduces and can completely override the negative effects of ozone pollution on the photosynthesis, growth, and yield of nearly all agricultural crops and trees that have been experimentally evaluated.
- Rising CO_2 can help plants overcome stresses imposed by the buildup of soil salinity from repeated irrigation.
- The ongoing rise in the atmosphere's CO_2 content is a powerful antidote for the deleterious biological impacts that might be caused by an increase in the flux of UV-B radiation at the surface of Earth due to depletion of the planet's stratospheric ozone layer.

Source: Chapter 3. "Plants Under Stress," *Climate Change Reconsidered II: Biological Impacts.* Nongovernmental International Panel on Climate Change. Chicago, IL: The Heartland Institute, 2014.

season moisture in late spring/early summer, most critically during June," but "by the late 20th–early 21st century, there remains no statistically significant relationship between moisture and growth." According to Koutavas, despite the "pronounced shift to greater aridity in recent decades," tree growth in the region experienced "a net increase over the last half-century, culminating with a sharp spike in AD

1988–1990," which implies the trees have acquired a "markedly enhanced resistance to drought." Koutavas says that result is "most consistent with a significant CO_2 fertilization effect operating through restricted stomatal conductance [the rate of passage of carbon dioxide (CO_2) entering, or water vapor exiting, through the stomata of a leaf] and improved water-use efficiency."

Naudts *et al*. (2014) "assembled grassland communities in sunlit, climate-controlled greenhouses and subjected these to three stressors (drought, zinc toxicity, nitrogen limitation) and their combinations," where "half of the communities were exposed to ambient climate conditions (current climate) and the other half were continuously kept at 3°C above ambient temperatures and at 620 ppm CO_2 (future climate)." They found "across all stressors and their combinations, future climate-grown plants coped better with stress, i.e. above-ground biomass production was reduced less in future than in current climate." They identify three mechanisms driving improved stress protection and conclude, "there could be worldwide implications connected to the alleviation of the stress impact on grassland productivity under future climate conditions," noting as an example that "enhanced protection against drought could mitigate anticipated productivity losses in regions where more frequent and more intense droughts are predicted."

Zong and Shangguan (2014) hydroponically cultivated maize (*Zea mays* L. cv. Zhengdan 958) seedlings in sand within two climate-controlled chambers and exposed them to CO_2 concentrations of either 380 or 750 ppm CO_2 until the end of the study. They also irrigated the seedlings with Hoagland solutions and "different N solutions (5 mM N as the nitrogen deficiency treatment and 15 mM N as the control)." The two scientists report "maize seedlings suffering combined N limitation and drought had a better recovery of new leaf photosynthetic potential than those suffering only drought with ambient CO_2." But with elevated CO_2, "the plants were able to maintain favorable water content as well as enhance their biomass accumulation, photochemistry activity, leaf water use efficiency and new leaf growth recoveries." Zong and Shangguan conclude, "elevated CO_2 could help drought-stressed seedlings to maintain higher carbon assimilation rates under low water content," noting that was the case "even under N-limited conditions, which allow the plants to have a better performance under drought following re-watering."

Song and Huang (2014) studied Kentucky Bluegrass plants obtained from field plots in New Brunswick, New Jersey (USA) in controlled environment chambers maintained at ambient and double-ambient atmospheric CO_2 concentrations (400 and 800 ppm, respectively). They divided the plants into sub-treatments of optimum temperature and water availability, drought-stressed (D) and heat-stressed (H) conditions, and a combined D and H environment. They report "the ratio of root to shoot biomass increased by 65% to 115% under doubling ambient CO_2 across all treatments with the greatest increase under D" (see Figure 5.3.3.2, panel C). They noted "the positive carbon gain under doubling ambient CO_2 was the result of both increases in net photosynthesis rate and suppression of respiration rate." Leaf net photosynthesis "increased by 32% to 440% with doubling ambient CO_2" and there was a significant decline (by 18% to 37%) in leaf respiration rate under the different treatments "with the greatest suppression under D + H." The two scientists concluded, "the increase in carbon assimilation and the decline in respiration carbon loss could contribute to improved growth under elevated CO_2 conditions," as they note has been found to be the case with several other plants, citing the studies of Drake *et al*. (1997), Ainsworth *et al*. (2002), Long *et al*. (2004), and Reddy *et al*. (2010).

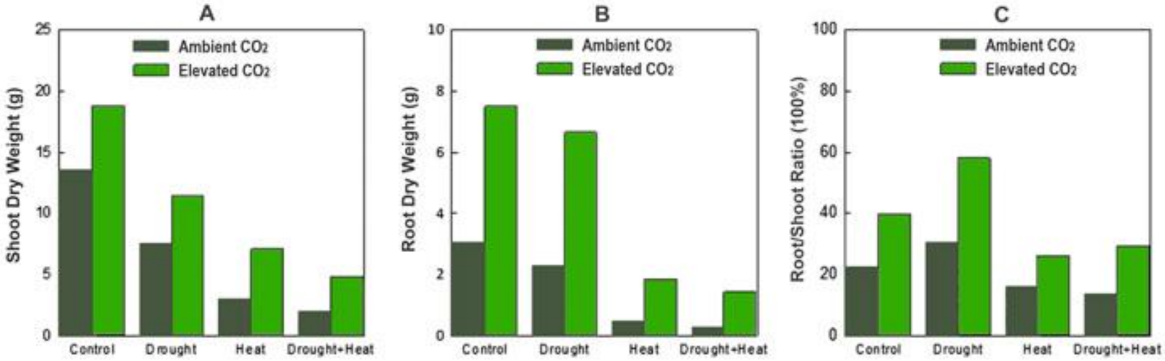
Lee *et al*. (2015) grew *Perilla frutescens* var. *japonica* 'Arum' – an herb of the mint family – from seeds for a period of 60 days in two controlled-environment chambers, where "the pots were flushed once a day and fertilized twice a week with a nutrient solution developed for leafy vegetables," and where after the first week the plants were exposed to either near-ambient or elevated atmospheric CO_2 concentrations (350 vs. 680 ppm, respectively) for the remainder of the experiment. Relative to the plants growing in near-ambient CO_2 air, as shown in Figure 5.3.3.3, they found the plants growing in the CO_2 enriched air experienced a higher photosynthetic rate, increased stomatal resistance, declining transpiration rates, and improved water-use efficiency. The elevated CO_2 concentration also reduced drought-induced oxidative damage to the plants.

Dias de Oliveira *et al*. (2015) conducted a field experiment to determine the interactive effects of CO_2, temperature, and drought on two pairs of sister lines of wheat (*Triticum aestivum L.*) over the course of a growing season. The experiment was conducted outdoors in poly-tunnels (steel frames covered in polythene) under all possible combinations of CO_2

concentration (400 or 700 ppm), temperature (ambient or +3°C above ambient daytime temperature), and water status (well-watered or terminal drought post anthesis). They found, among other things, that elevated CO_2 "increased grain yield and aboveground biomass." Terminal drought "reduced grain yield and aboveground biomass," but elevated CO_2 "was the key driver in the amelioration of [its negative] effects." They note "temperature did not have a major effect on ameliorating the effects of terminal drought."

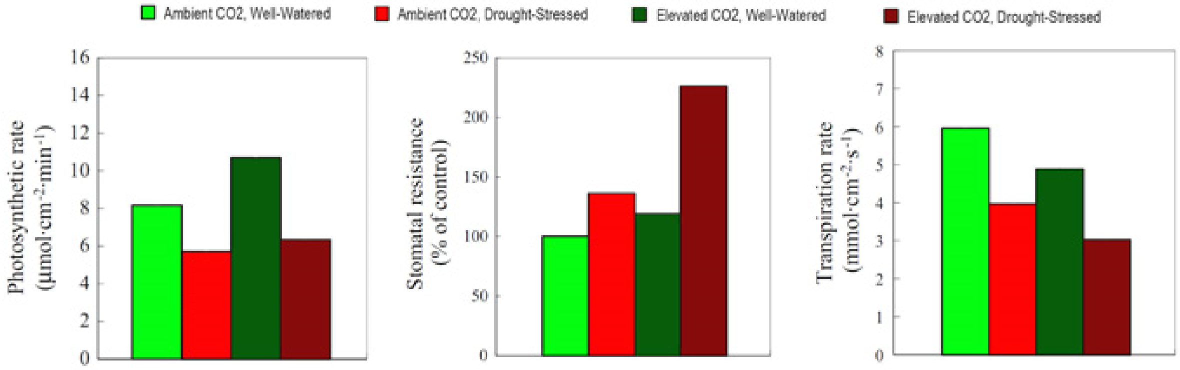
Chen *et al*. (2015) explain "drought stress is one of the most detrimental abiotic stresses for plant growth," in that it "leads to stomatal closure and reduces photosynthesis resulting from restricted CO_2 diffusion through leaf stomata and inhibition of carboxylation activity," as described by Flexas *et al*. (2004). They note "minimizing cellular dehydration and maintaining active photosynthesis are key strategies for plant survival or persistence through dry-down periods," as is described in more detail by Nilsen and Orcutt (1996).

Figure 5.3.3.2
Shoot dry weight, root dry weight, and root/shoot dry weight ratio of Kentucky Bluegrass grown under drought stress, heat stress, and drought and heat stress, under ambient and elevated CO_2 concentrations



Source: Song and Huang, 2014.

Figure 5.3.3.3
Effect of elevated CO_2 on photosynthetic rate, stomatal resistance, and transpiration in *P. frutescens* under well-watered and drought-stressed conditions



Source: Lee *et al*., 2015.

Hypothesizing that drought stress might be alleviated by the positive effects of atmospheric CO_2 enrichment, Chen *et al*. grew a cool-season grass – tall fescue (*Festuca arundinacea* Schreb. cv. Rembrandt) – in controlled-environment chambers maintained at either 400 or 800 ppm CO_2 under both well-watered (control) conditions or subjected to drought stress followed by re-watering. This work revealed, among other things, that "elevated CO_2 reduced stomatal conductance and transpiration rate of leaves during both drought stress and re-watering" and the "elevated CO_2 enhanced net photosynthetic rate with lower stomatal conductance but higher Rubisco and Rubisco activase activities during both drought and re-watering." They conclude, "the mitigating effects of elevated CO_2 on drought inhibition of photosynthesis and the enhanced recovery in photosynthesis on re-watering were mainly the result of the elimination of metabolic limitation from drought damages associated with increased enzyme activities for carboxylation."

Using *Chrysolaena obovata* plants cultivated within four open-top chambers inside a greenhouse, Oliveira *et al*. (2016) maintained half of the plants in air of 380 ppm CO_2 and half of them in air of 760 ppm CO_2 for a period of 45 days, after which for each CO_2 concentration they separated the plants into four water replacement treatments (in which the water used by the plant, lost to the soil and evaporation, is replaced so the plant never dries out): control (100% water replacement), low drought (75% water replacement), medium drought (50% water replacement), and severe drought (25% water replacement) of the total transpired water of the previous 48 hours, as determined by the before-and-after measured weights of each plant-pot combination. They report, "under elevated CO_2, the negative effects of water restriction on physiological processes were minimized, including the maintenance of rhizophore water potential, increase in water use efficiency, maintenance of photosynthesis and fructan reserves for a longer period."

Van der Kooi *et al*. (2016) searched library archives of the scientific literature between 1979 and 2014 for CO_2 enrichment studies of agricultural plants exposed to drought. For biomass effects, they identified "62 different data entries (for both dry and well-watered conditions) from 41 different experimental studies on 30 crop species," while for yield, they identified "19 data entries (for both dry and well-watered conditions) from 17 experimental studies on 8 crop species." They found C_3 and C_4 crops responded very similarly to atmospheric CO_2 enrichment when experiencing drought conditions. They conclude, "crops grown in areas with limited water availability will benefit from future elevated CO_2, regardless of their metabolism," noting "drought leads to stomatal limitation of photosynthesis in both C_3 and C_4 crops, which is alleviated [in both cases] when the plants are grown under elevated CO_2."

Schmid *et al*. (2016) investigated the effects of elevated CO_2 and drought on two barley cultivars, Golden Promise and Bambina, growing the cultivars in controlled environment chambers at two CO_2 levels (380 and 550 ppm) and two water levels (normal and 33% less water) in order to simulate drought conditions, based on average rainfall over the course of the growing season. They found grain dry weight was enhanced by 31% and 62% in Golden Promise (GP) and Bambina (BA) cultivars, respectively, under normal water conditions. Under reduced water conditions, elevated CO_2 proved even more beneficial, enhancing BA and GP grain dry weight by 50% and 150%, respectively, coming close to fully ameliorating the impact of drought on the two cultivars.

Schmid *et al*. also found total plant biomass was enhanced by CO_2 enrichment in both plants under normal (8% biomass enhancement for GP and 34% for BA) and simulated drought conditions (52% for GP and 21% for BA). The water use efficiency of both plants also was enhanced by elevated CO_2, including a 200% increase under reduced water conditions for GP when calculated based on grain yield. The edible portion of the plant, including grain number per plant and harvest index, were significantly enhanced by elevated CO_2 under both normal and water-stressed conditions.

Wijewardana *et al*. (2016) investigated the growth response of six maize hybrids to drought, UV-B radiation, and carbon dioxide (CO_2). The maize was grown in sunlit chambers under a variety of treatment conditions, including two levels of CO_2 (400 and 800 ppm), two levels of water stress (100% and 50% irrigation treatment based on evapo-transpiration measurements), and two levels of biologically effective UV-B radiation intensities (0 and 10 kJ m^{-2} d^{-1}). Compared with ambient conditions, alone or in combination with water and/or UV-B stress, elevated CO_2 significantly increased maize hybrid plant height, leaf number, and leaf area, with the magnitudes of the responses varying by hybrid. Elevated CO_2 increased total plant dry matter as well. Averaged across the six hybrids, elevated

CO_2 induced an average 13% increase in dry matter under adequate water and normal UV-B conditions, a 19% increase under UV-B stressed conditions, a 20% increase when water stressed, and a 10% increase under combined water and UV-B stressed conditions. Thus, although drought and UV-B stress had negative effects on maize hybrid growth, elevated CO_2 "caused a positive increase in both vegetative and physiological traits."

Roy *et al*. (2016) used the Montpellier (France) CNRS Ecotron facility to simulate elevated CO_2 (eCO_2) and extreme climate events (ECEs), co-occurring heat and drought events as projected for the 2050s, the effects of which they analyzed on the ecosystem-level for both carbon and water fluxes in the Ecotron's C_3 grassland. They report "eCO_2 not only slows down the decline of ecosystem carbon uptake during the ECE but also enhances its recovery after the ECE, as mediated by increases of root growth and plant nitrogen uptake induced by the ECE." They say their findings indicate "in the predicted near-future climate, eCO_2 could mitigate the effects of extreme droughts and heat waves on ecosystem net carbon uptake."

Da Silva *et al*. (2017) examined the interactive effects of elevated CO_2 and reduced water availability on a number of key physiological and growth traits for six-week-old Concord (*Vitis labrusca*) grape plants grown in controlled environment chambers at either ambient (400 ppm) or elevated (800 ppm) levels of atmospheric CO_2 for a period of 24 days under three water management treatments: full irrigation, in which the rootzone was irrigated to saturation three days per week; partial root drying, where alternating halfs of the rootzone were irrigated to saturation three days per week; and no irrigation, in which irrigation was suspended for the duration of the 24-day experiment.

Da Silva *et al.* report elevated CO_2 increased net photosynthesis by 24% and specific leaf weight by 16%, whereas it reduced stomatal density by 25% over the 24 days of enrichment. With respect to its influence on drought, "elevated CO_2 dramatically increased drought tolerance of grapevines" by enhancing plant water use efficiency, primarily because of observed CO_2-induced increases in net photosynthesis and corresponding CO_2-induced declines in stomatal conductance and transpiration rates. In the no irrigation treatment, water depletion in the root zone developed at a slower rate in the elevated CO_2 chambers, delaying the effects of drought by about four days. They concluded, "overall, elevated CO_2 improves the leaf carbon balance and this mitigates the deleterious effects of drought on grapevines."

Kumar *et al*. (2017) grew rice (*Oryza sativa*, cv. Naveen) in open-top chambers under two moisture regimes and three CO_2 concentrations over two consecutive growing seasons. Plant moisture regimes included well-watered, where the water depth of the soil was maintained at 3 ± 2 cm, or water-deficit, where surface irrigation was applied only when the soil water potential at 15 cm reached -60 kPa. Atmospheric CO_2 concentrations were maintained at ambient (400 ppm), mid-elevation (550 ppm), or high-elevation (700 ppm) during daylight hours only.

Kumar *et al*. found atmospheric CO_2 enrichment (to both 550 and 700 ppm) "exhibited a positive response on plant growth, grain yield and [water use efficiency] of rice as compared to ambient CO_2." Elevated levels of CO_2 increased grain yield by 15% to 18% under well-watered conditions and by 39% to 43% under water-deficit conditions. Under elevated CO_2 conditions there was a decline in water use of 11% to 14% under well-watered and 5% under water-deficit conditions. The water use efficiency (ratio of grain yield to total water input) in the two CO_2-enriched chambers increased by 30% to 35% under well-watered conditions and by approximately 48% under water deficit conditions, relative to that observed in the ambient CO_2 chambers.

Kumar *et al.* also report higher levels of CO_2 significantly altered leaf tissue parameters (e.g., relative water content, leaf water potential, and electrolyte leakage) under moisture stress, so as to help mitigate the negative impacts of water deficit. They also found the concentrations of certain antioxidant metabolites were reduced in plants growing under elevated CO_2 in the moisture-stress treatment. This observation further supports the notion that elevated CO_2 helps mitigate water stress in rice: The CO_2-induced mitigation of water stress reduces the production of harmful reactive oxygen species, which subsequently reduces the need for plants to produce antioxidant enzymes to counter them.

Wang *et al*. (2017) examined the interactive effects of elevated CO_2 and drought on soybean (*Glycine max*, cv. Yu 19) by growing plants from seed for 40 days in controlled-environment greenhouses under ambient and twice ambient CO_2 concentrations and three water regimes: well-watered (80% water holding capacity of the soil), moderate drought (60% water holding capacity), and severe drought (40% water holding capacity). Drought negatively impacted the net photosynthesis of the soybean plants, but the positive influence of elevated CO_2 was so great that even under severe drought conditions, the net photosynthetic rate was 73% greater than that observed under well-watered conditions at ambient CO_2. Water use efficiency also was enhanced by elevated CO_2, where it was “almost 2.5 times larger than that under ambient CO_2.”

Wang *et al*. also report that elevated CO_2 increased soil enzyme activities by stimulating plant root exudation (a below-ground response to pests) and “resulted in a longer retention time of dissolved organic carbon (DOC) in [the] soil, probably by improving the soil water effectiveness for organic decomposition and mineralization.” Consequently, they conclude “drought stress had significant negative impacts on plant physiology, soil carbon, and soil enzyme activities, whereas elevated CO_2 and plant physiological feedbacks indirectly ameliorated these impacts.”

Sekhar *et al*. (2017) investigated the interactive effects of elevated CO_2 and water stress on a drought-tolerant cultivar (selection-13) of mulberry (*Morus* spp.) trees. The experiment was conducted in open-top chambers where six-month-old saplings were planted into chambers of either ambient (400 ppm) or enriched (550 ppm) atmospheric CO_2. The scientists cut the plants every four months at stump height (30 cm above the soil surface) to create a coppice culture system (where new shoots grow from the stump). After one year, a subset of plants was subjected to drought stress, where all water was withheld for 30 days.

Sekhar *et al*. observed evidence of stress in the drought treatments under both elevated and ambient CO_2 conditions, but the stress was less under elevated CO_2. They report “plants grown under elevated CO_2 had more green leaves (58%) and individual leaf densities (60%) with less leaf senescence (78%) compared to their ambient controls.” In addition, they note there was “a significant decrease in total chlorophyll content (45%) in ambient CO_2 grown plants” compared to plants grown in high CO_2 conditions. Plants grown in the CO_2-enriched environment had greater net photosynthesis, water use efficiency, and aboveground fresh (92%) and dry (83%) biomass, as well as reduced stomatal conductance and transpiration. Trees growing in the CO_2-enriched environment produced less reactive oxygen species and triggered more and better antioxidant systems to combat the drought-induced oxidative stress.

Sekhar *et al*. say their results “clearly demonstrate that future increases in atmospheric CO_2 enhance the photosynthetic potential and also mitigate the drought-induced oxidative stress” in mulberry.

One of the effects predicted by computer models to result from increases in the atmosphere’s CO_2 content is that there will be an increase in the number of heavy precipitation events, which could lead to flooding and waterlogging of soils. Pérez-Jiménez *et al*. (2017) point out “the combined effect of waterlogging and elevated CO_2 has been scarcely studied,” while additionally noting the topic “has never been studied in fruit trees.” They performed the first such analysis by examining the interactive effects of elevated CO_2 and waterlogging on sweet cherry (*Prunus avium*).

Pérez-Jiménez *et al.* subjected one-year-old seedlings of a Burlat sweet cherry cultivar grafted onto one of two rootstocks (Gisela 5 and Gisela 6) to three weeks of growth in a controlled-environment chamber of either 400 or 800 ppm CO_2. After the first seven days, plants in each chamber were subjected to two additional treatments: a control treatment in which normal daily irrigation was allowed to counter daily water loss, or a waterlogging treatment where the water level was maintained at least 1 cm above the surface of the soil. Seven days later, the waterlogged plants were drained and returned to the control conditions.

Pérez-Jiménez *et al.* report the net photosynthesis of the cherry tree leaves was “markedly influenced by the CO_2 concentration,” such that “it was significantly higher after every phase of the experiment, in plants grafted on both rootstocks, at elevated CO_2.” Percentage increases in net photosynthesis due to elevated CO_2 in both rootstock plants ranged from 113% to 180% higher under control conditions (normal watering) and from 106% to 663% higher under waterlogged conditions. Pérez-Jiménez *et al.* also found there was a reduction in stomatal conductance in waterlogged plants under the ambient CO_2 treatment. They report “an atmosphere enriched with CO_2 improved the physiological status of waterlogged plants, reducing the need for a stomatal conductance reduction to mitigate water logging.” They conclude that “elevated CO_2 was able to increase photosynthesis and thereby help plants to overcome waterlogging.”

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5.3.4 Water Use Efficiency

> *Exposure to elevated levels of atmospheric CO_2 prompts plants to increase the efficiency of their use of water, enabling them to grow and reproduce where it previously has been too dry for them to exist.*

Another major environmental benefit typically ignored in climate change cost-benefit analyses is a CO_2-induced enhancement of plant water use efficiency, the ratio of water used in plant metabolism to water lost by the plant through transpiration. Numerous studies have confirmed that plants exposed to elevated levels of atmospheric CO_2 generally do not open their leaf stomatal pores – through which they take in air (including CO_2) and emit oxygen and water vapor (transpiration) – as wide as they do at lower CO_2 concentrations (Morison, 1985; NIPCC, 2014). In addition, they sometimes produce fewer of these pores per unit area of leaf surface at higher CO_2 levels (Woodward, 1987). Both of these changes have the effect of reducing rates of plant water loss by transpiration (Overdieck and Forstreuter, 1994); and the amount of carbon they gain per unit of water lost – or water-use efficiency – therefore typically rises (Rogers *et al*., 1983; NIPCC, 2014), greatly increasing their ability to withstand drought (Tuba *et al*., 1998).

As the atmosphere's CO_2 content continues to rise, plants will be able to grow and reproduce where it has previously been too dry for them to exist (Johnson *et al*., 1997). Consequently, terrestrial vegetation should become more robust and begin to win back lands previously lost to desertification (Idso and Quinn, 1983). The greater vegetative cover of the land produced by this phenomenon should reduce the adverse effects of soil erosion caused by wind and rain.

Section 5.3.4.1 summarizes recent research on the impact of elevated CO_2 and higher surface temperatures on water use efficiency by crops and Section 5.3.4.2 reviews research on trees. Section 5.3.5 addresses the *future* impact of elevated CO_2 and higher temperatures on plants.

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5.3.4.1 Agriculture

At the turn of the century, Wallace (2000) wrote that the projected increase in global population in the coming half-century (a median best-guess of 3.7 billion) is more certain to occur than is any other environmental change currently underway or reasonably anticipated. This population increase would require an increase in the food supply, which would require an increase in water for agriculture. "Over the entire globe," Wallace warned, "a staggering 67% of the future population of the world may experience some water stress," which would likely lead to food insufficiency, malnutrition, and starvation. The best response is to produce much more food per unit of available water – an improvement in plant water use efficiency that is already underway as atmospheric CO_2 levels rise.

Noting "looming water scarcity and climate change pose big challenges for China's food security," Zhao *et al*. (2014) state "previous studies have focused on the impacts of climate change either on agriculture or on water resources," while "few studies have linked water and agriculture together in the context of climate change and demonstrated how climate change will affect the amount of water used to produce per unit of crop, or virtual water content (VWC)."

Unlike the experiment-based studies reported in previous sections and below, Zhao *et al*. used a GIS-based Environmental Policy Integrated Climate (GEPIC) model to analyze the current spatial distribution of the VWC of various crops in China and the impacts of climate change on VWC in different future scenarios. They report "three general change trends exist for future VWCs of crops: continuous decline (for soybean and rice without considering CO_2 concentration changes) and continuous increase (for rice with considering CO_2 concentration changes) and first-decline-then-increase (other crop-scenario combinations)." They say the "integrated effects of precipitation, temperature and CO_2 concentration changes will benefit agricultural productivity and crop water productivity through all the future periods till the end of the century." Zhao *et al*. conclude, "climate change is likely to benefit food security and help alleviate water scarcity in China."

Pazzagli *et al*. (2016) grew two tomato (*Solanum lycopersicum*) cultivars – one potentially drought tolerant (ST 22) and one thought to be heat tolerant (ST 52) – in a controlled greenhouse environment from March to June 2014. The plants were subjected to three irrigation regimes (full irrigation, deficit irrigation, and partial root-zone drying) and two atmospheric CO_2 concentrations (380 and 590 ppm). Statistical analyses indicated there was a significant CO_2 effect on both cultivars for net photosynthetic rate, intrinsic water use efficiency (WUEi, photosynthetic rate/stomatal conductance), plant water use efficiency (WUEp, aboveground biomass/plant water use), root water potential, stem dry weight, leaf dry weight, total dry weight, and flower number. They write, "despite large differences between the cultivars, both of them showed significant improvements in plant water use efficiency under both reduced irrigation and CO_2 enrichment, as well as under the combination of the two treatments."

Cruz *et al*. (2016) studied the effects of CO_2 enrichment on cassava, an important food staple whose tuberous roots are the third-largest source of carbohydrates in tropical regions, after rice and maize. The plant is drought-tolerant and "even under adverse soil and climatic conditions, cassava can produce a satisfactory root yield, while other annual crops barely survive (El-Sharkawy and Cock, 1987)." To "help understand the interaction between elevated CO_2 levels and water deficit on growth, physiology and dry mass accumulation in cassava," they grew two- to three-month-old cassava plantlets in a climate-controlled greenhouse for 100 days at two CO_2 concentrations (390 or 750 ppm) for 12 hours per day and two water treatments (well-watered and water-stressed).

Cruz *et al*. found "water deficits led to reductions in the Leaf Elongation Rate of plants grown at ambient as well as CO_2-enriched concentrations," but "plants grown at 750 ppm of CO_2 maintained leaf growth two days longer than plants grown at 390 ppm." They further noted "three days after withholding water, photosynthesis and stomatal conductance were reduced in plants grown under ambient CO_2, while in plants under an elevated CO_2 concentration, these physiological functions remained similar to that of control plants grown under good water availability."

Continuing, Cruz *et al*. report "five days after withholding water plants grown with 750 ppm continued to have enhanced gas exchange compared with plants grown under 390 ppm." Moreover, "under drought stress, the instantaneous transpiration efficiency was always greatest for plants grown under elevated CO_2." They also found "the positive response of elevated CO_2 levels on total dry mass was 61% in the water-stressed plants and only 20% for the plants grown under good water availability."

Deryng *et al*. (2016) combined the results obtained for networks of field experiments and global crop models in order to derive a global perspective on crop water productivity (CWP) –the ratio of crop yield to evapotranspiration – for maize, rice, soybeans, and wheat under elevated CO_2. They report, "the projected increase in the air's CO_2 concentration would likely increase global CWP by

10–27% by the 2080s, with particularly large increases in arid regions (by up to 48%, for example, in the case of rain-fed wheat).” They add, “if realized in the fields,” the effects of elevated CO_2 could considerably mitigate global yield losses while reducing agricultural consumptive water use by 4% to 17%. They conclude their findings “quantify the importance of CO_2 effects on potential water savings and, in so doing, highlight key limitations of global hydrological models that do not consider effects of CO_2 on evapotranspiration.”

Kumar *et al*. (2017) grew rice in naturally sunlit and irrigated (flooded) controlled-environment chambers for two dry and two wet seasons. CO_2 treatments in the chambers included 195, 390, 780, and 1,560 ppm and were maintained at these levels for 22 hours a day. The chambers were flushed of air for one hour before dawn and one hour after dusk to flush out trace gases. Kumar *et al*. report “the current level of 390 ppmv [CO_2] was distinctly sub-optimal for rice biomass production.” The mean aboveground dry weight across all seasons was 1,744 g m^{-2} at the current or ambient CO_2 level (390 ppm), which value “decreased by 43% at 195 ppmv (0.5 x ambient), increased by 29% at 780 ppmv (2 x ambient) and increased by 42% at 1560 ppmv (4 x ambient).”

With respect to water use, Kumar *et al*. report whole-season crop water use under sub-ambient and current CO_2 conditions was 564 and 719 mm, rising to 928 and 803 mm at 780 and 1,560 ppmv CO_2, respectively. Although more water was used at the higher CO_2 concentrations, the amount of biomass produced per mm of water also increased (1.76, 2.43, 2.43, and 3.08 g m^{-2} mm^{-1} at 195, 390, 780 and 1,560 ppm CO_2, respectively).

Singh *et al*. (2017) examined the combined effects of elevated CO_2 and elevated ozone on the growth, biomass, and water use efficiency of chickpea (*Cicer arietinum*). Their experiment was conducted outdoors at a Free Air Ozone and Carbon Dioxide Enrichment (FAOCE) facility in New Delhi, India. Forty days after sowing, chickpea plants (cv. Pusa 5023) were subjected to one of four atmospheric treatments daily until the end of the growing season: normal air (AMB = 400 ppm CO_2, 30 ppb O_3), elevated ozone (EO = 400 ppm CO_2, 70 ppb O_3), elevated CO_2 (EC = 550 ppm CO_2, 30 ppb O_3), and elevated CO_2 and ozone (ECO = 550 ppm CO_2, 70 ppb O_3). Several growth and development parameters were measured or calculated from measurements, including crop phenology, plant height, aboveground biomass, crop growth rate, relative growth rate, and water use efficiency.

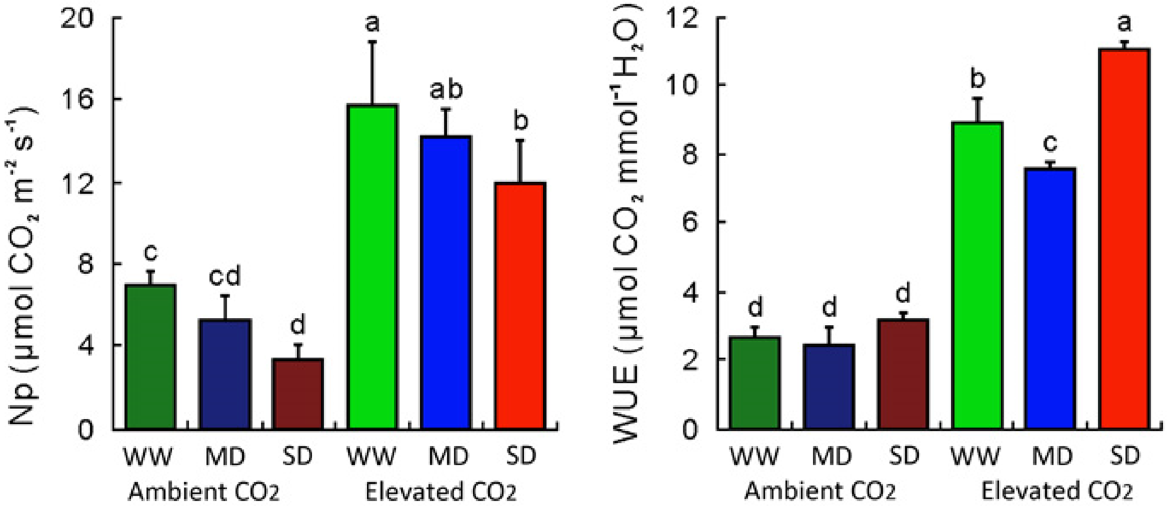
It was anticipated that elevated concentrations of ozone – a plant stressor – would negatively impact chickpea growth, whereas elevated concentrations of carbon dioxide – a plant nutrient – would enhance it. Singh *et al*. report both elevated CO_2 and elevated O_3 advanced plant phenological development, shortening the growth period by about 10 days and 14 days, respectively, compared to ambient conditions, albeit due to different mechanisms: Elevated CO_2 sped up the development and likely induced earlier senescence, whereas elevated O_3 damaged leaf chlorophyll content and nutrient status to enhance senescence.

Singh *et al*. also report chickpea plant height, growth rate, aboveground biomass, seed yield, and water use efficiency benefited from the approximate 37% increase in atmospheric CO_2. In contrast, these parameters were negatively impacted by elevated O_3 concentrations. When in combination, the positive effects of elevated CO_2 were strong enough to completely ameliorate the negative impacts of elevated O_3. Compared to ambient conditions, for example, seed yield was enhanced by 32% in the EC treatment, reduced by 22% in the EO treatment and increased by 10% in the ECO treatment. Similarly, water use efficiency increased by 44% in the EC treatment, declined by 22% in the EO treatment and experienced a 5% increase in the ECO treatment.

Wang *et al*. (2017) examined the interactive effects of elevated CO_2 and drought on soybean (*Glycine max*, cv. Yu 19), growing plants from seed for 40 days in controlled-environment greenhouses under ambient and twice ambient CO_2 concentrations and three water regimes: well-watered (80% water holding capacity of the soil), moderate drought (60% water holding capacity), and severe drought (40% water holding capacity). They found drought negatively impacted the net photosynthesis of the soybean plants, which declined by 52% and 23% in comparing the well-watered to the severe drought treatment under ambient and elevated CO_2 conditions, respectively. The positive influence of elevated CO_2 was so great that even under severe drought conditions, the net photosynthetic rate was 73% greater than that observed under well-watered conditions at ambient CO_2 (Figure 5.3.4.1.1, left panel). Water use efficiency also was enhanced by elevated CO_2 (right panel), where it was “almost 2.5 times larger than that under ambient CO_2.”

Wang *et al*. also report elevated CO_2 increased soil enzyme activities and “resulted in a longer retention time of dissolved organic carbon (DOC) in [the] soil, probably by improving the soil water

Figure 5.3.4.1.1
Net photosynthesis (Np) and water use efficiency (WUE) of soybean plants grown under various treatments of drought



WW = well-watered; MD = moderate drought; SD = severe drought) and atmospheric CO_2 (ambient and elevated, where elevated = twice ambient). *Source*: Wang *et al.*, 2017

effectiveness for organic decomposition and mineralization." They conclude "drought stress had significant negative impacts on plant physiology, soil carbon, and soil enzyme activities, whereas elevated CO_2 and plant physiological feedbacks indirectly ameliorated these impacts."

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5.3.4.2 Trees

Extensive research documents how elevated CO_2 levels improve water use efficiency by trees, enabling them to better withstand droughts and other changes in precipitation that may accompany climate change. This bodes well both for forestry and preservation of wildlife habitat.

Wang *et al.* (2012) note "empirical evidence from lab studies with a controlled CO_2 concentration and from free-air CO_2 enrichment (FACE) experiments have revealed significantly increased iWUE [intrinsic water-use efficiency] in response to rising CO_2," as demonstrated by the studies of Luo *et al*. (1996), Ainsworth and Rogers (2007), and Niu *et al*. (2011). They also note "tree-ring stable carbon isotope ratios ($\delta^{13}C$) have proven to be an effective tool for evaluating variations in iWUE around the world," citing Farquhar *et al*. (1989), Saurer *et al*. (2004), Liu *et al*. (2007), and Andreu *et al*. (2011). Working at a site in the Xinglong Mountains in the eastern part of northwestern China, Wang *et al*. extracted two cores from the trunks of each of 17 dominant living Qinghai spruce (*Picea crassifolia*) trees, from which they obtained ring-width measurements they used to calculate yearly mean basal area growth increments. Thereafter they used subsamples of the cores to conduct the analyses needed to obtain the $\delta^{13}C$ data required to calculate iWUE over the period 1800–2009. By calibrating the $\delta^{13}C$ data against climatic data obtained at the nearest weather station over the period 1954–2009, they were able to extend the histories of major meteorological parameters back to 1800. By comparing these weather data with the tree growth and water use efficiency data, they were able to interpret the impacts of climate change and atmospheric CO_2 enrichment on spruce tree growth and water use efficiency.

Wang *et al*. determined iWUE increased by approximately 40% between 1800 and 2009, rising very slowly for the first 150 years, but then more rapidly to about 1975 and then faster still until 1998, whereupon it leveled off for the remaining 11 years of the record. They say the main cause of the increasing trend in iWUE from 1800 to 1998 "is likely to be the increase in atmospheric CO_2," because "regression analysis suggested that increasing atmospheric CO_2 explained 83.0% of the variation in iWUE from 1800 to 1998 ($p<0.001$)."

Battipaglia *et al*. (2013) combined tree-ring analyses with carbon and oxygen isotope measurements made at three FACE sites to assess changes in water-use efficiency and stomatal conductance. They found elevated CO_2 increased water-use efficiency on average by 73% for sweetgum (*Liquidambar styraciflua*, +200 ppm $CO_{2)}$, 77% for loblolly pine (*Pinus taeda*, +200 ppm $CO_{2)}$, and 75% for poplar (*Populus sp.*, +153 ppm $CO_{2)}$. They say their findings provide "a robust means of predicting water-use efficiency responses from a variety of tree species exposed to variable environmental conditions over time and species-specific relationships that can help modeling elevated CO_2 and climate impacts on forest productivity, carbon and water balances."

Keenan *et al*. (2013) documented and analyzed recent trends in the water-use efficiencies (Wei) of forest canopies, using direct and continuous long-term measurements of CO_2 and water vapor fluxes, focusing on seven sites in the midwestern and northeastern United States. They compared their results with those derived from data obtained by others from 14 additional temperate and boreal forest sites.

Keenan *et al.* found "a substantial increase in water-use efficiency in temperate and boreal forests of the Northern Hemisphere over the past two decades." They determined "the observed increase is most consistent with a strong CO_2 fertilization effect," because, as they note, "of all the potential drivers of the observed changes in Wei, the only driver that is changing sufficiently and consistently through time at all sites is atmospheric CO_2."

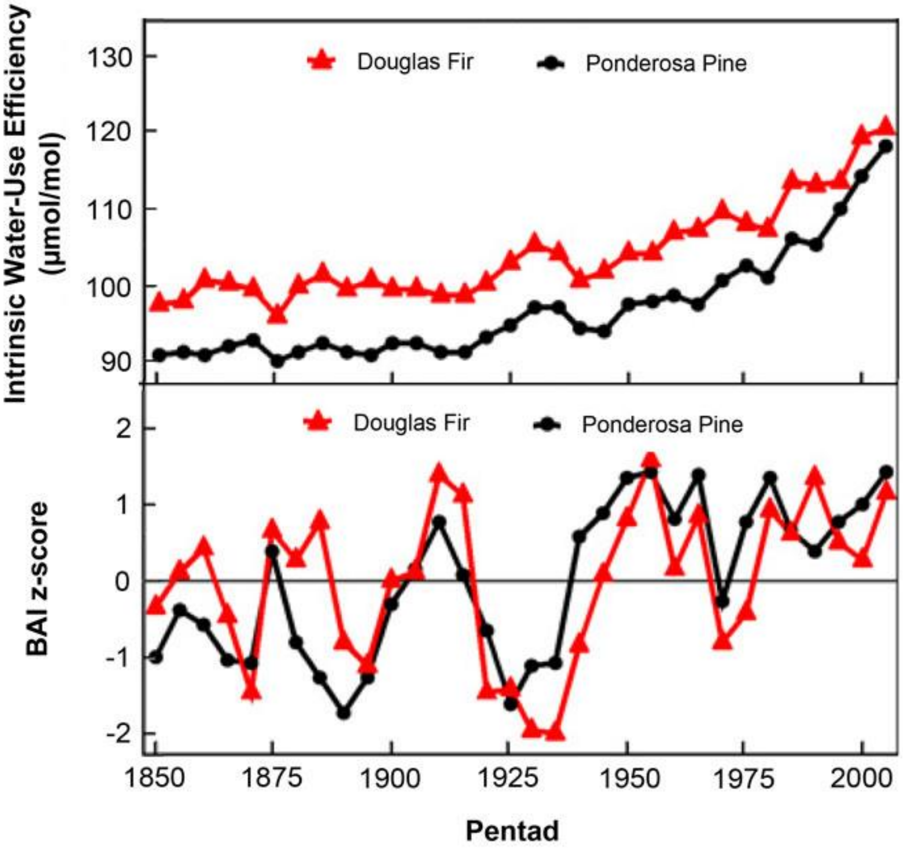
Keenan *et al*. additionally note "the direct tradeoff between water loss and carbon uptake through the stomata means that, as water-use efficiency increases, either evapotranspiration decreases or gross photosynthetic carbon uptake increases, or both occur simultaneously." They write "increases in Wei may account for reports of global increases in photosynthesis (Nemani *et al*., 2003), forest growth rates (Lewis *et al*., 2009; Salzer *et al*., 2009; McMahon *et al*., 2010), and carbon uptake (Ballantyne *et al*., 2012)," leading them to suggest "rising atmospheric CO_2 is having a direct and unexpectedly strong influence on ecosystem processes and biosphere-atmosphere interactions in temperate and boreal forests."

Soulé and Knapp (2015) collected tree-ring data from ponderosa pine (*Pinus ponderosa* var. *ponderosa* - PIPO) and Douglas fir (*Pseudotsuga menziesii* var. *glauca* - PSME) at 14 locations, from which they determined yearly changes (from AD 1850 to the present) in basal area index (BAI) and intrinsic water use efficience (iWUE). They determined both PIPO and PSME trees experienced "exponentially increasing iWUE rates during AD 1850–present, suggesting either increased net photosynthesis or decreased stomatal conductance, or both" (Figure 5.3.4.2.1, upper panel). They add "both species experienced above-average BAI in the latter half of the 20th century despite no favorable changes in climate" (lower panel), further noting "this response occurred at all sites, suggesting a pan-regional effect."

Working with four native tree species of China (*Schima superba, Ormosia pinnata, Castanopsis hystrix* and *Acmena acuminatissima*) from January 2006 to January 2010, Li *et al*. (2015) studied the effects of an approximate 300 ppm increase in the air's CO_2 concentration on the trees' WUE, which they did within open-top chambers exposed to full light and rain out-of-doors, either with (CN) or without (CC) added nitrogen fertilization. They found, compared to the control, the average increased extents of intrinsic WUE were 98% and 167% in CC and CN treatments for *S. superba*; 88% and 74% for *O. pinnata*; 234% and 194% for *C. hystrix*; and 153% and 81% for *A. acuminatissima*.

Ghini *et al*. (2015) conducted an experiment to observationally determine the response of two coffee cultivars to elevated levels of atmospheric CO_2 in the first FACE facility in Latin America. Small specimens of two coffee cultivars, Catuaí and Obatã, were sown in the field under ambient (~390 ppm) and enriched (~550 ppm) CO_2 conditions in August 2011 and allowed to grow under normal cultural growing conditions without supplemental irrigation for two years. No significant effect of CO_2 was observed on

Figure 5.3.4.2.1
Mean tree-ring iWUE values and basal-area index values for Douglas fir and Ponderosa Pine trees, 1850–2005



Source: Adapted from Soulé and Knapp, 2015.

the growth parameters during the first year. However, during the growing season of Year 2, net photosynthesis increased by 40% and plant water use efficiency by approximately 60%, regardless of cultivar. During the winter, when growth was limited, daily mean net photosynthesis "averaged 56% higher in the plants treated with CO_2 than in their untreated counterparts."

WUE in winter also was significantly higher (62% for Catuaí and 85% for Obatã). Such beneficial impacts resulted in significant CO_2-induced increases in plant height, stem diameter, and harvestable yield over the course of Year 2. Ghini *et al*. report the increased crop yield "was associated with an increased number of fruits per branch, with no differences in fruit weight."

Working in southern Chile, Urrutia-Jalabert *et al*. (2015) performed a series of analyses on tree-ring cores they obtained from long-lived cypress (*Fitzroya cupressoides*) stands, which they say "may be the slowest-growing and longest-lived high biomass forest stands in the world." Focusing on two of the more pertinent findings of their study, both the BAI and iWUE of *Fitzroya* experienced dramatic increases over the past century. The authors write, "the sustained positive trend in tree growth is striking in this old stand, suggesting that the giant trees in this forest have been accumulating biomass at a faster rate since the beginning of the [20th] century." Coupling that finding with the 32% increase in water use efficiency over the same time period, Urrutia-Jalabert *et al*. state "we believe that this increasing growth trend … has likely been driven by some combination of CO_2 and/or surface radiation increases," adding that "pronounced changes in CO_2 have occurred in parallel with changes in climate, making it difficult to distinguish between both effects."

Carles *et al*. (2015) subjected white spruce (*Picea glauca*) seedlings to a combination of two temperature regimes (ambient and ambient plus 5°C) and two levels of atmospheric CO_2 (380 and 760 ppm) over two growing seasons. They report "warmer temperatures and CO_2 elevation had a positive effect on the height and diameter growth of 2- and 3-year-old seedlings …" They also report that water use efficiency was "affected positively by the CO_2 treatment, showing a 51% increase that was consistent across families."

Wils *et al*. (2016) studied cores or discs extracted from five African juniper (*Juniperus procera*) trees of Gondar, Ethiopia, and one from the Hugumburda forest on the north-western escarpment of the Ethiopian Rift Valley, along with discs obtained from a *Mimusops caffra* tree growing in South Africa's KwaZulu-Natal and an *Acacia erioloba* growing in the Koichab Valley of Namibia. They report, "tree-ring intrinsic water-use efficiency (iWUE) records for Africa show a 24.6% increase over the 20th century." Because a high iWUE can partly counterbalance decreases in precipitation, Wils *et al.* conclude this finding "has important implications for those involved in water resource management and highlights the need for climate models to take physiological forcing into account." They note "the 24.6% increase in mean iWUE confirms that African trees are already adapting to increasing atmospheric CO_2 concentrations."

Huang *et al*. (2017) examined the relationship between BAI and iWUE indices derived from cores of Smith fir trees (also known as Yunnan fir) (*Abies georgei* var. *smithii*) growing at a high-elevation timberline site in the southeastern Tibetan Plateau, rising atmospheric CO_2 concentration, and climate. They hypothesized "if intrinsic water use efficiency ... has increased due to rising net photosynthetic rates under rising atmospheric CO_2 concentration over the past century, tree growth should have benefitted." They found iWUE rose by 27.83% over the period 1900 to 2006. They also report "the increasing iWUE is mainly caused by the rising atmospheric CO_2 concentration," and "iWUE would continue to increase in the near future."

Huang *et al*. note there also has been a strong increasing trend in BAI over the past century and conclude that trend is also largely driven by the aerial fertilization effect of atmospheric CO_2, being highly influenced in the short term by interannual variations in temperature. They report finding "a significant positive correlation ($r = 0.79$, $p < 0.01$) between BAI and iWUE," which they say indicates "changes in iWUE and tree growth were likely to have had a common cause, i.e., the CO_2 fertilization effect."

Choury *et al*. (2017) analyzed long-term trends in the BAI and WUEi of native Aleppo pines (*Pinus halepensis* Mill.) growing near the northern border of the Sahara Desert. They cored multiple trees from three locations so as to evaluate trends over the period 1925–2013, during which period mean annual temperatures rose by 1.5°C and atmospheric CO_2 concentrations rose by approximately 30%. They report "the BAI patterns of natural Aleppo pine stands did not show a decreasing trend over the last century, indicating that warming-induced drought stress has not significantly affected secondary growth of pines in the area; instead, BAI trends were stable or even showed a significant increase in the case of the North slope site." Similar results were noted for the trees' WUEi, which "increased by ca. 39% across sites between 1925 and 2013." Choury *et al*. conclude their study "highlights the substantial plasticity of Aleppo pine to warming-induced drought stress," adding, "the extent of such plastic responses for Aleppo pines growing at the southernmost limit of the species distribution area is, from a physiological point of view, remarkable."

Giammarchi *et al*. (2017) assessed the changes in productivity of two similarly aged Norway pine (*Picea abies*) forests and then examined "the role of several environmental drivers, such as atmospheric CO_2 levels, temperature, and precipitation regimes on the intrinsic water-use efficiency (iWUE) temporal patterns of the above-mentioned forests." They found an increase in forest productivity at both sites since the 1860s, paralleled by a significant increase of iWUE, which they say was "mainly triggered by a CO_2-driven increase in photosynthetic capacity, rather than by a reduction of stomatal conductance."

Weiwei *et al*. (2018) cored *Platycladus orientalis* trees, an evergreen coniferous species endemic to China, to investigate trends in tree-ring carbon discrimination and iWUE over the past century. They found both iWUE and BAI have increased with time. Both variables were positively correlated with atmospheric CO_2 concentration, which findings, the authors say, "are consistent with other studies conducted on the effects of elevated CO_2 on leaf physiological activity, which demonstrate that increased CO_2 promotes water use efficiency."

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5.3.5 Future Impacts on Plants

> *The productivity of the biosphere is increasing in large measure due to the aerial fertilization effect of rising atmospheric CO_2. The benefits of CO_2 enrichment will continue even if atmospheric CO_2 rises to levels far beyond those forecast by the IPCC.*

Atmospheric CO_2 enrichment is boosting biospheric productivity around the world, but will it continue to do so in coming decades and centuries? Extensive research has been conducted on the possible effects on plants of elevated CO_2 levels and higher temperatures in the future. In Chapter 4 of *Climate Change Reconsidered II: Biological Impacts* (NIPCC, 2014), NIPCC presented a thorough literature review of the subject, finding ample support for its conclusion that plants will flourish if temperatures and CO_2 levels rise in the future. The key findings of that chapter are summarized in Figure 5.3.6.1.

This section updates the literature review that appeared in *Biological Impacts*. Section 5.3.5.1 summarizes new research (most of it published since 2014) on the impacts of rising atmospheric CO_2 concentrations and temperatures on plants important for food production; Section 5.3.5.2 addresses future biospheric productivity; Section 5.3.5.3 addresses future biodiversity; Section 5.3.5.4 addresses future extinction; and Section 5.3.5.5 addresses future evolution.

Reference

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Figure 5.3.5.1
Key Findings: Impacts on Earth's vegetative future

- The vigor of Earth's terrestrial biosphere has been increasing with time, revealing a great post-industrial revolution greening of the Earth that extends across the entire globe. Over the past 50 years global carbon uptake has doubled from 2.4 ± 0.8 billion tons in 1960 to 5.0 ± 0.9 billion tons in 2010.

- The atmosphere's rising CO_2 content, which the IPCC considers to be the chief culprit behind all of its "reasons for concern" about the future of the biosphere, is most likely the primary cause of the observed greening trend.

- The observed greening of the Earth has occurred in spite of all the many real and imagined assaults on Earth's vegetation, including fires, disease, pest outbreaks, air pollution, deforestation, and climatic change. Rising levels of atmospheric CO_2 are making the biosphere more resilient to stress even as it becomes more lush and productive.

- Agricultural productivity in the United States and across the globe dramatically increased over the last three decades of the twentieth century, a phenomenon partly due to new cultivation techniques but also due partly to warmer temperatures and higher CO_2 levels.

- A future warming of the climate coupled with rising atmospheric CO_2 levels will further boost global agricultural production and help to meet the food needs of the planet's growing population.

- The positive direct effects of CO_2 on future crop yields are likely to dominate any hypothetical negative effects associated with changing weather conditions, just as they have during the twentieth and early twenty-first centuries.

- Plants have a demonstrated ability to adjust their physiology to accommodate a warming of both the magnitude and rate-of-rise typically predicted by climate models, should such a warming actually occur.

- Evidence continues to accumulate for substantial heritable variation of ecologically important plant traits, including root allocation, drought tolerance, and nutrient plasticity, which suggests rapid evolution is likely to occur based on epigenetic variation alone. The ongoing rise in the atmosphere's CO_2 content will exert significant selection pressure on plants, which can be expected to improve their performance in the face of various environmental stressors via the process of micro-evolution.

- As good as things currently are for world agriculture, natural selection and bioengineering could bring about additional beneficial effects. For example, highly CO_2-responsive genotypes of a wide variety of plants could be selected to take advantage of their genetic ability to optimize their growth in response to projected future increases in the atmosphere's CO_2 content.

Source: Chapter 4. "Earth's Vegetative Future," *Climate Change Reconsidered II: Biological Impacts.* Nongovernmental International Panel on Climate Change. Chicago, IL: The Heartland Institute, 2014.

5.3.5.1 Agriculture

The beneficial effects for agriculture of rising levels of CO_2 in the modern era were documented in detail in Chapter 3, Section 3.4 and earlier in this chapter in Section 5.2.2.3 and so do not need to be reported again here. But will those benefits continue? Agricultural species grown in elevated CO_2 environments often, but not always, at some point exhibit some degree of photosynthetic acclimation or down regulation, which is typically characterized by reduced rates of photosynthesis resulting from decreased activity and/or amount of rubisco, the primary plant carboxylating enzyme (Sims *et al*., 1999; Gavito *et al*., 2000; Ulman *et al*., 2000).

Ziska (1998), for example, reported that soybeans grown at an atmospheric CO_2 concentration of 720 ppm initially exhibited photosynthetic rates 50% greater than those observed in control plants grown at 360 ppm. However, after the onset of photosynthetic acclimation, CO_2-enriched plants displayed subsequent photosynthetic rates only 30% greater than their ambiently grown counterparts. Nevertheless, in nearly every reported case of CO_2-induced photosynthetic acclimation, the reduced rates of photosynthesis displayed by CO_2-enriched plants are *greater* than those exhibited by plants growing at ambient CO_2 concentrations

Several studies have tried to estimate the effects on agriculture of temperatures and CO_2 concentrations forecast by the IPCC. Mariani (2017) utilized a physiological-process-based crop simulation model to estimate the change in food production under five temperature and CO_2 scenarios for four crops (wheat, maize, rice, and soybean) that account for two-thirds of total global human caloric consumption. The scenarios were identified as Today, Pre-Industrial, Glacial, Future_560, and Future_800, which correspond to respective atmospheric CO_2 concentrations of 400, 280, 180, 560, and 800 ppm, and temperatures that were -1 (Pre-Industrial), -6 (Glacial), +2 (Future_560), and +4 °C (Future_800) different from the Today scenario. The results are shown in Figure 5.3.5.1.1.

Mariani found a return to glacial period conditions would reduce global production of the four keystone crops by 51% while a return to pre-industrial conditions – the IPCC's declared objective -- would reduce food production by 18%. Looking ahead, Mariani estimates a world with double the pre-industrial level of CO_2 and temperatures 2°C higher than today's levels (Future_560) would witness food production 15% higher. A world where CO_2 levels were even higher (800 pmm) and temperatures were 4°C higher than today's levels (Future_800) would witness food production 24% above today's values.

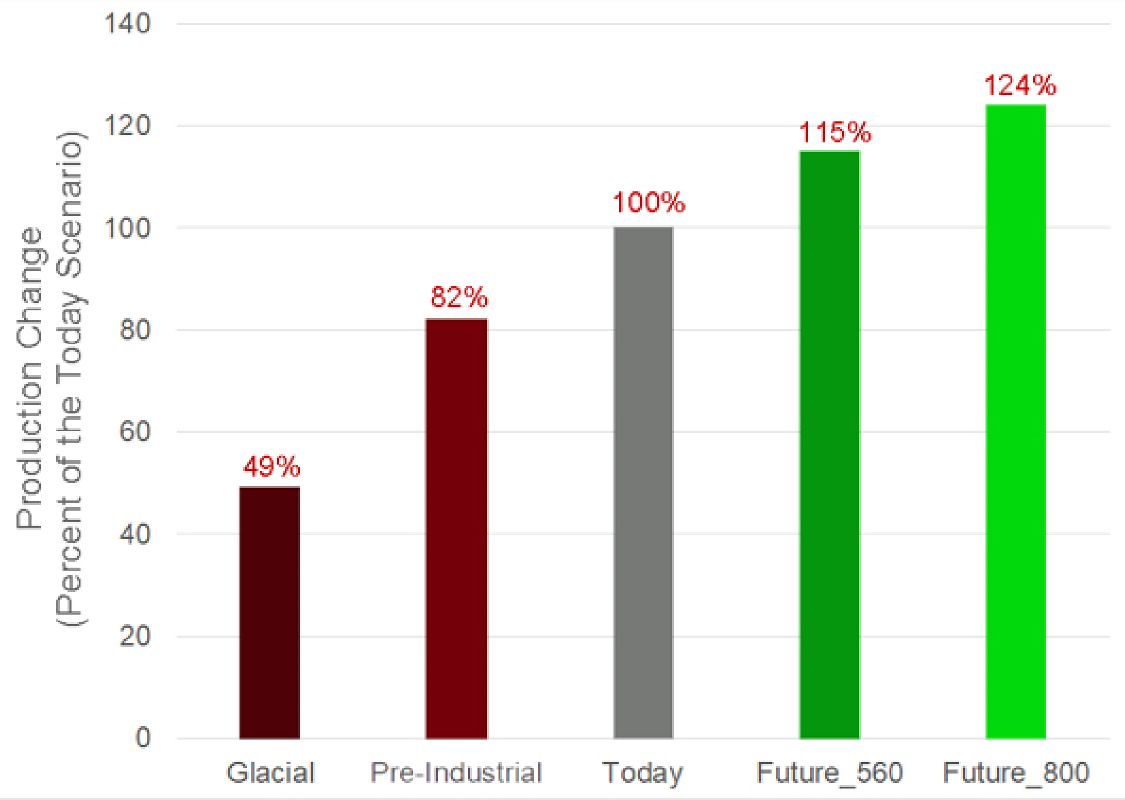
Mariani writes, "the return of temperature and CO_2 to glacial or pre-industrial values would give rise to serious disadvantages for food security and should be as far as possible avoided, as also highlighted by the results of Sage and Coleman (2001) and Araus *et al*. (2003)."

Ruiz-Vera *et al.* (2017) write, "with the continuous increase of atmospheric CO_2, it is critical to understand the role of sink limitation in the down-regulation of photosynthetic capacity under agricultural field conditions and the capacity of N [nitrogen] availability to mitigate it if agriculture is to meet future demand (Long *et al.*, 2004; Tilman and Clark, 2015)." They wonder if down regulation can be avoided by genetically increasing plant sink size and providing sufficient N so as to capitalize on "the full potential photosynthetic benefit of rising CO_2 [in] crops."

To investigate this possibility, Ruiz-Vera *et al.* designed an experiment to assess the potential of nitrogen fertilization to mitigate photosynthetic down regulation in tobacco (*Nicotiana tabacum L.*). The experiment was performed at a Free-Air CO_2 Enrichment (FACE) facility in Champaign, Illinois (USA) in 2015. Two tobacco cultivars of different sink strength were selected for study: Petit Havana (low sink capacity, producing small leaves) and Mammoth (high sink capacity, producing large leaves). After four weeks of initial growth in a greenhouse, plants of each cultivar were transplanted outdoors at the FACE facility where they were subjected in a full factorial design to two CO_2 levels (400 or 600 ppm) and two nitrogen applications (normal, 150 Kg N/ha, or high, 300 Kg N/ha). Over the next 48 days the scientists measured gas exchange, plant height, specific leaf area, leaf carbon and nitrogen content, leaf carbohydrates, and plant dry weight.

The authors report, "high sink strength resulting from rapid growth throughout the experiment appears to have prevented down-regulation in tobacco cv. Mammoth whereas the small stature of cv. Petite Havana appears to have resulted in progressive down-regulation." Nevertheless, despite down-regulation, photosynthetic uptake averaged over the growing season in Petit Havana was significantly higher (+11%) under elevated CO_2 regardless of nitrogen treatment. Ruiz-Vera *et al.* also report that increased nitrogen "partially mitigated the down-regulation of photosynthesis in cv. Petit Havana."

Figure 5.3.5.1.1
Percent change in the combined production of wheat, maize, rice, and soybean under five temperature and CO_2 scenarios



Columns from left to right are five climate scenarios: Glacial, 180 ppm CO_2 and -6°C relative to Today; Pre-Industrial, 280 ppm CO_2 and -1°C relative to Today; Today, 400 ppm CO_2; Future_560, 560 ppm CO_2 and +2°C relative to Today; and Future_800, 800 ppm CO_2 and +4°C relative to Today. *Source:* Mariani, 2017.

These findings and others, according to the authors, "confirm that under open-air conditions of CO_2 elevation in an agricultural field, down-regulation can be strongly offset in germplasm with a high sink capacity." Therefore, as they conclude, "down-regulation of photosynthetic capacity is not inevitable under field conditions where there is no limitation of rooting volume or interference with micro-climate if there is sufficient sink potential and nitrogen supply." This suggests society can capitalize on the full potential photosynthetic benefit of rising atmospheric CO_2 in crops by selecting cultivars with high sink capacity and/or adding supplemental nitrogen during the growing season.

Gesch *et al.* (2002) grew rice (*Oryza sativa* L.) in controlled environment chambers receiving atmospheric CO_2 concentrations of 350 ppm for about one month. Thereafter, plants were either maintained at 350 ppm CO_2 or switched to atmospheric CO_2 concentrations of 175 or 700 ppm for an additional 10 days to determine the effects of switching atmospheric CO_2 concentrations on photosynthesis, growth, and enzyme function in this important agricultural species.

Within 24 hours after the CO_2 concentration switch, plants placed in air of elevated CO_2 displayed significant increases in the activity of sucrose-phosphate synthase, a key enzyme involved in the production of sucrose. Plants moved to air of sub-ambient CO_2 exhibited significant reductions in the activity of this enzyme. Similarly, elevated CO_2 significantly increased the activity of ADP-glucose pyrophosphorylase, a key regulatory enzyme in starch synthesis, while sub-ambient CO_2 significantly reduced its activity.

Sucrose concentrations in mature source leaves of plants decreased following their transfer to air of high CO_2 concentration, while sucrose concentrations in sink organs (stems and sheaths) increased. At one day post-transfer, sucrose comprised only 43% of the total nonstructural carbohydrates present in these sinks. However, at 10 days post-transfer (the end of the experiment), sucrose made up 73% of the total nonstructural carbohydrates present in stems and sheaths.

Plants switched to air of elevated CO_2 concentration immediately displayed increases in their photosynthetic rates, while plants switched to sub-ambient CO_2 concentrations displayed immediate reductions in their photosynthetic rates. At the end of the experiment, plants growing at 700 ppm CO_2 still displayed photosynthetic rates 31% greater than those exhibited by unswitched controls, while plants subjected to 175 ppm CO_2 displayed photosynthetic rates 36% less than those exhibited by the same control plants. Ultimately, plants switched to atmospheric CO_2 concentrations of 700 and 175 ppm displayed total aboveground dry weights 54% greater and 18% less, respectively, than those exhibited by control plants maintained at 350 ppm CO_2.

The study by Gesch *et al.* shows that as the CO_2 content of the air rises, rice plants will likely exhibit increased rates of photosynthesis and carbohydrate production that should ultimately increase their biomass. The data acquired from this study suggest that rice plants may avoid the onset of photosynthetic acclimation by synthesizing and exporting sucrose from source leaves into sink tissues to avoid any photosynthetic end-product accumulation in source leaves. Through this mechanism, rice plants can take full advantage of the increasing atmospheric CO_2 concentration and stimulate their productivity and growth without exhibiting lower growth efficiencies resulting from photosynthetic acclimation.

In summary, many peer-reviewed studies suggest food production will continue to increase with increasing atmospheric CO_2 concentrations. Agricultural species may not necessarily exhibit photosynthetic acclimation, even under conditions of low soil nitrogen, for if a plant can maintain a balance between its sources and sinks for carbohydrates at the whole-plant level, acclimation should not be necessary. Because Earth's atmospheric CO_2 content is rising by an average of only 1.5 ppm per year, most plants should be able to adjust their relative growth rates by the small amount that would be needed to prevent low nitrogen-induced acclimation from occurring or expand their root systems by the small amount that would be needed to supply the extra nitrogen required to take full advantage of the CO_2-induced increase in leaf carbohydrate production. In the event a plant cannot initially balance its sources and sinks for carbohydrates at the whole-plant level, CO_2-induced acclimation represents a beneficial secondary mechanism for achieving that balance, redistributing resources away from the plant's photosynthetic machinery to strengthen sink development or enhance other nutrient-limiting processes.

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5.3.5.2 Biospheric Productivity

The vigor of Earth's terrestrial biosphere has been increasing with time, revealing a great post-Industrial Revolution greening of the Earth that extends across the entire globe, a phenomenon documented in Section 5.3.2 (see Zhu *et al.*, 2016; Campbell *et al.* 2017; and Cheng *et al.*, 2017). Nevertheless, it has been hypothesized that future greenhouse gas-induced climate changes could turn the terrestrial biosphere from a net carbon sink into a net carbon source (Cox *et al*., 2000; Matthews *et al*., 2005). Will biospheric productivity continue to improve during the twenty-first century and beyond?

Future biospheric productivity is difficult and probably impossible to predict due to our inability to forecast future local surface temperatures and other climatic conditions, poor understanding of feedbacks such as precipitation and cloud formation, and uncertainty over how much carbon is held in each of the four reservoirs (air, water, stone, and the biosphere) and the exchange rates among reservoirs. Different assumptions placed in the models used to forecast each of these variables can lead to dramatically different forecasts. In light of such uncertainty, the only scientific forecast is a continuation of past trends pointing to a continued greening of the Earth.

The physiological mechanisms whereby warmer temperatures and higher levels of CO_2 in the atmosphere lead to enhanced plant growth operate on a planetary scale. Research cited in the previous section demonstrates they are unlikely to be limited by photosynthetic acclimation or down-regulation. Computer models bear this out. Qian *et al*. (2010) analyzed the outputs of 10 models that were part of the Coupled Carbon Cycle Climate Model Intercomparison Project (C4MIP) of the International Geosphere-Biosphere Program and World Climate Research Program. All of the models, Qian *et al*. note, "used the same anthropogenic fossil fuel emissions from Marland *et al*. (2005) from the beginning of the industrial period until 2000 and the IPCC SRES A2 scenario for the 2000–2100 period."

The 10 models predicted a mean warming of 5.6°C from 1901 to 2100 in the northern high latitudes (NHL) and, Qian *et al*. found, "the NHL will be a carbon sink of 0.3 ± 0.3 $PgCyr^{-1}$ by 2100" [PgC is a petagram, one billion metric tonnes.]. They also state "the cumulative land organic carbon storage is modeled to increase by 38 ± 20 PgC over 1901 levels, of which 17 ± 8 PgC comes from vegetation [a 43% increase] and 21 ± 16 PgC from the soil [an 8% increase]," noting "both CO_2 fertilization and warming enhance vegetation growth in the NHL."

Thus over the course of the current century, even the severe warming predicted by some climate models would likely not be a detriment to plant growth and productivity in the NHL. In fact, it would likely be a benefit, enhancing plant growth and soil organic carbon storage.

Friend (2010) used the Hybrid6.5 model of terrestrial primary production and "the climate change anomalies predicted by the GISS-AOM GCM under the A1B emissions scenario for the 2090s [relative] to observed modern climate, and with atmospheric CO_2 increased from 375.7 ppm to 720 ppm" – a 92% increase – to calculate the changes in terrestrial plant production that would occur throughout the world in response to the projected climate changes alone and the projected concurrent changes in climate and atmospheric CO_2 concentration.

In response to projected climate changes between 2001–2010 and 2091–2100, Friend found net primary production (NPP) of the planet as a whole was reduced by 2.5%. When both climate and atmospheric CO_2 concentration were changed concurrently, however, Friend found a mean *increase* in global NPP of 37.3%. Thus, even for the magnitude of warming predicted to occur by the models relied on by the IPCC over the remainder of the twenty-first century, biospheric productivity can be expected to increase dramatically.

Lin *et al*. (2010) conducted a meta-analysis of pertinent data they obtained from 127 studies published prior to June 2009, in order to determine if the overall impact of a substantial increase in the air's CO_2 concentration on terrestrial biomass production would likely be positive or negative. They found for the totality of terrestrial plants included in their analysis, "warming significantly increased biomass by 12.3%," while noting there was a "significantly greater stimulation of woody (+26.7%) than herbaceous species (+5.2%)." They conclude, "results in this and previous meta-analyses (Arft *et al*., 1999; Rustad *et al*., 2001; Dormann and Woodin, 2002; Walker *et al*., 2006) have revealed that warming generally increases terrestrial plant biomass, indicating enhanced terrestrial carbon uptake via plant growth and net primary productivity."

New research continues to point to a positive future for Earth's terrestrial biosphere. Just one recent example is the discovery that seagrass meadows in Greenland could be emerging as a major carbon sink. Marbà *et al.* (2018) observed, "Seagrass meadows have been shown to rank amongst the most intense carbon-sink ecosystems of the biosphere with conservation and restoration programs aimed at protecting and restoring the carbon stocks and sink capacity lost with global seagrass decline." While the loss of seagrass in tropical areas has gained global attention, the expansion of seagrass meadows in Greenland has been overlooked. Seagrass meadows in Greenland "appear to be expanding and increasing their productivity," the authors write. "This is supported by the rapid growth in the contribution of seagrass-derived carbon to the sediment Corg pool, from less than 7.5% at the beginning of 1900 to 53% at present, observed in the studied meadows. Expansion and enhanced productivity of eelgrass meadows in the subarctic Greenland fjords examined here is also consistent with the on average 6.4-fold acceleration of Corg burial in sediments between 1940 and present."

According to Marbà *et al.*, "The expansion of seagrass in Greenland fjords represents a novel carbon sink, with limited significance at present due to the small size of the meadows. However, the potential for further expansion is huge, as the convoluted Greenland coastline represents about 12% of the global coastline." They conclude, "whereas the carbon sink associated with sediments under Greenland eelgrass meadows is likely to be very modest at present, it may reach significant levels along the 21st century."

In summary, the rising vitality of Earth's terrestrial biosphere observed during the twentieth and early twenty-first centuries by Zhu *et al.* (2016), Campbell *et al.* (2017), and Cheng *et al.* (2017) is very likely to continue through the twenty-first century and beyond. This is good news for humanity and for the natural world.

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5.3.5.3 Biodiversity

How will the ongoing rise in the air's CO_2 content affect the biodiversity of Earth's many ecosystems? Hundreds of studies have considered that question, often in the course of addressing other things, including:

- *genetic variability within species* (Hedhly, 2011; Rampino *et al.*, 2012; Hahn *et al.*, 2012; Oney *et al.*, 2013; Thilakarathne *et al.*, 2013; Marinciu *et al.*, 2013);
- *C_3 plants vs. C_4 plants* (Derner *et al.*, 2003; Zeng *et al.*, 2011; Hyovenen, 2011);
- *grasslands* (Ramseier *et al.*, 2005; Strengbom *et al.*, 2008; Steinbeiss *et al.*, 2008; Reich, 2009; Crain *et al.* 2012);
- *nitrogen fixers vs. non-nitrogen-fixers* (Roumet et al., 2000; Lilley et al., 2001); and
- *weeds vs. non-weeds* (Taylor and Potvin, 1997; Dukes, 2002).

The research gives good reason to believe Earth's increasing atmospheric CO_2 concentration will be *beneficial* to biodiversity by increasing niche security and expanding the ranges of nearly all the planet's many life forms. The historical record shows few cases of a negative effect of warming on diversity, even in cases where temperature increases were larger and more sudden than those forecast in coming centuries.

Jaramillo *et al.* (2010) looked back in time to the Paleocene-Eocene Thermal Maximum (PETM) of some 56 million years ago, which they noted "was one of the most abrupt global warming events of the past 65 million years." It was driven, as they described it, by "a massive release of 13C-depleted carbon" that led to "an approximate 5°C increase in mean global temperature in about 10,000 to 20,000 years." It was thought by many that Earth's tropical ecosystems "suffered extensively because mean temperatures are surmised to have exceeded the ecosystems' heat tolerance." But did the ancient warming of the world truly constitute a major problem for the planet's rainforests?

In an attempt to answer that question, Jaramillo *et al.* analyzed pollen and spore contents and the stable carbon isotopic composition of organic materials obtained from three tropical terrestrial PETM sites in eastern Colombia and western Venezuela. Their findings revealed that the onset of the PETM was "concomitant with an increase in diversity produced by the addition of many taxa (with some representing new families) to the stock of preexisting Paleocene taxa." They determined this increase in biodiversity "was permanent and not transient."

Hof *et al.* (2011) note recent and projected climate change is assumed to be exceptional because of its supposedly unprecedented velocity; they say this view has fueled the prediction that CO_2-induced increases in surface temperatures "will have unprecedented effects on earth's biodiversity," primarily by driving many species to extinction. It is widely assumed that Earth's plants and animals are unable to migrate poleward in latitude or upward in altitude fast enough to avoid extinction and also that current climate change simply outpaces evolutionary adaptation.

Hof *et al*. present evidence demonstrating "recent geophysical studies challenge the view that the speed of current and projected climate change is unprecedented." For example, they report Steffensen *et al*. (2008) showed temperatures in Greenland warmed by up to 4°C/year near the end of the last glacial period. They state this change and other rapid climate changes during the Quaternary (the last 2.5 million years) did not cause a noticeable level of broad-scale, continent-wide extinctions of species. Instead, the rapid changes appeared to "primarily affect a few specific groups, mainly large mammals (Koch and Barnosky, 2006) and European trees (Svenning, 2003)," with the result that "few taxa became extinct during the Quaternary (Botkin *et al*., 2007)."

Hof *et al*. speculate that "species may have used strategies other than shifting their geographical distributions or changing their genetic make-up." They note, for example, that "intraspecific variation in physiological, phenological, behavioral or morphological traits may have allowed species to cope with rapid climatic changes within their ranges (Davis and Shaw, 2001; Nussey *et al*., 2005; Skelly *et al*., 2007)," based on "preexisting genetic variation within and among different populations, which is an important prerequisite for adaptive responses," noting "both intraspecific phenotypic variability and individual phenotypic plasticity may allow for rapid adaptation without actual microevolutionary changes."

Hof *et al*. noted, "habitat destruction and fragmentation, not climate change *per se*, are usually identified as the most severe threat to biodiversity (Pimm and Raven, 2000; Stuart *et al*., 2004; Schipper *et al*., 2008)." And since "species are probably more resilient to climatic changes than anticipated in most model assessments of the effect of contemporary climate change on biodiversity," addressing habitat destruction and fragmentation, rather than climate change, should take priority, since those more direct and obvious effects of mankind are more destructive, more imminent, and more easily addressed than are the less direct, less obvious, less destructive, less imminent, and less easily addressed effects of the burning of fossil fuels.

Polley *et al*. (2012) looked for the impact of CO_2 enrichment on the composition and diversity of vegetation in tallgrass prairie communities. They hypothesized that "feedbacks from species change would amplify the initial CO_2 stimulation of aboveground net primary productivity (ANPP) of tallgrass prairie communities." To test that hypothesis, they "grew communities of perennial forb and C_4 grass species for 5 years along a field CO_2 gradient (250–500 ppm) in central Texas (USA) on each of three soil types, including upland and lowland clay soils and a sandy soil," measuring a number of plant physiological properties and processes, and ecosystem ANPP.

Polley *et al*. found CO_2 enrichment from 280 to 480 ppm "increased community ANPP by 0–117% among years and soils and increased the contribution of the tallgrass species *Sorghastrum nutans* (Indian grass) to community ANPP on each of the three soil types," noting the "CO_2-induced changes in ANPP and *Sorghastrum* abundance were linked." They write, "by favoring a mesic C_4 tall grass, CO_2 enrichment approximately doubled the initial enhancement of community ANPP on two clay soils," and conclude, "CO_2-stimulation of grassland productivity may be significantly underestimated if feedbacks from plant community change are not considered."

Royer and Cheroff (2013) analyzed "how atmospheric CO_2 and temperature relate to an angiosperm-dominated record of plant diversity," based on the specific types and proportions of pollen found in central Colombia and western Venezuela that dated back to the Palaeogene and early Neogene (65–20 million years ago), where the knowledge of pollen morphospecies richness came from Jaramillo *et al*. (2006); atmospheric CO_2 data came from the compilation of Beerling and Royer (2011), together with subsequent updates provided by Pagani *et al*. (2011) and Grein *et al*. (2011); and benthic $\delta^{18}O$ data came from the compilation of Zachos *et al*. (2008).

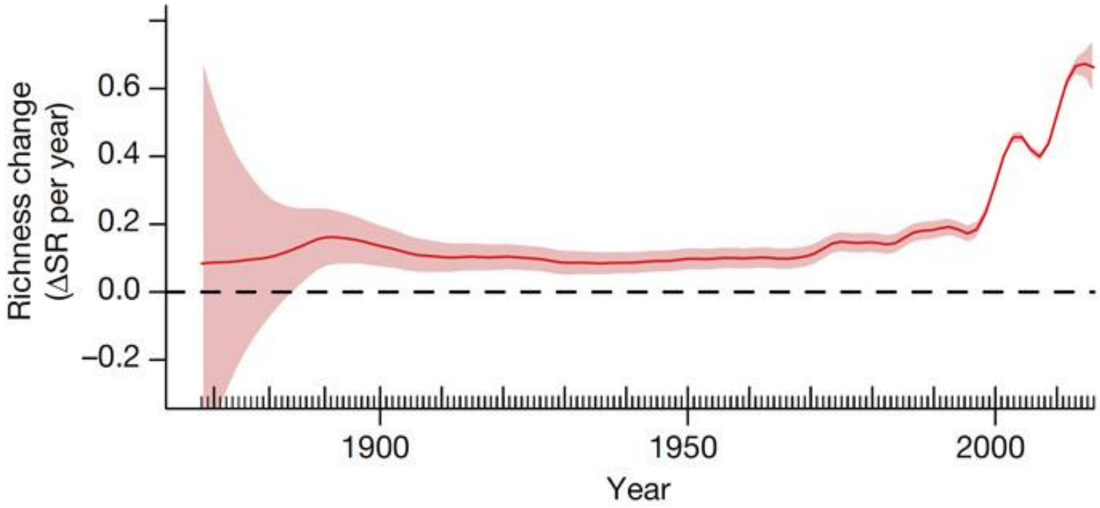
Royer and Cheroff report "pollen morphospecies richness from the neotropics of Colombia and Venezuela is more strongly correlated with atmospheric CO_2 than it is with temperature." In fact, "atmospheric CO_2 is the only dataset that mirrors (1) the low richness values at the beginning (Palaeocene) and end (Miocene) of the time series, (2) sustained high values during the mid-Eocene, and (3) a short-term spike in the late Palaeocene." In other words, higher atmospheric levels of CO_2 promoted plant diversity regardless of changes in global temperatures.

The 53-member research team of Steinbauer *et al*. (2018), publishing in the journal *Nature*, analyzed a massive continent-wide dataset of repeated plant surveys from 302 mountain summits across Europe dating back to 1871 in an effort to "assess the temporal trajectory of mountain biodiversity changes." Vegetation surveys were conducted predominantly on the uppermost 10 meters of elevation on each summit during the summer, with each summit being resurveyed one to six times between 1871 and 2016, for a total of 698 surveys over the period of study. Such surveys, in the words of the authors, were "optimal … for detecting changes in plant species richness over time."

Steinbauer *et al*. report there has been "a continent-wide acceleration in the rate of increase in plant species richness, with five times as much species enrichment between 2007 and 2016 as fifty years ago, between 1957 and 1966." (See Figure 5.3.5.3.1.) They note this trend of increasing biodiversity was "consistent across all [continental regions], with no single region showing the opposite pattern."

Despite such good news rooted in real-world observations, the team of researchers just could not bring themselves to reject the CO_2-induced global warming-extinction hypothesis. They opine that "accelerating plant species richness increases are expected to be a transient phenomenon that hides the accumulation of a so-called extinction debt," where "a rapid loss of alpine-nival species may occur under accelerated global warming." But extensive research

Figure 5.3.5.3.1
Rate of change in species richness



Red line is mean, shaded grey area represents ± standard error of the mean (SEM). *Source:* Steinbauer *et al.,* 2018.

on alpine ecosystems, reported earlier in Section 5.3.2, finds no basis for such concern.

Additional research summarized in the next two sections, addressing extinction and evolution, exposes the faulty assumptions underlying forecasts that climate change will reduce plant diversity. In summary, fear that climate change might reduce biodiversity is contradicted by the historical record and by what we know about the mechanisms whereby warmer temperatures and higher levels of CO_2 in the atmosphere benefit plant life.

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5.3.5.4 Extinction

According to the Working Group II contribution to the IPCC's Fifth Assessment Report, a "large fraction of both terrestrial and freshwater species faces increased extinction risk under projected climate change during and beyond the 21st century, especially as climate change interacts with other stressors, such as habitat modification, over-exploitation, pollution, and invasive species (*high confidence*)" (IPCC 2014, pp. 14-15). Like so many of the IPCC's other predictions, this one ignores natural variability and extensive data on plant and animal life that contradict it.

The IPCC takes advantage of the public's false perception that extinctions are often or only the result of human disturbances to the natural order. In reality, the vast majority of extinctions have nothing to do with human behavior. According to Raup (1986), "five extinctions stand out consistently as the largest and they are conventionally labeled mass extinctions. The five are terminal Ordovician (-440 million years ago), late Devonian (-365 million years ago), terminal or late Permian (-250 million years ago), terminal Triassic (-215 million years ago), and terminal Cretaceous (65 million years ago). The ranking of the five depends somewhat on database and metric, but the Permian event usually emerges as the largest, with published estimates of species kill ranging as high as 96 percent" (p. 1529).

Raup warns that our knowledge of these mass extinctions and many smaller ones in the distant past relies on a database of only about 250,000 known fossil species, "an extremely small sample of past life because of the negligible probability of preservation and discovery of any given species" (p. 1528). Nevertheless, he says "up to 4 billion species of plants and animals are estimated to have lived at some time in the geologic past, most of these in the last 600 million years (Phaneromic time). Yet there are only a few million species living today. Thus, extinction of species has been almost as common as origination."

More recently, Jablonski (2004) observed, "Extinction is a fundamental part of nature – more than 99% of all species that ever lived are now extinct." He also warns that our understanding of past and future extinctions is limited not only by the absence of fossil records observed by Raup but by our ignorance of how many species *currently* exist. "The most daunting obstacle to assessing and responding to these problems is the lack of anything close to a full accounting of present-day biodiversity: the 1.75 million known species probably represent less than 10% of the true inventory, and the figure is surely less than 1% for genetically distinct populations."

What follows the extinction of a species or a larger group of related species (called a "clade")? Jablonski writes, "post-extinction periods are famously important in opening opportunities for once-marginal groups, for example the expansion of mammals after the dinosaurs' demise." Similarly, Erwin (2001) writes, "However much one may mourn the passing of trilobites, conodonts, ammonoids, richtofenid brachiopods, and even dinosaurs, there is no denying the profound evolutionary impetus mass extinctions have provided to the history of life. Mass extinctions create new evolutionary opportunities and redirect the course of evolution."

Extinctions, then, are not unnatural or objectively bad things: They occur constantly even in the absence of human action, they are as "natural" as the origination of species and they create opportunities (ecological niches) for new species or improve the success of other, better-adapted species. Viewed in this context, the IPCC's worries about humans causing more extinctions seem naïve. We do not even know how many species currently exist; we do not know how the number of species driven to extinction by human action in the past (e.g., the dodo and passenger pigeon) compares to the number made extinct by other causes during that same period (perhaps thousands and possibly millions), or how other species may *benefit* from the extinction of a few. The IPCC itself admits "only a few recent species extinctions have been attributed as yet to climate change (*high confidence*)" (IPCC, 2014, p. 4) and even those claims have been controversial.

The IPCC bases its forecasts of extinctions due to climate change on computer models, often referred to as *bioclimatic envelope models,* that rely on unrealistic and invalidated assumptions about the ability of plants and animals to adapt to changes in their environment, forecasts of temperature and precipitation changes, and the assumption that natural ranges are fully occupied *but for* climatic reasons, failing to account for many different reasons such as disease, competition, and more.

Focusing now on plants rather than animals (the possible extinction of animals is addressed in Section 5.4), Willis and MacDonald (2011) note that extinction scenarios are typically derived from “a suite of predictive species distribution models (e.g., Guisan and Thuiller, 2005)” that “predict current and future range shifts and estimate the distances and rates of movement required for species to track the changes in climate and move into suitable new climate space.” They write that one of the most-cited studies of this type, that of Thomas *et al*. (2004), “predicts that, on the basis of mid-range climatic warming scenarios for 2050, up to 37% of plant species globally will be committed to extinction owing to lack of suitable climate space.”

In contrast, Willis and MacDonald point out that “biotic adaptation to climate change has been considered much less frequently.” This phenomenon – sometimes referred to as *evolutionary resilience* – is “the ability of populations to persist in their current location and to undergo evolutionary adaptation in response to changing environmental conditions (Sgro *et al*., 2010).” They note this approach to the subject “recognizes that *ongoing change is the norm in nature* and one of the dynamic processes that generates and maintains biodiversity patterns and processes [italics added],” citing MacDonald *et al*. (2008) and Willis *et al*. (2009).

Willis and MacDonald examined the effects of significant and rapid warming on Earth’s plants during several previous intervals of the planet’s climatic history that were as warm as, or even warmer than, what the IPCC typically predicts for the next century. These intervals included the Paleocene-Eocene Thermal Maximum, the Eocene climatic optimum, the mid-Pliocene warm interval, and the Eemian interglacial. Their approach relies on empirical, data-based, reconstructions of the past – unlike the IPCC’s approach, which is built on theoretical model-based projections of the future.

Willis and MacDonald found, “persistence and range shifts (migrations) seem to have been the predominant terrestrial biotic response (mainly of plants) to warmer intervals in Earth’s history,” while “the same responses also appear to have occurred during intervals of rapid climate change.” In addition, they note “evidence for global extinctions or extinctions resulting from reduction of population sizes on the scale predicted for the next century owing to loss of suitable climate space (Thomas *et al*., 2004) is not apparent.”

Also questioning the accuracy of standard bioclimatic envelope models, Feurdean *et al.* (2012) note “models run at finer scales (Trivedi *et al*., 2008; Randin *et al*., 2009) or including representations of plant demography (Hickler *et al*., 2009) and more accurate dispersal capability (Engler and Guisan, 2009) appear to predict a much smaller habitat and species loss in response to climate model predictions than do more coarse-scale models (Thomas *et al*., 2004; Thuiller *et al*., 2005; Araujo *et al*., 2008).”

Feurdean *et al*. analyzed seven fossil pollen sequences from Romania situated at different elevations “to examine the effects of climate change on community composition and biodiversity between 15,000 and 10,500 cal. yr BP,” a period “characterized by large-amplitude global climate fluctuations occurring on decadal to millennial time scales (Johnsen *et al*., 1992; Jouzel *et al*., 2007).” They sought to understand “how repeated temperature changes have affected patterns of community composition and diversity” and identify “recovery processes following major disruptions of community structure.”

Feurdean *et al*. report “community composition at a given time was not only the product of existing environmental conditions, but also the consequence of previous cumulative episodes of extirpation and recolonization.” They note “many circumpolar woody plants were able to survive when environmental conditions became unfavorable” and “these populations acted as sources when the climate became more favorable again.” That behavior, they write, “is in agreement with modeling results at the local scale, predicting the persistence of suitable habitats and species survival within large-grid cells in which they were predicted to disappear by coarse-scale models.”

Bocsi *et al*. (2016) write, “projections of habitat loss due to climate change assume that many species will be unable to tolerate climate conditions outside of those found within their current distributional ranges.” To explore whether that assumption is justified, they “compared the climatic conditions between occurrences in U.S. native vs. U.S. non-native ranges using 144 non-invasive plant species,” quantifying “differences in January minimum temperature, July maximum temperature and annual precipitation as indicators of climatic tolerance.”

They also compared "modelled potential distributions throughout the U.S. based on native and total ranges to test how expanded climatic tolerance translates into predicted geographical range."

Bocsi *et al*. report that "plants' native ranges strongly underestimate climatic tolerance, leading species distribution models to under-predict potential range," further noting "the climatic tolerance of species with narrow native ranges appears most prone to underestimation." They conclude, "many plants will be able to persist *in situ* with climate change for far longer than projected by species distribution models."

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5.3.5.5 Evolution

Various researchers (e.g., Gonzalo-Turpin and Hazard, 2009; Steinbauer, *et al.*, 2018) have asserted that alpine and other ecosystems are "threatened by global warming" and the many species that comprise them "are at risk of extinction." Hansen (2006) has claimed life in alpine regions is in danger of being "pushed off the planet" by rising temperatures.

Researchers have been unable to identify any species of plants that have been "pushed off the planet" in alpine regions (Walther *et al*., 2005; Kullman, 2007; Holzinger *et al*., 2008; Randin *et al*., 2009; Erschbamer *et al*., 2009). Research continues to confirm the ability of plants (and terrestrial animals and marine life, discussed in Sections 5.4 and 5.5 below) to adjust to changes in their environment.

Stocklin *et al*. (2009) studied the highly structured alpine landscape in the Swiss Alps for evidence of evolutionary processes in four plants (*Epilobium fleischeri*, *Geum reptans*, *Campanula thyrsoides*, and *Poa alpina*), testing for whether genetic diversity within their populations was related to altitude and land use, while seeking to determine whether genetic differentiation among populations was related more to different land use or to geographic distances. They determined the within-population genetic diversity of the four species was high and mostly not related to altitude and population size, while genetic differentiation among populations was pronounced and strongly increasing with distance, implying "considerable genetic drift among populations of alpine plants."

Based on their findings and the observations of others, Stocklin *et al*. note "phenotypic plasticity is particularly pronounced in alpine plants," and "because of the high heterogeneity of the alpine landscape, the pronounced capacity of a single genotype to exhibit variable phenotypes is a clear advantage for the persistence and survival of alpine plants." Hence, they conclude "the evolutionary potential to respond to global change is mostly intact in alpine plants, even at high altitude."

Ensslin and Fischer (2015) studied how plants respond to transplantation to different elevations on Mt. Kilimanjaro, Tanzania, in order to determine whether there is sufficient quantitative genetic (among-seed family) variation in and selection on life-history traits and their phenotypic plasticity. They transplanted seed families of 15 common tropical herbaceous species of the montane and savanna vegetation zones of Mt. Kilimanjaro to watered experimental gardens in those zones and then measured species performance, reproduction, and some phenological traits.

They found "seed families within species responded differently to warming," suggesting "some genotypes may persist" and "species may subsequently adapt to warming." They also "found genetic variation in all trait means and in some trait plasticities to transplantation," which is "the prerequisite for adaptive evolution of traits and of plasticities to changes in environmental conditions." They also reported, "because selection on the measured traits did not change between gardens, it appears that the adaptive potential of these species will not be compromised by high temperatures." Ensslin and Fischer conclude "evolutionary adaptation seems a probable scenario for most of the studied common species and might alleviate the negative responses to warming."

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5.4 Impact on Terrestrial Animals

> *The IPCC's forecasts of possible extinctions of terrestrial animals are based on computer models that have been falsified by data on temperature changes, other climatic conditions, and real-world changes in wildlife populations.*

The Working Group II contribution to the IPCC's Fifth Assessment Report quoted in Section 5.3.6.4, claiming "a large fraction of both terrestrial and freshwater species faces increased extinction risk under projected climate change during and beyond the 21st century," appears to be a retreat from the Fourth Assessment Report, wherein the IPCC claimed "new evidence suggests that climate-driven extinctions and range retractions are already widespread" and the "projected impacts on biodiversity are significant and of key relevance, since global losses in biodiversity are irreversible (*very high confidence*)" (IPCC, 2007). Unfortunately, the IPCC has not retreated far enough to catch up to the truth.

Before undertaking a survey of the literature on increasing surface temperatures and terrestrial animals, it is necessary to acknowledge that virtually all studies alleging to find a negative effect are based on the IPCC's climate models, which are known to exaggerate the likely warming, frequency of extreme weather, and other possibly harmful climatic conditions in the twenty-first century and beyond. The IPCC's forecasts were rigorously critiqued in Chapter 2 citing many sources (e.g., Diffenbaugh *et al.*, 2008; Armstrong *et al.*, 2008; Sardeshmukh *et al.*, 2015; Landsea, 2015; Burn and Palmer, 2015; Camargo and Wing, 2016; Stapleton *et al.*, 2016; Crockford, 2016, 2017; Christy, 2017; and Sutton *et al.*, 2018). A previous volume in the *Climate Change Reconsidered* was devoted to debunking the IPCC's physical science findings (NIPCC, 2013). The significance of this cannot be stressed enough: Virtually all predictions of future extinctions due to climate change are invalid because researchers assume too much warming, droughts, extreme weather, and other kinds of climate change.

Section 5.4.1 presents some of the extensive research showing terrestrial animals have the ability to adapt to changes in climate as great as or even greater than those forecast by the IPCC. Section 5.4.2 looks at the most probable future impact of climate change on terrestrial animals. Although there likely will be some changes in terrestrial animal population dynamics, few if any will be driven even close to extinction. Real-world data indicate warmer temperatures and higher atmospheric CO_2 concentrations will be highly beneficial, favoring a proliferation of species.

A chapter of a previous volume in the *Climate Change Reconsidered* series, Chapter 5 of *Climate Change Reconsidered II: Biological Impacts* (NIPCC, 2014), reviewed and analyzed IPCC-based species extinction claims, highlighting many of the problems inherent in the models on which such claims are based. The model projections were then evaluated against real-world observations of various animal species and their response to what the IPCC has called the unprecedented rise in atmospheric CO_2 and temperature of the twentieth and twenty-first centuries. NIPCC's key findings regarding terrestrial animals appear in Figure 5.4.1.

Figure 5.4.1
Key Findings: Impacts on terrestrial animals

- The IPCC's forecast of future species extinction relies on a narrow review of the literature that is highly selective and based almost entirely on model projections as opposed to real-world observations; the latter often contradict the former.

- Numerous shortcomings are inherent in the models utilized in predicting the impact of climate on the health and distributions of animal species. Assumptions and limitations make them unreliable.

- Research suggests amphibian populations will suffer little, if any, harm from rising surface temperatures and CO_2 levels in the atmosphere and they may even benefit.

- Although some changes in bird populations and their habitat areas have been documented in the literature, linking such changes to climate change remains elusive. Also, when there have been changes, they often are positive, as many species have adapted and are thriving in response to rising temperatures of the modern era.

- Polar bears have survived historic changes in climate that have exceeded those of the twentieth century or are forecast by computer models to occur in the future. In addition, some populations of polar bears appear to be stable despite rising temperatures and summer sea ice declines. The biggest threat they face is not from climate change but hunting by humans, which historically has taken a huge toll on polar bear populations.

- The net effect of climate change on the spread of parasitic and vector-borne diseases is complex and at this time appears difficult to predict. Rising temperatures increase the mortality rates as well as the development rates of many parasites of veterinary importance and temperature is only one of many variables that influence the range of viruses and other sources of diseases.

- Existing published research indicates rising temperatures likely will not increase and may decrease plant damage from leaf-eating herbivores, as rising atmospheric CO_2 boosts the production of certain defensive compounds in plants that are detrimental to animal pests.

- Empirical data on many other animal species, including butterflies, other insects, reptiles, and mammals, indicate warmer temperatures and higher CO_2 levels in the atmosphere tend to foster the expansion and proliferation of animal habitats, ranges, and populations, or otherwise have no observable impacts one way or the other.

- Multiple lines of evidence indicate animal species are adapting and in some cases evolving to cope with climate change of the modern era.

Source: Chapter 5. "Terrestrial Animals," *Climate Change Reconsidered II: Biological Impacts.* Nongovernmental International Panel on Climate Change. Chicago, IL: The Heartland Institute, 2014.

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5.4.1 Evidence of Ability to Adapt

> *Animal species are capable of migrating, evolving, and otherwise adapting to changes in climate that are much greater and more sudden than what is likely to result from the human impact on the global climate.*

Even assuming its climate models were unbiased and reasonably accurate, the IPCC's forecast of future animal extinctions still would not be reliable because it depends on species distribution models based on assumptions about the immobility of species that are contradicted by real-world observations. The failure of those models with respect to plants was documented in Section 5.3.6.4 above. Here we turn to the adaptability of Earth's terrestrial animals, while Section 5.5.1 will consider the adaptability of aquatic life.

The IPCC improperly characterizes the adaptive responses (e.g., range shifts, phenotypic or genetic adaptations) of many species as supporting their model-based extinction claims, when in reality such adaptive responses provide evidence of species resilience. The "climate envelope" approach used to predict shifts in the ranges of Earth's many animal species – and sometimes their extinction – fails to accurately describe the way real animals respond to climate change in the real world.

Behavioral plasticity (the ability of a species to alter its behavior), developmental plasticity (changes in the timing of events in a species' development), migration, and evolutionary adaptation are mechanisms by which living organisms will successfully confront the challenges that may be presented to them by rising surface temperatures, as the recent research summarized in Sections 5.4.1.1 through 5.4.1.4 shows.

5.4.1.1 Amphibians

Li *et al.* (2013) synthesized the research literature on the influence of global climate change on amphibians. They report, "evidence is lacking on poleward shifts in amphibian distributions and on changes in body sizes and morphologies of amphibians in response to climate change." They also note "we have limited information on amphibian thermal tolerances, thermal preferences, dehydration breaths, opportunity costs of water conserving behaviors and actual temperature and moisture ranges amphibians experience." And even when the information *is* available, they say, "there remains little evidence that climate change is acutely lethal to amphibians." They conclude, "we must remember that climate change will likely have both positive and negative effects on amphibians and that geographic regions will vary in terms of both the severity of and species sensitivities to climate change."

Lindstrom *et al.* (2013) describe how species move into regions where they historically have not been present – called an "invasion front" in biology. They note the biology of species populations at an invasion front "differs from that of populations within the range core, because novel evolutionary and ecological processes come into play …" Seeking to determine how individual members of a given species disperse at an invasion front, they analyzed an extensive dataset they derived by radio-tracking invasive cane toads (*Rhinella marina*) over the first eight years following their arrival at a site in tropical Australia.

Lindstrom *et al*. found "pioneer toads spent longer periods in dispersive mode and displayed longer, more directed movements while they were in dispersive mode." They discovered "overall displacement per year was more than twice as far for toads at the invasion front compared with those tracked a few years later at the same site."

Lindstrom *et al*. concluded "studies on established populations (or even those a few years post-establishment) thus may massively underestimate dispersal rates at the leading edge of an expanding population." They note that "this, in turn, will cause us to under-predict the rates at which native taxa can expand into newly available habitat under climate change."

Orizaola and Laurila (2016) note some organisms can respond to changing environmental conditions "through migration, plasticity and/or genetic adaptation," while others, "due to habitat fragmentation and low dispersal capacities, … must respond to environmental change *in situ*," citing Chevin *et al*. (2010). They "examined variation in developmental plasticity to changing temperature in the pool frog (*Pelophylax lessonae*) across its distribution by studying populations from central areas (Poland), edge populations (Latvia) and northern marginal populations (Sweden)."

Orizaola and Laurila report, "plasticity in larval life-history traits was highest at the northern range margin," where when reared at induced high temperatures, "larvae from marginal populations shortened larval period and increased growth rate more than larvae from central and edge populations." They write that "the detection of high levels of developmental plasticity in isolated marginal populations suggests that they may be better able to respond to the temperature regimes expected under climate change than often predicted, reflecting the need to incorporate geographic variation in life-history traits into models forecasting responses to environmental change."

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5.4.1.2 Birds

Smit *et al.* (2013) investigated the effects of air temperature on body temperature and the behavior of the White-browed Sparrow-Weaver (*Plocepasser mahali*) at two sites 100 kilometers apart in the southern Kalahari Desert of South Africa, over two consecutive summer seasons. Among other things, they found a relatively large variation in body temperature both within and between conspecific populations, which suggested to them that "an arid-zone passerine responds differently to prevailing weather conditions in two locations over its range and that it also responds to seasonal changes in weather conditions" – which further suggests "a species' current range may not be an accurate representation of its climatic tolerance."

"Taken together with the data of Glanville *et al*. (2012)," Smit *et al*. write, this result "suggests that the thermal physiology of endotherms [warm-blooded animals] is far more flexible than previously thought and could potentially contribute to the adaptation of populations under changing climatic conditions," citing Boyles *et al*. (2011)," so that "when predicting species' responses to climate change, their sensitivity (sensu Williams *et al*., 2008) should be resolved at the population, rather than species, level."

Atkinson *et al.* (2013) note "Hawaiian honeycreepers are particularly susceptible to avian malaria and have survived into this century largely because of persistence of high elevation refugia on Kaua'I, Maui and Hawai'I Islands, where transmission is limited by cool temperatures." Because the long-term stability of these refugia could be threatened by future warming and "since cost effective and practical methods of vector control in many of these remote, rugged areas are lacking, adaptation through processes of natural selection may be the best long-term hope for recovery of many of these species." In a study devised to explore this possibility, Atkinson *et al.* discovered and documented what they describe as the "emergence of tolerance rather than resistance to avian malaria in a recent rapidly-expanding low-elevation population of Hawai'I 'Amakihi (*Hemignathus virens*) on the island of Hawai'i."

Atkinson *et al.* determined "experimentally infected low-elevation birds had lower mortality, lower reticulocyte counts during recovery from acute infection, lower weight loss, and no declines in food consumption relative to experimentally infected high elevation Hawai'I 'Amakihi in spite of similar intensities of infection." They state that the "emergence of this population provides an exceptional opportunity for determining physiological mechanisms and genetic markers associated with malaria tolerance that can be used to evaluate whether other, more threatened species have the capacity to adapt to this disease." Their finding "opens the possibility that other native honeycreepers may also be able to adapt to this disease through processes of natural selection."

Thompson *et al.* (2015) investigated the effects of a 4°C increase in ambient temperature – similar to that typically predicted for southern Africa by the year 2080 – on certain physiological variables of 10- to 12-gram Cape white-eye *Zosterops virens*, a passerine bird species endemic to South Africa. The scientists report "there was no significant difference in resting metabolism, body mass and intraperitoneal body temperature between birds housed indoors at 4°C above outside ambient temperature and those housed indoors at outside ambient temperature." They conclude, "the physiological flexibility of Cape white-eyes will aid them in coping with the 4°C increase [in air temperature] predicted for their range by 2080."

Nilsson *et al.* (2016) write that in a warming world, many "organisms in hot environments will not be able to passively dissipate metabolically generated heat," noting they will have to revert to evaporative cooling, which is "energetically expensive and promotes excessive water loss." They explored "the use of hyperthermia in wild birds captured during the hot and dry season in central Nigeria," revealing the presence of "pronounced hyperthermia in several species with the highest body temperatures close to predicted lethal levels." They also found "birds let their body temperature increase in direct relation to ambient temperatures, increasing body temperature by 0.22°C for each degree of increased ambient temperature." They also note that "to offset the costs of thermoregulation in ambient temperatures above the upper critical temperature, birds are willing to let their body temperatures increase by up to 5°C above normal temperatures." Nilsson *et al.* state "this flexibility in body temperatures may make birds well adapted to meet future global increases in ambient temperature," citing the similar prior conclusions of Khaliq *et al.* (2014) and Thompson *et al.* (2015).

Gladalski *et al.* (2016) investigated the response of Great Tits (*Parus major*) and Blue Tits (*Cyanistes caeruleus*) to an extreme variation in spring temperature that occurred in central Poland between 2013 and 2014; the spring of 2013 was the coldest in 40 years, whereas the spring of 2014 was the warmest in 40 years. They gathered data from two habitats (an urban parkland and a deciduous forest) in Lódź (central Poland), part of an ongoing long-term study into the "breeding biology of hole-nesting birds occupying nestboxes." By comparing their observations from the two spring temperature extremes, the authors observed the effects of extreme thermal conditions on the plasticity of breeding phenology and double broodedness of both bird species. They report, "extremely low spring temperatures in 2013 (coldest spring in 40 years) resulted in birds laying [eggs] unusually late," and this phenomenon "was followed in 2014 by the earliest breeding season on record (warmest spring in 40 years)."

Gladalski *et al.* also found "the breeding date of Great Tits and Blue Tits turned out to be a flexible trait" and that "populations of both tit species may tune their egg-laying dates to diverse weather conditions by about 3 weeks," while in some cases they have both early and late clutches. They conclude "such a buffer of plasticity may be sufficient for Blue Tits and Great Tits to adjust the timing of breeding to the upcoming climate changes."

Vengerov (2017) evaluated "changes in the phenology of breeding and reproductive output of the Song Thrush (*Turdus philomelos*) under conditions of increase in spring air temperature," examining reproductive data collected at the Voronezh Nature Reserve every four or five days over the period 1987–1990 and 2008–2012. A total of 459 nests were observed over the nine years of study, during which time there was a statistically significant increase in spring temperatures.

Vengerov determined higher temperatures lead to an "earlier arrival of the birds from wintering grounds," "earlier and more synchronous breeding of the majority of nesting pairs," "an increase in clutch size," a higher proportion of pairs producing two broods per season, and a reduction in "predation pressure on bird nests … which markedly improves reproductive success." Vengerov writes, "climate warming is conducive to increasing breeding productivity of the Song Thrush population as a whole."

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5.4.1.3 Mammals

Coulson *et al.* (2011) write, "environmental change has been observed to generate simultaneous responses in population dynamics, life history, gene frequencies, and morphology in a number of species." They studied these adaptive responses in Yellowstone Park wolves, using "survival and reproductive success data, body weights, and genotype at the K locus (*CBD103*, a β-defensin gene that has two alleles and determines coat color), which were collected from 280 radio-collared wolves living in the park between 1998 and 2009." They noted "body weight and genotype at the K locus vary across U.S. wolf populations" and that both traits influence fitness, citing the studies of Schmitz and Kolenosky (1985), Anderson *et al*. (2009), and MacNulty *et al*. (2009).

Coulson *et al.* say their results "reveal that, for Yellowstone wolves, (i) environmental change will inevitably generate eco-evolutionary responses; (ii) change in the mean environment will have more profound population consequences than changes in the environmental variance; and (iii) environmental change affecting different functions can generate contrasting eco-evolutionary dynamics," which suggests that "accurate prediction of the consequences of environmental change will probably prove elusive."

Maldonado-Chaparro *et al.* (2015) "aimed to characterize patterns of phenotypic change in morphological (body mass), life-history (reproductive success and litter size), and social (embeddedness) traits of female yellow-bellied marmots (*Marmota* *flaviventris*) in response to climatic and social variation." They used data collected over a period of 36 years on a population in Colorado, using "mixed effect models to explore phenotypically plastic responses" while testing for individual variations in mean trait values and plasticity.

Maldonado-Chaparro *et al.* report "all examined traits were plastic and the population's average plastic response often differed between spatially distinct colonies that varied systematically in timing of snowmelt, among age classes and between females with different previous reproductive experiences." In addition, they detected "individual differences in June mass and pup mass plasticity," all of which led them to conclude that in the case of yellow-bellied marmots, "plasticity plays a key role buffering the effects of continuous changes in environmental conditions."

Smith and Nagy (2015) note American pikas (*Ochotona princeps*) "have been characterized as an indicator species for the effects of global warming on animal populations," citing the works of Smith *et al*. (2004), Beever and Wilkening (2011), and Ray *et al*. (2012). They investigated the resilience of a pika metapopulation residing near Bodie, California that was exposed to several decades of natural warming, testing for a relationship between pika extinctions/ recolonizations and chronic/acute temperature warming.

With respect to chronic temperature warming, Smith and Nagy report that despite a relatively high rate of patch (islands of pika-suitable habitat) turnover across the study location, there was "a near balance" of pika patch extinctions and recolonizations during the past four decades. Statistical analyses performed on the patch turnover and historic temperature data revealed there was "no evidence that warming temperatures have directly and negatively affected pika persistence at Bodie." The only significant correlation they found among the two parameters occurred between mean maximum August temperature and the number of pika recolonizations the following year, which correlation was *positive*, indicating higher August temperatures led to a greater rate of pika recolonization the next year, "in the opposite direction of the expectation that climate stress inhibits recolonizations."

With respect to acute temperature warming, defined as the number of hot summer days exceeding a temperature threshold of 25°C or 28°C (77°F or 82.4°F), Smith and Nagy write, "neither warm chronic nor acute temperatures increased the frequency of extinctions of populations on patches and relatively cooler chronic or acute temperatures did not lead to an increase in the frequency of recolonization events."

Varner *et al*. (2016) also studied American pikas (*Ochotona princeps*), these populations living in two habitat ranges in Oregon. One range comprised an elevation, landscape, and climate typical of the American pika's range, while the other was situated within an atypical low-elevation landscape and climate that "appears to be unsuitable [as a pika habitat], based on the species' previously described thermal niche." The researchers sought to quantify behavioral differences among the two populations, including differences pertaining to foraging and territorial behaviors. They collected 417 observer-hours of behavioral data in July 2011, 2012, and 2013, during which they made 5,250 pika detections.

Varner *et al*. report there were "substantial differences" in behavior between pika populations at the two habitats. They noted "low-elevation pikas do not invest as much time or energy in caching food for winter" and were more likely to spend time in forested areas off the open talus landscape around midday than pikas living at higher elevations. Pikas in the lower elevation and warmer habitat had smaller home range sizes compared to those at the higher elevation site.

Varner *et al*. write their findings "indicate that behavioral plasticity likely allows pikas to accommodate atypical conditions in this low-elevation habitat and that they may rely on critical habitat factors such as suitable microclimate refugia to behaviorally thermoregulate." They conclude, "these results suggest that behavioral adjustments are one important mechanism by which pikas can persist outside of their previously appreciated dietary and thermal niches."

Loe *et al*. (2016) analyzed "responses in space use to rain-on-snow and icing events and their fitness correlates, in wild reindeer in high-Arctic Svalbard." This work revealed that "range displacement among GPS-collared females occurred mainly in icy winters to areas with less ice, lower over-winter body mass loss, lower mortality rate, and higher subsequent fecundity, than the departure area." The researchers say their study provides "rare empirical evidence that mammals may buffer negative effects of climate change and extreme weather events by adjusting behavior in highly stochastic environments." They conclude, "under global warming, behavioral buffering may be important for the long-term population persistence in mobile species with long generation time and therefore limited ability for rapid evolutionary adaptation."

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5.4.1.4 Reptiles

Logan *et al*. (2014) say "tropical ectotherms [cold-blooded animals] are thought to be especially vulnerable to climate change because they are adapted to relatively stable temperature regimes, such that even small increases in environmental temperature may lead to large decreases in physiological performance." Nevertheless, they hypothesize that tropical organisms may mitigate the detrimental effects of warming through evolutionary change in thermal physiology.

To determine whether and how thermal physiology is subject to natural selection, Logan *et al*. "measured survival as a function of the thermal sensitivity of sprint speed in two populations of *Anolis sagrei* lizards from the Bahamas," quantifying the relationship between thermal performance and survival of 85 males from a non-manipulated population in order "to test whether a simulated change in thermal environment would increase or otherwise alter selection on thermal performance." They repeated the test on a population of 80 males they transplanted from an interior forested habitat to a warmer, more thermally variable site.

Logan *et al*. report, "when we simulated a rapid change in the thermal environment by transplanting a population of lizards to a warmer and more thermally variable habitat, we observed strong natural selection on thermal physiology," which implies "rapid climate change may result in directional selection on thermal physiology, even in species whose thermoregulatory behaviors are thought to shelter them from natural selection." They warn "evolutionary change will not occur unless thermal performance traits are heritable," but ultimately conclude, "even if the amount of warming expected through the end of the century occurred during a single breeding season, this species could hypothetically compensate for as much as 30% of that environmental change through evolutionary adaptation alone."

"[B]iologists have increasingly recognized that evolutionary change can occur rapidly," Stuart *et al*. (2014) confirm, and therefore "real-time studies of evolution can be used to test classic evolutionary hypotheses," one of which is that "negative interactions between closely related species can drive phenotypic divergence." They say "an opportunity to study such real-time divergence between negatively interacting species has been provided by the recent invasion of the Cuban brown anole lizard, *Anolis sagrei*, into the southeastern United States, where *Anolis carolinensis* is the sole native anole." There, they studied "the eco-evolutionary consequences of this interaction."

Stuart *et al*. report, "on small islands in Florida, we found that the lizard *Anolis carolinensis* moved to higher perches following invasion by *Anolis sagrei* and, in response, adaptively evolved larger toepads after only 20 generations," illustrating that "interspecific interactions between closely related species can drive evolutionary change on observable time scales."

Barrows and Fisher (2014) studied congeneric lizards in southern California, noting "species and species assemblages extant today survived multiple past climate shifts throughout the Pleistocene." One potential mechanism for their survival could have been behavioral adaptation, whereby the lizards shuttle between sun and shade to maintain a preferred body temperature (Tb) that is independent of ambient temperature, as described by Dawson (1967). More recently, Lopez-Alcaide *et al*. (2014) discovered "*Sceloporus adleri* can alter its thermoregulatory behavior to maintain its preferred Tb for key physiological processes when environmental temperatures were increased by 6°C."

Barrows and Fisher (2014) constructed a set of habitat suitability models (HSMs) for an assemblage of four sympatric species of lizards within the genus *Sceloporus* – *S. magister*, *S. occidentalis*, *S. vandenburgianus*, and *S. orcutti* – in order to predict their distributions under three climate conditions: the last glacial maximum of ca 20 kya, the present, and the end of the current century as foreseen by the IPCC (2013). They say their results suggest the elevational heterogeneity of the landscape they studied "provided suitable habitat for these species throughout a past cold climate extreme and will likely continue to do so under predicted future warming."

Llewelyn *et al*. (2016) tested for intraspecific variation in climate-relevant traits in the rainforest sunskink (*Lampropholis coggeri*). They tested for four traits that are potentially important in determining a lizard species' climate sensitivity: critical thermal minimum, critical thermal maximum, thermal optimum for sprinting, and desiccation rate. Working in the Wet Tropics Bioregion of Australia, the researchers studied 12 populations of *L. coggeri*. They found "substantial variation both through time and across space in the measured traits," which the authors say suggests the lizards possess both "strong plasticity and substantial geographic variation." They conclude that if physiological variability similar to that observed in rainforest sunskinks occurs in tropical rainforest species more generally, "these several taxa may not be as climatically specialized" and therefore "not as vulnerable to climate change, as previously thought."

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5.4.2 Future Impacts on Terrestrial Animals

> *Although there likely will be some changes in terrestrial animal population dynamics, few if any will be driven even close to extinction.*

As noted in the introduction to Section 5.4, the IPCC's climate model simulations bear no resemblance to real-world observations of global warmth and the simulations are diverging further from reality over time (Green and Armstrong, 2014; Christy, 2017). Given that the IPCC's species-modeling research relies almost exclusively on those failed climate models, it comes as little surprise that its species extinction predictions are also failing.

Hundreds of studies, including those summarized here, have concluded that although there likely will be some changes in terrestrial animal population dynamics, few if any will be driven even close to extinction. Real-world data indicate warmer temperatures and higher atmospheric CO_2 concentrations will be beneficial, favoring a maintenance or even proliferation of species.

Anchukaitis and Evans (2010) write, "widespread amphibian extinctions in the mountains of the American tropics have been blamed on the interaction of anthropogenic climate change and a lethal pathogen," but they note that "limited meteorological records make it difficult to conclude whether current climate conditions at these sites are actually exceptional in the context of natural variability," challenging the contention that modern warming was the primary culprit in the demise of the Monteverde golden toad (*Bufo periglenes*).

Anchukaitis and Evans developed annual proxy records of hydroclimatic variability over the past century within the Monteverde Cloud Forest of Costa Rica, based on measurements of the stable oxygen isotope ratio ($\delta^{18}O$) made on trees lacking annual rings, as described in the papers of Evans and Schrag (2004) and Anchukaitis *et al*. (2008). Their work led them to conclude "the extinction of the Monteverde golden toad appears to have coincided with an exceptionally dry interval caused by the 1986–1987 El Niño event." They say their analysis suggests "the cause of the specific and well-documented extinction of the Monteverde golden toad was the combination of the abnormally strong ENSO-forced dryness and the lethality of the introduced chytrid fungus, but was not directly mediated by anthropogenic temperature trends, a finding from paleoclimatology that is in agreement with statistical reanalysis (Rohr *et al*., 2008; Lips *et al*., 2008) of the 'climate-linked epidemic hypothesis'."

Willis *et al*. (2010) considered the IPCC's (IPCC, 2007a) contentions that "global temperatures will increase by 2–4°C and possibly beyond, sea levels will rise (~1 m ± 0.5 m), and atmospheric CO_2 will increase by up to 1000 ppm." They note it is "widely suggested that the magnitude and rate of these changes will result in many plants and animals going extinct," citing studies that suggest "within the next century, over 35% of some biota will have gone extinct (Thomas *et al*., 2004; IPCC, 2007b) and there will be extensive die-back of the tropical rainforest due to climate change (e.g. Huntingford *et al*., 2008)."

Willis *et al*. go on to note some biologists and climatologists have pointed out "many of the predicted increases in climate have happened before, in terms of both magnitude and rate of change (e.g. Royer, 2008; Zachos *et al*., 2008), and yet biotic communities have remained remarkably resilient (Mayle and Power, 2008) and in some cases thrived (Svenning and Condit, 2008)." They report that those who mention such things are often "placed in the 'climate-change denier' category," although the purpose for pointing out these facts is simply to present "a sound scientific basis for understanding biotic responses to the magnitudes and rates of climate change predicted for the future through using the vast data resource that we can exploit in fossil records."

Willis *et al*. focus on "intervals in time in the fossil record when atmospheric CO_2 concentrations increased up to 1200 ppm, temperatures in mid- to high-latitudes increased by greater than 4°C within 60 years, and sea levels rose by up to 3 m higher than present," describing studies of past biotic responses that indicate "the scale and impact of the magnitude and rate of such climate changes on biodiversity." What emerges from those studies, they write, "is evidence for rapid community turnover, migrations, development of novel ecosystems and thresholds from one stable ecosystem state to another." And, most importantly, they report "there is very little evidence for broad-scale extinctions due to a warming world." They conclude, "based on such evidence we urge some caution in assuming broad-scale extinctions of species will occur due solely to climate changes of the magnitude and rate predicted for the next century," reiterating that "the fossil record indicates remarkable biotic resilience to wide amplitude fluctuations in climate."

Mergeay and Santamaria (2012) introduce nine papers in a special issue of *Evolutionary Applications*, all of which were based on contributions to a meeting on Evolution and Biodiversity held in Mallorca, Spain (April 12–15, 2010) and a preparatory e-conference. Shine (2012) opens the special issue by "showing how evolution can rapidly modify ecologically relevant traits in invading as well as native species." Bijlsma and Loeschcke (2012) then "tackle the interaction of drift, inbreeding and environmental stress," while Angeloni *et al*. (2012) "provide a conceptual tool-box for genomic research in conservation biology and highlight some of its possibilities for the mechanistic study of functional variation, adaptation and inbreeding."

Van Dyck (2012) shows "an organism's perception of its environment is subject to selection, a mechanism that could reduce the initial impact of environmental degradation or alleviate it over the longer run." Urban *et al*. (2012) contend "certain consequences of global change can only be accounted for by interactions between ecological and evolutionary processes," and Lemaire *et al*. (2012) highlight "the important role of evolution in predator-prey interactions."

Focusing on eco-evolutionary interactions, Palkovacs *et al*. (2012) "review studies on phenotypic change in response to human activities" and "show that phenotypic change can sometimes cascade across populations, communities and even entire ecosystems," while Bonduriansky *et al*. (2012) examine "non-genetic inheritance and its role in adaptation," dissecting "the diversity of epigenetic and other transgenerational effects." Finally, Santamaria and Mendez (2012) "build on the information reviewed in all previous papers to identify recent advances in evolutionary knowledge of particular importance to improve or complement current biodiversity policy."

"Overall," Mergeay and Santamaria conclude, "these nine papers offer compelling evidence for the role of evolutionary processes in the maintenance of biodiversity and the adaptation to global change."

In summary, terrestrial animals are able to adapt to climate change occurring on scales that surpass those forecast even by the IPCC. Claims to the contrary invariably rely on the IPCC's flawed forecasts of future climate conditions and species survival models that overlook or ignore the documented real-world responses to change by many species. Climate change is not a threat to terrestrial animals and its impact on wildlife is not a cost. History suggests it may even be a benefit.

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5.5. Impact on Aquatic Life

> *The IPCC’s forecasts of dire consequences for life in the world’s oceans rely on falsified computer models and are contradicted by real-world observations.*

The Working Group I contribution to the IPCC’s Fifth Assessment Report (IPCC, 2013) warns that rising atmospheric CO_2 concentrations will harm aquatic life via changes in ocean temperature/heat content, salinity, and pH balance. That warning is based on the climate-model-driven claim that human emissions of CO_2 will cause Earth to warm unnaturally.

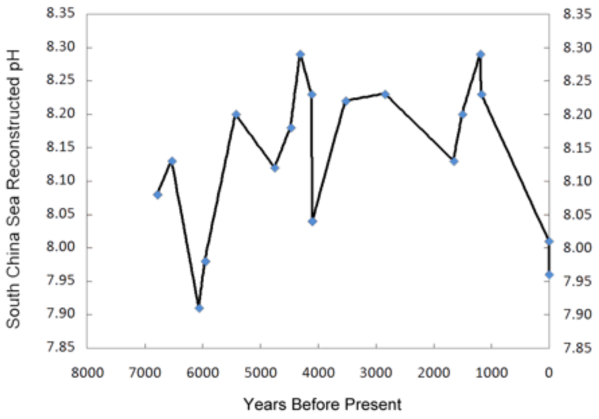
As noted in the introduction to this section, the IPCC’s climate model simulations bear no resemblance to real-world observations of global warmth and the simulations are diverging further from reality over time (Green and Armstrong, 2014; Christy, 2017). Therefore, the assumptions about temperature, precipitation, weather, and other climate factors typically fed into the models used to forecast the impact of climate change on marine life are invalid, invalidating the models outputs.

Several researchers have specifically noted the sensitivity of ocean warming projections to “temperature biases associated with differing instrumentation” (Gouretski and Koltermann, 2007) and data-processing methods (Carson and Harrison, 2008). Lyman *et al.* (2006) point out that ocean temperature is highly variable and “this variability is not adequately simulated in the current generation of coupled climate models used to study the impact of anthropogenic influences on climate,” which “may complicate detection and attribution of human-induced climate influences.”

Natural variability is also the rule and not the exception regarding ocean pH levels. Liu *et al.* (2009) studied 18 samples of fossil and modern *Porites* corals recovered from the South China Sea, employing ^{14}C dating and positive thermal ionization mass spectrometry to generate high precision $\delta^{11}B$ (boron) data. From that data they reconstructed the paleo-pH record of the past 7,000 years that is depicted in Figure 5.5.1.

Figure 5.5.1 shows there is nothing unusual, unnatural, or unprecedented about the two most recent pH values (shown on the far right edge of the figure). Hence, there is no compelling reason to believe they were significantly influenced by the nearly 40% increase in the air’s CO_2 concentration that occurred during Industrial Revolution. As for the

Figure 5.5.1
Reconstructed pH history of the South China Sea



Source: Created from Table 1 of Liu *et al.*, 2009.

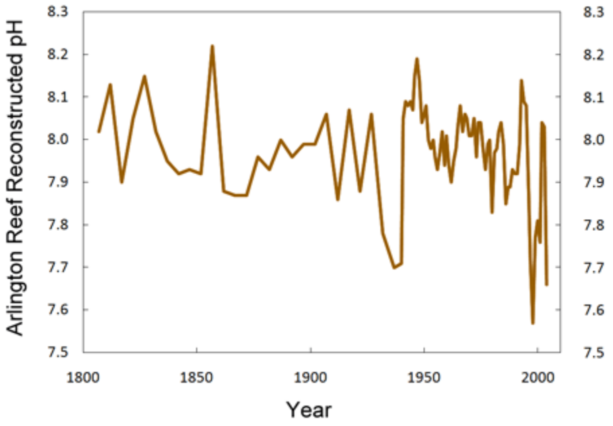
prior portion of the record, Liu *et al*. note there is also "no correlation between the atmospheric CO_2 concentration record from Antarctica ice cores and

Wei *et al*. (2009) derived the pH history of Arlington Reef (off the northeast coast of Australia) that is depicted in Figure 5.5.2. As can be seen there, there was a ten-year pH minimum centered at about 1935 (which obviously was not CO_2-induced) and a shorter more variable minimum at the end of the record (which also was not CO_2-induced); and apart from these two non-CO_2-related exceptions, the majority of the data once again fall within a band that exhibits no long-term trend, such as would be expected to have occurred if the gradual increase in atmospheric CO_2 concentration since the inception of the Industrial Revolution were truly making the global ocean less basic.

Coral bleaching models also are flawed, many assuming a fixed thermal tolerance not exhibited by corals in the real world, as documented below. For fish, models are often too coarse, assuming a broad species-specific response to change when in fact responses can vary by genetic lineages and even among populations within those lineages.

In contrast to the alarming projections of the IPCC's flawed computer models, real-world observations suggest aquatic species, like terrestrial plants and animals, are built to survive changes in their environment, including those that might develop in a world of increasing atmospheric CO_2. A previous

Figure 5.5.2
Reconstructed pH history of Arlington Reef off the northeast coast of Australia



Source: Adapted from Wei *et al.*, 2009.

volume in the *Climate Change Reconsidered* series (Idso *et al.*, 2014) found hundreds of peer-reviewed studies suggesting a much better future is in store for Earth's aquatic life. NIPCC's 2014 key findings regarding aquatic life, which challenge the alarming and negative projections of the IPCC, are presented in Figure 5.5.3.

More recent research is summarized below in Sections 5.5.1 on the ability of corals and fish to adapt to climate change and Section 5.5.2, on the likely future impacts of climate change on aquatic life. Many laboratory and field studies demonstrate toleration, adaptation, and even growth and developmental improvements in aquatic life in response to higher temperatures and reduced water pH levels. When these observations are considered, the pessimistic projections of the IPCC give way to considerable optimism with respect to the future of the planet's marine life.

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Figure 5.5.3
Key Findings: Impacts on aquatic life

- Multiple studies from multiple ocean regions confirm ocean productivity tends to increase with temperature. Subjects of this research include phytoplankton and macroalgae, corals, crustaceans, and fish.
- Rising seawater temperature is conducive to enhanced coral calcification, leading some experts to forecast coral calcification will increase by about 35% beyond pre-industrial levels by 2100 and no extinction of coral reefs will occur in the future.
- Many aquatic species demonstrate the capability to adjust their individual critical thermal maximum (the upper temperature at which the onset of behavioral incapacitation occurs) upwards in response to temperature increases of the amount forecast by the IPCC.
- Aquatic life has survived decadal, centennial, and millennial-scale climate oscillations that have persisted for millions of years. Evidence indicates aquatic species are well-equipped to adapt to forecasted increases in temperature, if necessary.
- Caution should be applied when interpreting results from laboratory-based studies of lower seawater pH levels. Such studies often are incapable, or fall far short, of mimicking conditions in the real world and thus they frequently yield results quite different than what is observed in nature.
- Rising atmospheric CO_2 levels do not pose a significant threat to aquatic life. Many aquatic species have shown considerable tolerance to declining pH values predicted for the next few centuries and many have demonstrated a likelihood of positive responses in empirical studies.
- The projected decline in ocean pH levels in the year 2100 (as compared to preindustrial times) may be significantly overstated, amounting to only half of the 0.4 value the IPCC predicts.
- The natural variability of oceanic pH is often much greater than the change in pH levels forecast by the IPCC.

- Natural fluctuations in pH may have a large impact on the development of resilience in marine populations, as heterogeneity in the environment with regard to pH and $p\mathrm{CO_2}$ exposure may result in populations that are acclimatized to variable pH or extremes in pH.

- For those aquatic species showing negative responses to pH declines in experimental studies, there are adequate reasons to conclude such responses will be largely mitigated through phenotypic adaptation or evolution during the many decades to centuries the pH concentration is projected to fall.

Source: Chapter 6. "Aquatic Life," *Climate Change Reconsidered II: Biological Impacts.* Nongovernmental International Panel on Climate Change. Chicago, IL: The Heartland Institute, 2014.

5.5.1 Evidence of Ability to Adapt

> *Aquatic life demonstrates tolerance, adaptation, and even growth and developmental improvements in response to higher temperatures and reduced water pH levels.*

The effects of climate change on coral reefs and fish have been extensively studied. As the recent research summarized here indicates, corals and fish are capable of tolerance, acclimation, and adaptation, allowing them to successfully cope with future changes in their aquatic environment.

5.5.1.1 Corals

By inducing changes in ocean water chemistry that can lead to reductions in the calcium carbonate saturation state of seawater (Ω), which lowers the water's pH level, it has been predicted that elevated levels of atmospheric $\mathrm{CO_2}$ may reduce rates of coral calcification, possibly leading to slower-growing – and, therefore, weaker – coral skeletons, and in some cases even death (Barker and Ridgwell, 2012). Such projections, however, often fail to account for the fact that coral calcification is a biologically mediated process and in the real world, living organisms tend to find a way to meet and overcome the many challenges they face. Coral calcification in response to so-called "ocean acidification" is no exception.

Pelejero *et al*. (2005) developed a reconstruction of seawater pH spanning the period 1708–1988, based on the boron isotopic composition (δ^{11}B) of a long-lived massive *Porites* coral from Flinders Reef in the western Coral Sea of the southwestern Pacific. They found "no notable trend toward lower δ^{11}B values" over the 300-year period, which began "well before the start of the Industrial Revolution." Instead, they say "the dominant feature of the coral δ^{11}B record is a clear interdecadal oscillation of pH, with δ^{11}B values ranging between 23 and 25 per mil (7.9 and 8.2 pH units)," which "is synchronous with the Interdecadal Pacific Oscillation." Furthermore, they calculated aragonite saturation state values from the Flinders pH record that varied between about 3 and 4.5, which values encompass, in their words, "the lower and upper limits of aragonite saturation state within which corals can survive." Nevertheless, they report the "skeletal extension and calcification rates for the Flinders Reef coral fall within the normal range for *Porites* and *are not correlated with aragonite saturation state* [italics added]."

Working with specimens of *Montipora capitata*, Bahr *et al*. (2017) investigated the "direct and interactive effects of temperature, irradiance, and $p\mathrm{CO_2}$" on the growth of this important Hawaiian reef-building coral. Their work was accomplished at the Hawaii Institute of Marine Biology, University of Hawaii, in a mesocosm system that represented present and projected conditions of climate change, including 12 experimental regimes consisting of two temperature levels (ambient and +2°C), three irradiance conditions (ambient, 50% reduction, and 90% reduction) and two *p*CO2 values (ambient and twice ambient). Over a period of approximately two years, several replicates of the various treatment conditions were conducted. The authors measured net coral calcification and through statistical analysis were able to untangle its relationship among these three factors.

The analysis revealed that temperature and irradiance were the primary factors driving net calcification of *M. capitata* and "the effect of $p\mathrm{CO_2}$ acting alone and/or with other predictors did not contribute to the multiple regression model." Bahr *et al.* conclude, "ocean warming in shallow water environments with high irradiance poses a more immediate threat to coral growth than acidification for this dominant coral species." Indeed, ocean acidification appears to pose no threat to *M. capitata* since its influence carried no predictive power in their regression model of factors influencing net calcification.

McCulloch *et al.* (2017) developed geochemical proxies (δ11B and B/Ca) from *Porites* corals located on Davis Reef, a mid-shelf reef located east-northeast of Townsville, Queensland, Australia in the central Great Barrier Reef, and Coral Bay, which is part of the Ningaloo Reef coastal fringing system of Western Australia. They obtained seasonal records of dissolved inorganic carbon (DIC) and pH of the corals' calcifying fluid (cf) at these locations for the period 2007–2012. The records revealed that coral colonies from both reef locations "exhibit strong seasonal changes in pHcf, from ~8.3 during summer to ~8.5 during winter," which "represents an elevation in pHcf relative to ambient seawater of ~0.4 pH units together with a relatively large seasonal range in pHcf of ~0.2 units."

These observations, McCulloch *et al.* note, "are in stark contrast to the far more muted changes based on laboratory-controlled experiments," which laboratory-based values are "an order of magnitude smaller than those actually observed in reef environments." With respect to DICcf , they report that the "highest DICcf (~ x 3.2 seawater) is found during summer, consistent with thermal/light enhancement of metabolically (zooxanthellae) derived carbon, while the highest pHcf (~8.5) occurs in winter during periods of low DICcf (~ x 2 seawater)."

The proxy records also revealed that coral DICcf was inversely related (r2 ~ 0.9) to pHcf. Commenting on this relationship, McCulloch *et al.* say it "indicate[s] that the coral is actively maintaining both high (~x 4 to x 6 seawater) and relatively stable (within ± 10% of mean) levels of elevated Ωcf year-round." Or, as they explain it another way, "we have now identified the key functional characteristics of chemically controlled calcification in reef-building coral. The seasonally varying supply of summer-enhanced metabolic DICcf is accompanied by dynamic out-of-phase upregulation of coral pHcf. These parameters acting together maintain elevated but near-constant levels of carbonate saturation state (Ωcf) of the coral's calcifying fluid, the key driver of calcification."

The implications of the McCulloch *et al.* findings are enormous, for they reveal that "pHcf upregulation occurs largely independent of changes in seawater carbonate chemistry, and hence ocean acidification," demonstrating "the ability of the coral to 'control' what is arguably one of its most fundamental physiological processes, the growth of its skeleton within which it lives." Furthermore, McCulloch *et al.* say their work presents "major ramifications for the interpretation of the large number of experiments that have reported a strong sensitivity of coral calcification to increasing ocean acidification," explaining that "an inherent limitation of many of these experiments is that they were generally conducted under conditions of fixed seawater pHsw and/or temperature, light, nutrients, and little water motion, hence conditions that are not conducive to reproducing the natural interactive effects between pHcf and DICcf that we have documented here." They conclude that "since the interactive dynamics of pHcf and DICcf upregulation do not appear to be properly simulated under the short-term conditions generally imposed by such artificial experiments, the relevance of their commonly reported finding of reduced coral calcification with reduced seawater pH must now be questioned."

Moving from ocean pH to temperature, the ability of coral reefs to survive climate change "will depend partly on the relative rates of increase of thermal tolerance and of environmental temperatures" (Bay and Palumbi, 2015). The degree of thermal tolerance depends, in large measure, on an organism's ability to adapt (evolutionary change) and/or acclimate (physiological change) to temperature stress. In long-lived organisms, acclimation generally produces the more rapid response.

A growing body of work demonstrates the strong potential for recovery from coral bleaching at various places around the world, with perhaps an evolving potential for corals to successfully recover from increasingly more intense warming episodes in the face of rising global temperatures.

Yamano *et al.* (2011) report, "although most studies of climate change effects on corals have focused on temperature-induced coral bleaching in tropical areas, poleward range shifts and/or expansions may also occur in temperate areas, as suggested by geological records and present-day eyewitnesses in several localities," citing the work of Greenstein and Pandolfi (2008) and Precht and Aronson (2004).

Yamano *et al*. collected records of coral species occurrence from eight temperate regions of Japan, where they obtained "the first large-scale evidence of the poleward range expansion of modern corals, based on 80 years of national records ... where century-long measurements of *in situ* sea-surface temperatures have shown statistically significant rises." They determined "four major coral species categories, including two key species for reef formation in tropical areas, showed poleward range expansions since the 1930s, whereas no species demonstrated southward range shrinkage or local extinction," adding "the speed of these expansions reached up to 14 km per year," which they say "is far greater than that for other species." They conclude that "temperate areas may serve as refugia for tropical corals in an era of global warming."

Carilli *et al.* (2012) write "there is evidence that corals may adapt to better withstand heat stress via a number of mechanisms," noting "corals might acquire more thermally-resistant symbionts (Buddemeier and Fautin, 1993; Rowan, 2004), or might increase their own physiological mechanisms to reduce bleaching susceptibility by producing oxidative enzymes (Coles and Brown, 2003) or photoprotective compounds (Salih *et al*., 2000)." They point out that evidence suggests the susceptibility of a given coral or reef to bleaching depends on the thermal history of that coral or reef (Thompson and Van Woesik, 2009; Donner, 2011; Brown *et al*., 2002).

Carilli *et al.* "collected cores from massive *Porites sp.* corals in the Gilbert Islands of Kiribati to investigate how corals along a natural gradient in temperature variability responded to recent heat stress events," examining "changes in coral skeletal growth rates and partial mortality scars (Carilli *et al*., 2010) to investigate the impact of the bleaching event in 2004 (Donner, 2011) on corals from different temperature variability regimes."

They found the spatial patterns in skeletal growth rates and partial mortality scars found in corals from the central and northern islands suggest "corals subject to larger year-to-year fluctuations in maximum ocean temperature were more resistant to a 2004 warm-water event," and "a subsequent 2009 warm event had a disproportionately larger impact on those corals from the island with lower historical heat stress." They say their study indicates "coral reefs in locations with more frequent warm events may be more resilient to future warming."

Bellantuono *et al.* (2012) "tested the response of *Acropora millepora* to thermal preconditioning by exposing coral nubbins to 28°C (3°C below bleaching threshold) for 10 days, prior to challenging them with water temperatures of 31°C for 8 days." Additionally, "in another treatment (non-preconditioned), corals were exposed to 31°C without prior exposure to the 28°C treatment." They discovered that short-term preconditioning to higher-than-ambient temperatures (but still 3°C below the experimentally determined bleaching threshold) for a period of ten days provided thermal tolerance for the coral and its symbionts.

Bellantuono *et al*. say their findings suggest "the physiological plasticity of the host and/or symbiotic components appears to play an important role in responding to ocean warming." They describe some real-world examples of where this phenomenon may have played a crucial role in preserving corals exposed to extreme warm temperatures in the past, citing Fang *et al*., 1997; Middlebrook *et al*., 2008; and Maynard *et al*., 2008.

"To uncover the long-term impacts of elevated temperature exposure to corals from reefs that experience episodic upwelling," Mayfield *et al.* (2013) conducted a mesocosm-based experiment whereby *P. damicornis* specimens collected from an upwelling coral reef on Houbihu (a small embayment within Nanwan Bay, southern Taiwan) were exposed for nine months to nearly 30°C, a temperature the corals normally encounter *in situ* for just a few hours per year (Mayfield *et al*., 2012).

They found, "upon nine months of exposure to nearly 30°C, all colony (mortality and surface area), polyp (*Symbiodinium* density and chlorophyll *a* content), tissue (total thickness), and molecular (gene expression and molecular composition)-level parameters were documented at similar levels between experimental corals and controls incubated at 26.5°C, suggesting that this species can readily acclimate to elevated temperatures that cause significant degrees of stress, or even bleaching and mortality, in conspecifics of other regions of the Indo-Pacific."

Mayfield *et al*. say "there is now a growing body of evidence to support the notion that corals inhabiting more thermally unstable habitats outperform conspecifics from reefs characterized by more stable temperatures when exposed to elevated temperatures," citing Coles (1975), Castillo and Helmuth (2005), and Oliver and Palumbi (2011).

Graham *et al*. (2015) document coral reef responses to the major warming-induced bleaching event of 1998 that caused unprecedented region-wide mortality of Indo-Pacific corals. They report, "following loss of more than 90% live coral cover, 12 of 21 reefs recovered towards pre-disturbance live coral states, while nine reefs underwent regime shifts to fleshy macroalgae." They determined recovery was favored when reefs were structurally complex and in deeper water; when the density of juvenile corals and herbivorous fishes was relatively high; and when nutrient loads were low. In a commentary on these findings, Pandolfi (2015) writes, "the fact that more than half of the reefs fully recovered after the bleaching event is a promising outcome for the future of coral reefs." Pandolfi writes, "put simply, many reef corals just might be capable of adapting fast enough to survive current rates of global environmental change," citing the work of Pandolfi *et al*. (2011) and Munday *et al.* (2013).

Bay and Palumbi (2015) conducted a laboratory-based experiment to investigate the temperature acclimation of a reef-building coral, *Acropora nana*. Colonies were subjected to three baseline temperature regimes, ambient (29°C), elevated (31°C), and variable (29–33°C, mimicking the diel tidal fluctuation range). After zero, two, seven, and 11 days of treatment, samples were taken and evaluated for their response to acute temperature stress (five hours of 34°C temperature). After seven days of exposure to each coral colony's respective baseline temperature regime, *A. nana* specimens subjected to acute temperature stress displayed a "striking increase in heat tolerance," which tolerance was higher in corals acclimated to elevated and variable temperature regimes as opposed to the ambient treatment.

Bay and Palumbi say their findings suggest corals "can track environmental temperatures better than previously believed," and that the observed temperature acclimation may provide "some protection for this species of coral against slow onset of warming ocean temperatures." They also note "such rapid change in heat sensitivity runs contrary to coral bleaching models based on fixed thermal tolerance that are currently used to predict coral bleaching and climate change response," citing the works of Liu *et al*. (2013) and Logan *et al*. (2013), which suggest predictions of future coral reef demise due to rising ocean temperatures are overstated.

In addition to acclimation, corals likely have another important tool in *adaptation*. Physiological acclimation, as that found by Bay and Palumbi (2015) is generally assumed to be the more common (and most rapid) mode of stress response among long-lived organisms like corals. But the work of Dixon *et al*. (2015) reveals there is also "the potential for rapid adaptation at the genetic level based on standing genetic variation." They studied *Acropora millepora* corals inhabiting two thermally divergent locations separated by 5° of latitude on the Great Barrier Reef: Princess Charlotte Bay and Orpheus Island.

Dixon *et al*. established 10 crosses according to a diallel scheme by "cross-fertilizing gametes from four adult colonies from the two locations." The heat tolerances of the larval crosses were analyzed based on their odds of survival after approximately 30 hours exposure to 35.5°C temperatures. Among many findings, Dixon *et al*. report "parents from the warmer location (Princess Charlotte Bay) conferred significantly higher thermo-tolerance to their offspring relative to parents from the cooler location (Orpheus Island); a dam from warmer Princess Charlotte Bay conferred a fivefold increase in survival odds and a sire from Princess Charlotte Bay conferred an additional twofold increase."

Dixon *et al*. conclude their study "demonstrates heritability of coral stress-related phenotypic and molecular traits and thus highlights the adaptive potential stemming from standing genetic variation in coral metapopulations." They write, "the genetic rescue scenario, therefore, emerges as a plausible mechanism of rapid coral adaptation to climate change, especially if the natural connectivity of corals across latitudes is enhanced by assisted colonization efforts."

Madeira *et al*. (2015) collected a large number of octocorals in the spring and summer of 2013 from a pristine sandy intertidal shore in Troia, Setubal, Portugal, during midday at low tide, when temperatures were normally at their daily extreme warmth, while simultaneously recording air temperature, intertidal water temperature, salinity, and pH. In the laboratory, they analyzed the activities of several antioxidant defense enzymes and other biomarkers, along with total octocoral protein content. They found "this species is able to withstand low tide conditions in warmer temperatures without evidence of thermal or oxidative stress." And they also state that, as observed by McClanahan *et al*. (2007), corals that experience the greatest temperature variability – at higher latitudes, as in this study – are also "the corals most capable of surviving in challenging conditions." Consequently, they predict "this species is likely to be quite resilient" or even to "thrive under future climate warming conditions."

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5.5.1.2 Fish

Thermal tolerance, acclimation, and adaptation are evident in freshwater and ocean fish species as well. They may alter their ranges or behavior; over time, they can even evolve traits, such as body size, resistance to parasitic infection, and swimming ability, that make it easier for them to cope with a changing environment. A growing body of evidence, including the recent research summarized here, shows fish are not the fragile creatures the IPCC makes them out to be.

Seebacher *et al.* (2012) analyzed six populations of mosquitofish (*Gambusia holbrooki*) from coastal and mountain environments and compared their capacity for thermal acclimation, demonstrating that mosquitofish populations “are divided into distinct genetic lineages and that populations within lineages have distinct genetic identities.” They report “there were significant differences in the capacity for acclimation between traits (swimming performance, citrate synthase and lactate dehydrogenase activities), between lineages, and between populations within lineages,” thereby demonstrating “there can be substantial variation in thermal plasticity between populations within species.”

Noting “many predictions of the impact of climate change on biodiversity assume a species-specific response to changing environments,” Seebacher *et al*. say “this resolution can be too coarse and that analysis of the impacts of climate change and other environmental variability should be resolved to a population level,” since their findings suggest some populations of a species may be able to cope with a change others may not be able to tolerate.

Stitt *et al*. (2014) studied the upper thermal tolerance and capacity for acclimation in three captive populations of brook trout (*Salvelinus fontinalis*), which they obtained from three ancestral environments that differed in their upper thermal tolerance and capacity for acclimation. Building on a number of pioneering studies of thermal performance in cold-water fish (e.g., Fry *et al*., 1946; Brett, 1952; Brett *et al*., 1958; McCauley, 1958), they say their research revealed “populations can possess substantial thermal acclimation capacity, as well as heritable variation in thermal tolerance among populations,” further citing the work of Danzmann *et al*. (1998) and Timusk *et al*. (2011).

Stitt *et al*. report the three populations they studied “differed in their upper thermal tolerance and capacity for acclimation, consistent with their ancestry,” in that “the northernmost strain had the lowest thermal tolerance, while the strain with the most southern ancestry had the highest thermal tolerance.” They conclude, “with changing climatic conditions, populations of brook trout may have some degree of plasticity to cope with acute and chronic thermal stressors.”

Shama *et al*. (2014) write, “empirical evidence is accumulating that marine species might be able to adapt to rapid environmental change if they have sufficient standing variation (the raw material for evolutionary change) and/or phenotypic plasticity to mount fast responses,” citing the studies of Munday *et al*. (2013) and Sunday *et al*. (2014). They used a combined experimental approach – transgenerational plasticity (TGP) along with quantitative genetics – to partition the relative contributions of maternal and paternal (additive genetic) effects to offspring body size, a key fitness component of marine sticklebacks.

Shama *et al*. found "TGP can buffer short-term detrimental effects of climate warming and may buy time for genetic adaptation to catch up, therefore markedly contributing to the evolutionary potential and persistence of populations under climate change."

Narum and Campbell (2015) note "thermal adaptation is a widespread phenomenon in organisms that are exposed to variable and extreme environments," adding "some organisms may alter their distribution or behavior to avoid stressors and others may acclimate through physiological plasticity, [and] many species evolve adaptive responses to local conditions over generations through natural selection," citing Dahloff and Rank (2000), Hoffman *et al*. (2003), and Kavanagh *et al.* (2010). They continue, "evolutionary adaptation to local environments has been demonstrated across a wide variety of taxa" – citing Keller and Seehausen (2012) – "and is expected to play a critical role for species with limited dispersal capabilities."

Narum and Campbell "tested for differential transcriptional response of ecologically divergent populations of redband trout (*Oncorhynthus mykiss gairdneri*) that had evolved in desert and montane climates." They reared each pure strain and their F1 cross "in a common garden environment … exposed over four weeks to diel water temperatures that were similar to those experienced in desert climates within the species' range," after which "gill tissues were collected from the three strains of fish (desert, montane, F1 crosses) at the peak of heat stress and tested for mRNA expression differences across the transcriptome with RNA-seq."

Narum and Campbell found "redband trout from a desert climate have a much larger number of strongly differentially expressed genes than montane and F1 strains in response to heat stress, suggesting that a combination of genes has evolved for redband trout to adapt in their desert environment."

Cure *et al.* (2015) assessed the size structure and habitat associations of juvenile *Choerodon rubescens*, a popular reef fish, during the summer and autumn of 2013 (January–May) by means of an underwater visual census conducted across available shallow water habitats towards the southern range edge of their historic distribution. They report "high abundances of juveniles (up to 14 fish/40 m^2) were found in areas where they were previously absent or in low abundance." Based on the size structure of the populations they encountered, they say "recruitment was estimated to occur during summer 2011–12 and 2012–13," which "coincides with water temperatures 1 to 2°C higher than long-term averages in the region, making conditions more favorable for recruits to survive in greater numbers." They say their finding "mirrors the well-established patterns observed on the east coast of Australia," citing the studies of Booth *et al.* (2007), Figueira *et al.* (2009), Figueira and Booth (2010), and Last *et al*. (2011).

In 1980, heated water from a nuclear power plant in Forsmark, Sweden began to be discharged into Biotest Lake, an adjacent artificial semi-enclosed lake in the Baltic Sea created in 1977. The heated water has raised the temperature of the lake by 6–10°C compared to the surrounding Baltic Sea, but other physical conditions between the lake and the sea are very similar.

A few years after the power plant began operation, scientists conducted a study to determine the effect of the lake's increased temperatures on the host-parasite dynamics between a fish parasite, the eyefluke (*Diplostomum baeri*), and its intermediate host, European perch (*Perca fluviatilis*). That analysis, performed in 1986 and 1987, revealed that perch in Biotest Lake experienced a higher degree of parasite infection compared to perch living in the cooler confines of the surrounding Baltic Sea (Höglund and Thulin, 1990), which finding is consistent with the IPCC's concerns that rising temperatures may lead to an increase in infectious diseases.

Mateos-Gonzales *et al*. (2015) returned to Biotest Lake and reexamined the host-parasite dynamic. They note Biotest Lake "provides an excellent opportunity to study the effect of a drastically changed environmental factor, water temperature, on the evolution of host-parasite interactions, in a single population recently split into two." They compared the prevalence and intensity of parasitic infection in perch populations growing in warmer Biotest Lake versus the natural population from the surrounding cooler Baltic Sea in 2013 and 2014. They also conducted a controlled laboratory experiment in which they exposed perch from both locations to *D. baeri*, comparing their infection rates.

The field results indicated the "intensity of infection in Baltic fish was on average 7.2 times higher than in the corresponding Biotest fish." In addition, Baltic fish were found to acquire "slightly more parasites as they age," whereas Biotest fish did not. With respect to the laboratory tests, Mateos-Gonzales *et al*. report exposure to parasites "did not have an effect in fish from the Biotest Lake, but it did in fish from the Baltic Sea," increasing their intensity of infection by nearly 40%.

Mateos-Gonzales *et al*. write the findings present "a dramatic contrast" to those reported nearly three decades earlier when Biotest fish were infected at a rate of "almost twice" that of Baltic fish. Compared to 1986/87, the intensity of parasitic infection in Biotest fish has fallen almost 80%, whereas it has decreased only slightly in Baltic fish. The authors conclude their results illustrate "how an increased temperature has potentially aided a dramatic change in host-parasite dynamics." They further note this adaptation has "direct implications for consequences of global climate change, as they show that fast environmental changes can lead to equally rapid evolutionary responses."

Veilleux *et al*. (2015) sequenced and assembled "*de novo* transcriptomes of adult tropical reef fish exposed developmentally or trans-generationally to projected future ocean temperatures and correlated the resulting expression profiles with acclimated metabolic traits from the same fish." They "identified 69 contigs [overlapping DNA sequences] representing 53 key genes involved in thermal acclimation of aerobic capacity," noting "metabolic genes were among the most upregulated trans-generationally, suggesting shifts in energy production for maintaining performance at elevated temperatures." They also found "immune- and stress-responsive genes were upregulated trans-generationally, indicating a new complement of genes allowing the second generation of fish to better cope with elevated temperatures."

Veilleux *et al*. conclude, "the plasticity of these genes and their strong correlation to known acclimating phenotypic traits suggests that they may be critical in aiding reef fishes and possibly other marine organisms to survive in a warmer future environment."

Madeira *et al*. (2016) examined the cellular stress response of a tropical clownfish species (*Amphiprion ocellaris*) exposed to elevated temperatures over a period of one month. Their experiment was conducted in a controlled laboratory setting in which they subjected juvenile *A. ocellaris* to either ambient (26°C) or elevated (30°C) temperatures, examining several biomarkers (e.g., stress proteins and antioxidants) in several tissue types (brain, gills, liver, intestine, and muscle) at zero, seven, 14, 21, and 28 days of temperature treatment. They write, "results showed that exposure time significantly interacted with temperature responses and tissue-type, so in fact time influenced the organisms' reaction to elevated temperature." At Day 7 they observed significantly higher levels of biomarkers in fish in the high temperature environment, indicative of a typical thermal stress response. Thereafter, biomarker levels stabilized, showing either "a significant decrease in comparison with controls or no significant differences from the control" through the end of the experiment, which observations they suggest are indicative of temperature acclimation.

Madeira *et al*. write, "*A. ocellaris* probably lives far from its upper thermal limit and is capable of adjusting the protein quality control system and enzymes' activities to protect cell functions under elevated temperature," adding "these results suggest that this coral reef fish species presents a significant acclimation potential under ocean warming scenarios of +4°C."

Munday *et al*. (2017) reared offspring of wild-caught breeding pairs of the coral reef damselfish, *Acanthochromis polyacanthus*, for two generations at current-day and two elevated temperature treatments (+1.5 and +3.0°C), consistent with current climate change predictions, while "length, weight, body condition and metabolic traits (resting and maximum metabolic rate and net aerobic scope) were measured at four stages of juvenile development." They found "significant genotype x environment interactions indicated potential for adaptation of maximum metabolic rate and net aerobic scope at higher temperatures," noting "net aerobic scope was negatively correlated with weight," and indicating "any adaptation of metabolic traits at higher temperatures could be accompanied by a reduction in body size."

Munday *et al*. write their results suggest there is "a high potential for adaptation of aerobic scope to high temperatures, which could enable reef fish populations to maintain their performance as ocean temperatures rise." They also report "recent studies indicate that plasticity may be especially important in enabling populations of marine species to adjust to climate change," citing among others Munday (2014), Shama *et al*. (2014), and Thor and Dupont (2015), while also noting "this type of adaptive plasticity may buffer populations against the immediate effects of environmental change and give genetic adaptation time to catch up," citing the study of Chevin and Lande (2010).

Madeira *et al*. (2017) examined the acclimation potential of the common clownfish (*Amphiprion ocellaris*) to rising temperature, exposing juvenile fish to seawater temperatures of either 26° or 30°C for a period of four weeks, during which time they measured two biochemical markers – one involved in preventing protein damage (heat shock protein 70, Hsp70) and another involved in dealing with it (ubiquitin, Ub) – to determine the presence of thermal damage to cellular proteins.

Madiera *et al*. say there were no differences in survival rates among the control and elevated temperature treatments. However, they report that thermal stress was observed in the fish after one week of exposure (both biomarkers increased significantly), after which Ub levels decreased, which the authors say suggests "the animals were able to acclimate." Thereafter, "as the juveniles acclimated to the new temperature conditions, Hsp70 kept showing increased levels in order to maintain cellular homeostasis, while the degree of irreversible damage (protein denaturation) started to decrease, as shown by lower Ub levels." Thus, Madiera *et al*. conclude "*A. ocellaris* is capable of displaying a plastic response to elevated temperature by adjusting the protein quality control system to protect cell functions, without decreasing survival."

Madiera *et al*. say the observed physiological acclimation in *A. ocellaris* "may come as counterintuitive, considering that tropical species have evolved in a relatively stable thermal environment and are therefore expected to exhibit narrower thermal reaction norms," yet acclimate they did, indicating clownfish "do not seem to be in immediate danger due to direct effects of warming oceans."

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5.5.2 Future Impacts on Aquatic Life

> *The pessimistic projections of the IPCC give way to considerable optimism with respect to the future of the planet's marine life.*

The experimental and observational research cited in Section 5.5.1 suggests an optimistic outlook on the future of Earth's marine life and this is in fact what researchers predict, contradicting the IPCC's pessimistic outlook.

Starting again with acidification, Loaiciga (2006) used a mass-balance approach to "estimate the change in average seawater salinity caused by the melting of terrestrial ice and permanent snow in a warming earth." He applied "a chemical equilibrium model for the concentration of carbonate species in seawater open to the atmosphere" in order to "estimate the effect of changes in atmospheric CO_2 on the acidity of seawater." Assuming that the rise in the planet's mean surface air temperature continues unabated and that it eventually causes the melting of *all* terrestrial ice and permanent snow – an extreme assumption – Loaiciga calculated that "the average seawater salinity would be lowered not more than 0.61%o from its current 35%o."

Loaiciga also reports that across the range of seawater temperature considered (0 to 30°C) "a doubling of CO_2 from 380 ppm to 760 ppm increases the seawater acidity [lowers its pH] approximately 0.19 pH units." He thus concludes that "on a global scale and over the time scales considered (hundreds of years), there would not be accentuated changes in either seawater salinity or acidity from the rising concentration of atmospheric CO_2."

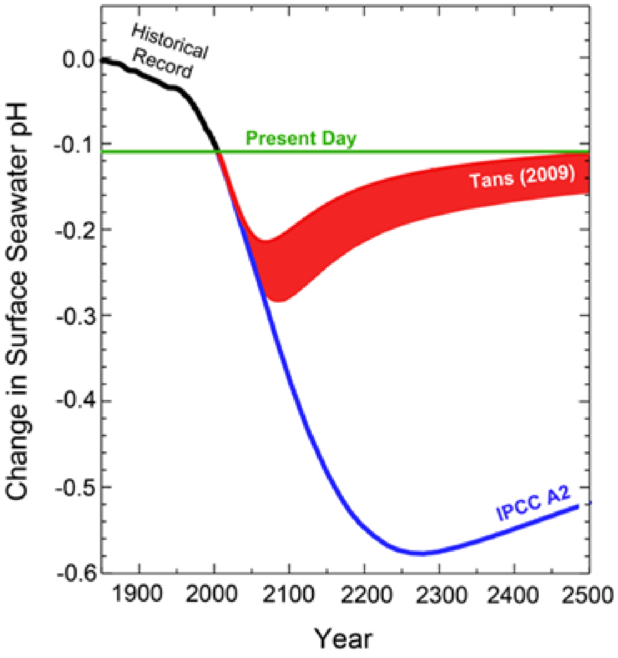
Similarly, an analysis of Tans (2009), the results of which are included in Figure 5.5.2.1 below, estimated the decline in oceanic pH by the year 2100 is likely to be only about half of that projected by the IPCC and that this drop will begin to be ameliorated shortly after 2100, gradually returning oceanic pH to present-day values beyond AD 2500.

Turning to temperature, Brown *et al.* (2010) write, "climate change is altering the rate and distribution of primary production in the world's oceans," which in turn "plays a fundamental role in structuring marine food webs (Hunt and McKinnell, 2006; Shurin *et al*., 2006)," which are "critical to maintaining biodiversity and supporting fishery catches." They note the "effects of climate-driven production change on marine ecosystems and fisheries can be explored using food web models that incorporate ecological interactions such as predation and competition," citing the work of Cury *et al*. (2008).

Brown *et al*. used the output of an ocean general circulation model driven by a "plausible" greenhouse gas emissions scenario (IPCC, 2007, scenario A2) to calculate changes in climate over a 50-year time horizon, the results of which were fed into a suite of models for calculating primary production of lower trophic levels (phytoplankton, macroalgae, seagrass, and benthic microalgae). Those results were used as input to "twelve existing Ecopath with Ecosim (EwE) dynamic marine food web models to describe different Australian marine ecosystems," which protocol ultimately predicted "changes in fishery catch, fishery value, biomass of animals of conservation interest, and indicators of community composition."

Brown *et al*. state that under the IPCC's "plausible climate change scenario, primary production will *increase* around Australia" with "overall positive linear responses of functional groups to primary production change," and that "generally this benefits fisheries catch and value and leads to increased biomass of threatened marine animals such as turtles and sharks." They conclude the primary production increases suggested by their work to result from future IPCC-envisioned greenhouse gas emissions and their calculated impacts on climate "will provide opportunities to recover overfished fisheries, increase profitability of fisheries and conserve threatened biodiversity."

Figure 5.5.2.1
The change in surface seawater pH vs. time and as calculated by Tans and the IPCC



Sources: Red band is from Figure 5 of Tans, 2009 representing two emission scenarios. Blue line is the IPCC's forecast based on emission scenario A2 from IPCC, 2007.

In a comprehensive literature review published in *Science*, Pandolfi *et al*. (2011) summarize what they describe as "the most recent evidence for past, present and predicted future responses of coral reefs to environmental change, with emphasis on rapid increases in temperature and ocean acidification and their effects on reef-building corals."

Focusing here only on Pandolfi *et al*.'s findings with respect to the future of coral reefs, they write, "because bleaching-susceptible species often have faster rates of recovery from disturbances, their relative abundances will not necessarily decline." In fact, they say "such species could potentially increase in abundance, depending on how demographic characteristics and competitive ability are correlated with thermal tolerance and on the response of other benthic taxa, such as algae," while they further note "the shorter generation times typical of more-susceptible species (Baird *et al*., 2009) may also confer faster rates of evolution of bleaching thresholds, which would further facilitate maintenance of, or increases to, the relative abundance of thermally sensitive but faster-evolving species (Baskett *et al*., 2009).”

In summing up their analysis, Pandolfi *et al*. state emerging evidence for variability in the coral calcification response to acidification, geographical variation in bleaching susceptibility and recovery, responses to past climate change, and potential rates of adaptation to rapid warming “supports an alternative scenario in which reef degradation occurs with greater temporal and spatial heterogeneity than current projections suggest.” Further noting that “non-climate-related threats already confronting coral reefs are likely to reduce the capacity of coral reefs to cope with climate change,” they conclude “the best and most achievable thing we can do for coral reefs currently to deal with climate change is to seek to manage them well,” by reducing more direct anthropogenic impacts such as fishing, pollution, and habitat destruction.

Gurney *et al.* (2013) also note the expected future importance of reef management, writing, “given that climate change impacts on coral reefs cannot be mitigated directly, the question arises whether reduction of stressors that originate and can be managed at a local scale (i.e. local-scale stressors) provides a tractable opportunity to increase the potential of coral reefs to cope with inevitable changes in the climate,” citing Pandolfi *et al.* (2011) and Hughes *et al.* (2007). They use a simulation model validated for four sites in Bolinao, Philippines to “simulate future reef state for each site 40 years into the future under scenarios involving the cumulative impact of fishing, poor water quality and thermal bleaching-induced mortality related to climate change.”

Gurney *et al.* simulated 18 scenarios, “all possible combinations of different levels of fishing pressure (three levels), coral mortality due to bleaching (three levels) and water quality (two levels).” Water quality was represented in the model through the combined effects of nutrification and sedimentation, for which they examined two scenarios: unregulated (the current situation, with high nutrification and sedimentation) and highly regulated (no impact of nutrification and sedimentation).They examined three fisheries management approaches: no reduction in fishing pressure (zero fisheries management), a 50% reduction in fishing pressure, and “no-take marine reserves” (zero fishing pressure).

Gurney *et al.* write, “our analysis of the cumulative impact of bleaching, poor water quality and fishing indicate that management of the two local stressors will significantly influence future reef state under climate change.” They conclude, “our research supports the paradigm that managing local-scale stressors is critical to the persistence of coral reefs in the context of global climate change, a concept that is widely advocated,” citing Pandolfi *et al.* (2011) and Donner (2009) “but still subject to debate,” citing Keller *et al.* (2009) and Baker *et al.* (2008).

Baker (2014) lists some of the processes described by Bay and Palumbi (2014) that indicate “reef-building corals may have a broad repertoire of responses to deal with warming temperatures.” In addition to their capacity for “maintaining diverse allelic variation,” as described by Bay and Palumbi, Baker also mentions “front-loading genes involved in heat stress,” citing Barshis *et al*. (2013) and Kenkel *et al*. (2013); “employing rapid acclimatization pathways,” citing Palumbi *et al*. (2014), DeSalvo *et al*. (2010), and Kenkel *et al*. (2013); “changing the composition of their algal symbiont communities,” citing Baker *et al*. (2004) and Berkelmans and van Oppen (2006); and “maintaining a healthy pool of microbial associates” in order “to prevent infection and disease during recovery from heat stress,” citing Bourne *et al*. (2009).

Baker closes, optimistically, that “these diverse responses provide hope that the world’s remaining corals may still contain the adaptive ingredients needed to survive.”

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5.6 Conclusion

> *Combustion of fossil fuels has helped and will continue to help plants and animals thrive leading to shrinking deserts, expanded habitat for wildlife, and greater biodiversity.*

Many of the scholars and advocates who write about climate change are either unfamiliar with or overlook the environmental benefits created by human use of fossil fuels. Chemists and biologists should know better: Fossil fuels are composed mainly of hydrogen and carbon atoms, two of the most abundant elements found in nature. They are not "pollutants" but share a common chemical basis with all of life on Earth.

Geologists should know better, too. The global carbon cycle acts to buffer the impact of man-made carbon dioxide (CO_2) by including it in exchange processes among carbon reservoirs that are huge compared to the human contribution. The size of the human contribution to atmospheric CO_2 concentrations is so small it may be less than the margin of error in measurements of known exchange rates among carbon reservoirs. Geologists ought to realize that current atmospheric CO_2 levels are not unprecedented and indeed are low when considered over geologic time scales. Because CO_2 is essential to plant and animal life, it is possible human use of fossil fuels may avert an ecological disaster.

Fossil fuels directly benefit the environment by making possible huge (orders of magnitude) advances in efficiency, making it possible to meet human needs while using fewer natural resources. Fossil fuels make it possible for humanity to flourish while still preserving much of the land needed by wildlife to survive. And the prosperity made possible by fossil fuels has made environmental protection both highly valued and financially possible, producing a world that is cleaner and safer than it would have been in their absence.

This chapter also finds the CO_2 released when fossil fuels are burned improves the productivity of ecosystems and has a positive effect on plant characteristics, including rates of photosynthesis and biomass production and the efficiency with which plants utilize water. Atmospheric CO_2 enrichment ameliorates the negative effects of a number of environmental plant stresses including high temperatures, air and soil pollutants, herbivory, nitrogen deprivation, and high levels of soil salinity. With the help of the ongoing rise in the air's CO_2 content, humankind should be able to meet the food needs of a growing population without occupying much of the land needed by wildlife to survive.

Although there likely will be some changes in terrestrial animal population dynamics, few (if any) will be driven even close to extinction. In a number of instances, real-world data indicate warmer temperatures and higher atmospheric CO_2 concentrations will be beneficial, favoring a proliferation of terrestrial species. Similarly, many laboratory and field studies of aquatic life demonstrate tolerance, adaptation, and even growth and developmental improvements in response to higher temperatures and reduced water pH levels. When these observations are considered, the pessimistic projections of the IPCC give way to considerable optimism with respect to the future of the planet's terrestrial and marine life.